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From temporary arrangements to permanent change: Assessing the transitional capacity of city street experiments

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ABSTRACT

In response to acute urban mobility and livability challenges, city street experiments have emerged as a way to explore possible solutions for alternative futures. While the added value of these experiments to improve urban living conditions is widely acknowledged, their potential to stimulate larger system change remains unknown. This paper uses the defining characteristics of transition experiments and a multi-level perspective of transitions in order to assess the transitional capacity of city street experiments. We devise an assessment framework to systematically assess six case studies in Amsterdam and Munich, revealing emerging patterns of experimentation within urban mobility systems.

Introduction

The transition to more sustainable and livable cities is a formidable one: an entire urban mobility system, including user behavior, government policies and market strategies, organizational frameworks, institutional arrangements, and existing infrastructure, must be overhauled (Berger et al., 2014). City street experiments offer a low-cost, low-risk way to explore potential routes towards increased sustainability and livability. As “intentional and temporary changes to the street use, regulation and or form, featuring a shift from motorized to non-motorized dominance and aimed at exploring systemic change in urban mobility and public life” (Bertolini, 2020), these practices offer a glimpse of “radically different arrangement of the urban mobility system” (Bertolini, 2020, p. 736) that look “beyond… mobility itself to reconceive streets as public places for social interaction and conviviality” (Prytherch, 2021). While city street experiments are not new - well-known examples like the Ciclovía in Bogotá, Columbia date back to the 1970’s (Montero, 2017) and the first Parking Day took place in 2005 (Parking Day, 2021) - they have increased popularity over the last years in response to acute sustainability challenges (Bertolini, 2020).

Examples of these experiments include subtle modifications, like the remarking of street intersections to more radical projects, such as the closure of entire streets to traffic for pedestrian activities. With help from the recent coronavirus pandemic (Combs, 2020; Glaser & Krizek, 2021; Transport for London, 2021), current measures ranging from ‘Parklets’ or the temporary conversion of parking spaces, to the temporary closure of entire streets to motorized traffic are the product of government-led efforts to take back the streets for leisure, socializing and playing (Iveson, 2013). By temporarily altering the streetscape, street experiments allow city makers to meet current spatial and social demands. At the same time, they offer the opportunity to test potential solutions to long-term challenges such as air pollution, noise, traffic-related accidents and road congestion. In particular, city street experiments have resulted in a number of benefits including increased social cohesion (Zieff, Chaudhuri & Musselman, 2016) and economic activity (Littke, 2016) feelings of safety and well-being (Meyer, Bridges, Schmid, Hecht & Porter, 2019) and physical activity (D’Haese et al., 2015). These added values represent possible change pathways to be learnt from and extrapolated to a wider scale or the long-term, a potential of city street experiments that is, however, often undervalued and underused (Bertolini, 2020).

Experimentation has been lauded as a useful tool in urban planning (Savini & Bertolini, 2019), especially in the context of the sustainability transition (Moloney & Horne, 2015; Evans et al., 2021). Still, the experimentation with city streets remains in its infancy, in both practice and research. Only a handful of studies have been conducted regarding their impacts (Bertolini, 2020; Meyer et al., 2019) and a critical reflection on their transitional capacity has yet to be made. This may be due in part to the common positioning of city street experiments as ‘one-off, fun events’ (Hipp, Bird, van Bakergem & Yarnall, 2017) and a failure to rec-

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ognize their long-term potential. How, then, can city street experiments create, build upon and exert their transitional capacity within the urban mobility system?

To answer this question, this paper explores the possible 'ingredients' needed to foster purposeful street experimentation within the context of a sustainable urban mobility transition. Our aim is two-fold. First, by introducing and immediately employing an assessment framework for the transitional capacity of city street experiments, we take the initial and, in our opinion, much-needed step towards conceptualizing the relationship between such initiatives and system change. Second, we identify emerging patterns to be pursued by future research, as well as initial lessons for practitioners of city street experiments.

The paper is structured as follows. We begin with a theoretical overview of transition studies, the backbone of our assessment framework, positioning city street experiments within this body of literature. Next, we present our assessment framework and research methodology, including our case selection strategy, and data collection methods. We then describe six case studies in Amsterdam and Munich, followed by a discussion of the results from the assessment framework and a reflection on this method of research. In the conclusions we highlight possible implications of these results for research and practice.

Framing a transition within the urban mobility system: the multi-level perspective (MLP)

The field of transition studies specifically looks at the role of socio-technological innovations in the transition towards more sustainable practices with an emphasis on experimentation and learning. Much of the literature regarding 'systems in transition' employ Rip and Kemp's (1998) 'multilevel' model of innovation, which distinguishes between the macrolevel of the 'sociotechnical landscape', the meso level 'regime', and the micro level 'niche' (Geels, 2005; Späth & Rohracher, 2012). The MLP has been utilized often in framing transitions within urban mobility (Geels, 2012; Grin, Rotmans, Schot, Geels & Loorbach, 2010; Switzer, Bertolini & Grin, 2013), and more recently applied as a framework for understanding the transitional capacity of city street experiments (see Bertolini, 2020 and Glaser and Krizek 2021). Generally speaking, changes at the landscape level put pressure on the regime, creating windows of opportunity for niches to emerge and develop.

According to Geels (2005): "Whether or not transitions take place depends partly on strategic maneuvering, the building of coalitions and power, and partly on wider developments at regime and landscape level that create or close windows of opportunity (p. 469)." Strategic maneuvering occurs at the niche level and is the result of individual agency from local actors, including users, policy makers, and civil society groups (Switzer et al., 2013). Related to this, individuals aggregate and build coalitions, leading to more resources meaning a higher degree of momentum for niches (Geels, 2012). This all occurs against the backdrop of developments at the regime and landscape levels, where external factors have just as much of an effect on the capability of such experiments to 'break-through' (Savini & Bertolini, 2019).

Literature regarding sustainable transition within urban mobility points to the factors that can determine change. A sustainable transition involves co-evolutionary developments between industry, markets, user behavior, policy, infrastructure and spatial arrangements (Geels et al., 2017; Moradi & Vagnoni, 2018). Based on this theory, we outline four 'dimensions of system change' across which developments within urban mobility system can be measured: behavioral, institutional, material, and organizational.

The first dimension, *behavioral*, is defined as 'a shift in individual use and behavior'. It refers to changing the behavioral patterns of individual users, whose lifestyles are inextricably linked to mobility (Bertolini, 2012). Without access to basic services, taking part in modern-day social and economic life is not possible, and mobility is essential to access many of them. Such users however have limited incentives to address sustainability transitions (Geels, 2011, Berger et al., 2014), making the altering of their behavior difficult. This is partly due to the magnitude of the transition and the fact that developments at the landscape level (where many of the mobility needs arise) cannot be directly influenced by individuals. Mobility choices vary per user and are the result of cost benefit assessments related to a combination of socio-demographic, economic and cultural conditions, habit, as well as the attractiveness of locations or transport options (Switzer et al., 2013). "This has important sociological implications, since there is no general 'social mobility movement' but various conflicting issues which take precedence depending on who is demanding the change (Vasconcellos, 2018)." While a change in the mobility pattern of one single actor does not mean system change, larger shifts are possible as a result of "aggregated" individual actions at multiple loci (Geels, 2013).

The second dimension, *institutional*, is defined here as 'alterations to city-wide mobility and public space policies, legal and financial frameworks, cultural/social norms'. Sustainability-oriented policies in the mobility domain can adopt variegated approaches and instruments, including market-based, information-based and regulatory instruments (Holden, 2007). "To be effective, these instruments should contribute to a coherent policy framework and aim to stimulate, enable, and empower the actors along the mobility domain to engage in more sustainable production and consumption" (Berger et al., 2014, p. 311). Market-based instruments intend to spark change via taxes and subsidies. Information-based instruments are grounded in the assumption that "better informed consumers will make more socially desirable decisions" (Ibid., 2014). They aim to provide awareness so that individuals will make informed choices and ultimately change their behavior voluntarily. Regulatory instruments in the field of mobility mostly respond to health and safety concerns (e.g. speed limits, low emission zones, and lanes for bicycles and public transport), but are often linked to environmental sustainability issues and result in modifications in spatial planning like restrictions to the access of vehicles.

The third dimension of change, *material*, involves 'a physical change in the composition of the streetscape' including an alteration of the physical form (e.g. installment of furniture, greenery, removal of parking spaces, street layout and markings, and distribution of road space). Although a relatively underdeveloped concept within the literature on transitions (Coenen, Raven & Verbong, 2010), the role of the built environment represents an essential aspect in the transition towards increased sustainability of the urban mobility system. Existing infrastructure must be overhauled in order to make physical space for different modes of transportation and other uses. This includes an alteration of the physical form of predominantly car-oriented streetscapes with new layouts (priority to bicycles and pedestrians, space for socializing or lounging), the addition of usable objects (street furniture, bicycle sharing), greenery, and new programming. In the chapter 'First we shape cities, then they shape us' Gehl (2010) writes "Planning and design can be used to influence the extent and character of outdoor activities. Invitations to do something outdoors other than just walking should include protection, security, reasonable space, furniture and visual quality" (p. 21).

Transitions are multi-actor processes that involve interactions between many social groups and the creation of coalitions (Geels, 2005). This fourth dimension, *organizational*, includes 'a shift in the network of players, organizations and/or state, market, and civic collaborations'. The transition towards greater sustainability in urban mobility is a collective effort, dependent on a network of actors as urban mobility "affects a great variety of different economic, public and social interest groups (Lindenau & Böhler-Baedeker, 2014, p. 348)". One way forward is through collaboration between businesses, service providers, users, and the public sector. New coalitions and actor networks involving multiple actors or stakeholders lead to an increased efficiency by sharing resources. potentially leading to fewer vehicles in urban areas, less pollution, and lower prices for goods (Cleophas, Cottrill, Ehmke & Tierney, 2019).

Framing the transitional capacity of city street experiments

Experimentation is one example of a niche development that occupies a central position within the field of sustainability transitions (Evans & Karvonen, 2016*)*. By means of experiments, policy makers often celebrate the innovative potential of start-ups, local associations and new technologies in addressing sustainable development (Savini & Bertolini, 2019). Such experimentation often occurs in urban contexts and is seen to offer a crucial mechanism to develop transformative knowledge and catalyze social learning (Wolfram, 2016). “As precious yet-to-germinate microcosms of sustainable systems and practices, the alternative socio-technical configurations embodied in experiments are applied and tested in real-life contexts with the aim of technological, social and institutional learning (Evans et al., 2016*,* p. 15).”

Contrary to scientific experiments, the experiments conducted in the context of transitions are not designed to establish facts about a single causal relationship but aim to simulate a complex process of social and technological co-evolution with emergent properties (Evans & Karvonen, 2016). Evans and Karvonen (2016) offers a number of types of experiments, including sustainability experiments, grassroots experiments, ‘bounded socio-technical experiments’, and ‘transition experiments’. The latter are characteristically social and mobilizing, challenge-driven, aiming to make a step towards long-term change by way of an inclusive and participatory process between diverse participants. Because of this, and in combination with an extensive literature review, Bertolini, 2020 suggests framing of city street experiments as transition experiments, in order to understand how change within the urban mobility system can be achieved, and to center an assessment framework of their transitional potential around five defining characteristics derived from Roorda et al. (2014): their being *radical, challenge-driven, feasible, strategic* and *communicative*.

Bertolini, 2020 sketch of how the characteristics of transition experiments can be applied to city street experiments provides a stepping-stone for our assessment framework. City street experiments aim to provide a glimpse of a drastically different future scenario, wherein streets are for mixed uses including socializing, playing, and exercising - that is, ‘for people’ (Gehl, 2010) - rather than for traffic. When one acknowledges the novelty of this concept in light of the dominance of private automobility, city street experiments are particularly *radical* or “fundamentally different from dominant practices” (Bertolini, 2020, p. 746). By aiming to take back these ‘quintessential social public space(s)’ (Mehta, 2015) from the dominance of automobiles, city street experiments represent the testing of novel ideas for the first time in an urban context.

City street experiments can also be *challenge-driven* by “making a step toward a potentially long-term change pathway to address a societal challenge” (Bertolini, 2020, p. 747). While most current examples of street experiments seem to be focused on the event itself, they do have the potential to connect to long-term pathways towards system wide change, with which they often share aims. he popular and highly referenced Pavement to Plazas program in New York City represents street experimentation with explicit system-wide transformative side effects (Bertolini, 2020; Lydon & Garcia, 2015). This program was embedded in a city-wide strategy to structurally transform streetways into other uses, while deploying new bike-sharing programs and improved public transportation services (Sadik-Khan & Solomonow, 2017). This multifaceted quality of city street experiments and the ambition to address numerous challenges in one go (e.g. mobility, public space, social), further supports the *challenge-driven* characteristic. Moreover, experiments that model themselves after examples that (could) have achieved system-wide change, like the well-known *leefstraat* (living street) model from Belgium (Loorbach et al., 2016), the *ciclovias* of Latin America (Sarmiento, Díaz Del Castillo, Triana, Acevedo, Gonzalez, & Pratt, 2017) and the open streets of North America (see Eyler, Hipp and Lokuta 2015), can be considered challenge-driven.

The third characteristic of transition experiments is *feasible*, or “easy to be realized in the short-term and with readily available resources” (Bertolini, 2020, p. 747). Such experiments demand not only funding, but are also dependent on support from stakeholders, altered regulations of street use, and the provision of alternative transportation and parking options. A relevant aspect in this respect is the temporary condition of city street experiments. Important to note here is, however, the current literature’s lack of specificity with the designation ‘short-term’. While existing research has explored the different time-frames of experiments (see Kuhlberg, Hipp, Eyler & Chang, 2014), their preparation time has yet to be a focus of study. An important detail in regards to this characteristic is the fact that city street experiments are not simply temporary, but typically of very short duration. Some experiments last for one day, while others span the time frame of several weeks.

City street experiments can also be *strategic*, or “capable of generating lessons for reaching envisioned fundamental changes” (Bertolini, 2020). An important component to this characteristic is the monitoring and assessment of experiment effects both during and following its completion. In their review of the Pavement to Plazas experiment, Sadik-Khan and Solomonow (2017) stress that monitoring, publishing and publicly debating the effects of their experiments was an integral part of their longer-term change strategy. Because city street experiments are concerned with more than improving problems only related to traffic, but also impacts on physical activity, well-being, social capital, perceptions, and economic activity, methods for measuring these more qualitative benefits should be included, beyond a narrow mobility focus.

City street experiments can lastly be considered as *communicative*, “reaching and possibly mobilizing the broader public” (Bertolini, 2020, p. 748). Especially for those examples which target a physical redesign of public space, experiments act as a billboard for their own promotion. The collaborative nature of city street experiments furthers this mobilizing aspect, as a multitude of actors, including civicand market parties, are brought into contact and connected by a shared goal. This process, similar to other forms of community activism (VanHoose & Savini, 2017), is fueled by bonding and bridging social capital and has the potential to result in an awakened or increased sense of community (Ibid.). Involving stakeholders in the decision-making process encourages them to take ownership of sustainable mobility ideas and, at the same time, provides policy-makers the opportunity to incorporate local expertise to reach the best possible outcome (Lindenau & Böhler-Baedeker, 2014). The *communicative* aspect works in two directions - experiments and their organizers can actively promote themselves by sharing information and creating awareness via social media or outreach programs, or experiments can open up, garnering media attention from the outside-in (e.g. news coverage, social media).

These five characteristics of city street experiments occur in different strengths across existing experiments and can be construed as ‘flocking’ together. For instance, *radical, feasible* and *communicative* go hand in hand and appear to be the strongest characteristics of current experiments (Bertolini, 2020). The *radical* nature of these experiments acts as a magnet for attention from news outlets and social media, contributing to their *communicative* capacity via a “virtual awareness” (Ibid., p. 15) and likewise, increasing their *feasibility* through the garnering of support and resources. The other two characteristics, *strategic* and *challenge-driven*, prove to be the weakest due to often “non-existing links with broader and longer-term urban policies and with social and organizational learning processes that reach beyond the event (Ibid., p.19).”

This balancing act has been suggested as a key challenge for city street experiments and their impact on system change. The very attributes that sets city street experiments apart is their temporality and informality, however, their positioning as one-off, fun events, rather than as long-term strategies (Hipp et al., 2017) has the potential to limit their range of influence. In fact, “several of the barriers, tensions and challenges identified by the literature seem to concern the weak relationship with city-wide, mainstream policy, financial, legal, and organisational frameworks" (Bertolini, 2020, p. 744). In their analysis of open street initiatives in the United States, Hipp et al. (2017) note the limited impact of open streets in the U.S. as directly related to their low frequency. Such one-time events are unable to generate transformative processes that may influence other contexts and practices (Savini & Bertolini, 2019). Conversely, experiments that last longer and even become permanent are often more strategic and challenge-driven but likewise, tend to be less radical (Bertolini, 2020).

Knowledge regarding the specific interaction between characteristics is further limited, however it represents a crucial step in understanding the transitional capacity of city street experiments. As mentioned earlier, critical assessments of city street experiments are few and far between, with most evaluations focusing on the experiment itself with no mention of their impacts (Bertolini, 2020). In the next section we introduce an assessment framework for the transitional capacity of city street experiments, aiming to fill this knowledge gap.

Transitional capacity of city street experiments: an assessment framework

Drawing from the transition literature and existing knowledge regarding city street experiments, their potential and challenges, we conceptualize the urban mobility 'system' as follows: Cities are composed of several mobility regimes including active modes, public transportation, and the most dominant, private automobility. Against the backdrop of developments at the landscape level (e.g. awareness for climate change) innovative ideas to meet challenges expressed on a local level are outed in the form of niche experiments. These experiments - temporary, local and place-specific - pop up, allowing users to explore possible solutions, potentially unlocking trajectories upheld by system regimes.

In order to understand *how* this process works, including barriers and challenges of change for city street experiments, we operationalize the transitional capacity of city street experiments using the five characteristics of transition experiments (C1-C5) as proposed by Bertolini, 2020 and discussed above. Each characteristic is further defined by indicators from existing literature (Bertolini, 2020; Glaser & Krizek, 2021; Roorda et al., 2014).

To operationalize change at the system level, we adapted the framework of the MLP to the urban mobility system using four dimensions: *behavioral* change (D1) in the behavior of users; *institutional* change or alterations to city-wide policies, legal and financial frameworks (D2); *material* change in the physical composition of the streetscape (D3) and *organizational* change in the network of players, organizations and/or state, market, and/or civic collaborations (D4).

For the purpose of theoretical exercise, the analysis is structured around the following working hypothesis: the greater the presence of the five characteristics, the greater potential change is realized (see Fig. 2). It is important to realize that these hypothesized relationships, like all frameworks conceptualizing transitions, are heuristic and not a "truth machine" (Geels, 2012, p. 474). Any evidence of an experiment leading to change on a system level is the result of multiple processes, actions, actors and levels representing different, potential change pathways extending well beyond the scope of our framework. This framework is therefore used heuristically, in order to guide us in identifying any emergent patterns inherent to city street experiments and their transitional capacity for system change in urban mobility, as a base for further, more focused enquiries.

Research methodology

In order to explore the relationship outlined above, a qualitative and explorative, multi-embedded case-study design was adopted. The use of a multi-embedded case study design provides a holistic and meaningful understanding of a complex phenomenon (Yin, 2009) such as the transition towards sustainability in urban mobility. We selected Munich and Amsterdam as our cases (n = 2) and local examples of city street experiments as the embedded unit of analysis (n = 6). The two cities were chosen for their comparability in terms of ambitions to reduce car use and evidence of street experimentation in recent years. At the start of 2020, both cities published policy-documents announcing their ambitions and plan to have fewer cars in the city (Gemeente Amsterdam, 2020; Referat für Stadtplanung und Bauordnung, 2020). Both Munich and Amsterdam have become more open to experimenting and processes are being facilitated, most recently accelerated in Munich, in particular, by the coronavirus pandemic. In Amsterdam, successful street experiments have been institutionalized, such as the 'living streets', with a clear process and financial support for organizers. In Munich, experiments are primarily seen as pilot projects used for promotion of the city's campaign for less cars. (. While these cities share a common position in this transition, they differ in their urban governance patterns, offering insight into the impact of contextual factors on the transitional capacity of city street experiments.

We first made an inventory of city street experiments occurring after 2016 - for data accessibility reasons - in each city. From this catalog, six case studies were selected for the analysis based on the following criteria: (1) experiments must feature the streetscape (the road and adjacent public space) as the object of transformation and (2) they must have been implemented with the intention of being temporary, regardless of whether they later became permanent or were repeated elsewhere.

A a total of 13 interviews with selected stakeholders from the six case studies were conducted between March and November 2021 (see Table A 2 in Appendix). With the intent of reaching a balanced representation, actors directly involved in the experiment, including experiment initiators (n = 4) and project managers (n = 4), as well as 'helicopter viewers' (Ehnert et al., 2018) including policy-makers (n = 2) and urban designers (n = 1) with a general knowledge of the urban context were interview subjects. Where possible, secondary data provided by policy documents, research articles, news articles and social media was collated to contextualize and triangulate interview responses and assessment results. The fieldwork was conducted by two local research teams, based in the respective cities. Each team followed the same interview and analysis guide, which outlined all steps in the research process in order to ensure comparability of the data. To avoid misunderstandings, interviews were conducted in the local language and translated into English afterwards.

To assess the transitional capacity of each case study, the interview data was coded following the transition experiment framework (see Table A1 in the Appendix) and rated on a scale from '0–2' (0 = weak, 1 = average; 2 = strong). The research team members independently read the interview transcripts and relevant additional documents, scoring each of the six case studies based on the 32 components using the numerical scale. In order to reach a final score for each case, the researchers compared individual scores by way of a qualitative discussion within each team, an approach that has been applied in at least three other studies of a similar research design (Dill, Smith & Howe, 2017 and Norton, 2008; Glaser & Krizek, 2021). The components on the experiment level were tallied up to equal a Transition Score, while the components of the dimensions on the system level were added up for an Impact Score. On this point, we again stress the heuristic value of this scoring exercise; it is a way to help identify emerging relationships and more systematically compare cases and should not be viewed as a hard performance measure.

Because we are interested in change that occurred *as a result* of the experiment and outlasted it, this method poses one obvious limitation: accounting for the longitudinal aspect of the phenomenon 'change'. Our approach involves a single snapshot of the experiments at a moment in their possible change trajectory. This is especially important to remember for those experiments which were finished most closely to the time of writing, and less of an issue for experiments that were completed years ago, assuming any change would have occurred in that time. Moreover, for experiments that were not formally monitored or assessed, change before and after is considerably more difficult to measure. Furthermore, we recognize the enormous challenge that is upending a system so em-

Table A1
Transition experiment framework.

Capacity components (C1-C5)	
C1	**Radical: The experiment fundamentally differs from dominant practices**
C1.1.	The experiment is the first of its kind in the urban context
C1.2.	The experiment alters the use of streetscape for socializing, playing, exercising
C1.3.	The experiment includes a shift from motorized to non-motorized mobility
C2	**Challenge-driven: The experiment makes a step toward a potentially long-term change pathway to address a societal challenge**
C2.1.	The experiment models already established examples of city street experiments
C2.2.	The experiment is connected to existing policies or programs within the same city
C2.3.	The experiment is interdisciplinary in its ambition, combining objectives and goals (e.g. mobility, public space, social)
C3	**Feasible: The experiment can be realized in the short-term and with readily available resources**
C3.1.	Preparations for the experiment took no longer than six months
C3.2.	The necessary resources were made available
C3.3.	The experiment is well organized and communicated (signage, markings, arranging of permits)
C3.4.	The experiment garnered support from its residents, local businesses and other stakeholders
C3.5.	The experiment made arrangements for alternative transport (passenger and freight) and parking options
C4	**Strategic: the experiment generates lessons for reaching envisioned fundamental changes**
C4.1.	The experiment recognizes drivers and barriers to long-term change
C4.2.	The experiment was monitored, assessed and/or evaluated (e.g. citizen consultation)
C4.3.	The evaluation of the experiment is linked to long-term policy development
C4.4.	The experiment uses data collection methods, especially aiming to broaden mainstream mobility data (e.g. well-being, equity, social capital)
C4.5.	The experiment has the ambition to scale up or be repeated (e.g. in other locations, or in more locations)
C5	**Communicative: the experiment reaches and mobilizes the broader public**
C5.1.	The experiment garners attention from the outside-in (e.g. news coverage, social media)
C5.2.	The experiment garners attention by actively promoting itself from the inside-out (e.g. outreach programs, social media)
C5.3.	The experiment actively builds coalitions in order to achieve its goals
C5.4.	The experiment awakens or increases a sense of community
C5.5.	The physical presence of the experiment draws attention

Dimensions of change (D1-D4)	
D1	**Behavioral: there is evidence of a shift in individual use and behavior**
D1.1.	The experiment ignited a shift in mobility behavior from private automobility to alternative transportation options
D1.2.	The experiment ignited a different use of the streetscape
D1.3.	The experiment ignited social interactions
D2	**Institutional: there is evidence of alterations to city-wide mobility and public space policies, legal and financial frameworks, cultural/social norms**
D2.1.	The experiment led to the introduction of regulatory instruments (e.g. speed limits, environmental zones, lanes for public transport, closure to traffic)
D2.2.	The experiment led to the introduction of market-based instruments (e.g. taxes and subsidies)
D2.3.	The experiment led to the introduction of information-based instruments (e.g. providing awareness so that
D2.4.	individuals will make informed choices and ultimately change their behavior voluntarily)
D3	**Material: There is evidence of a physical change in the composition of the streetscape**
D3.1.	The experiment ignited an alteration of the physical form of the streetscape (e.g. installment of furniture, greenery, removal of parking spaces, layout of the street)
D3.2.	The experiment was scaled up (e.g. replication, spatial and/or temporal extension)
D4	**Organizational: There is evidence of a change in the network of players, organizations and/or state, market, and civic collaborations**
D4.1.	The experiment led to the creation of new organizations or groups (e.g. dedicated work group or task force, social media)
D4.2.	The experiment led to new relationships within existing organizations or groups (e.g. across municipal departments)
D4.3.	The experiment led to new relationships between existing organizations (e.g. municipality and commercial party)

Table A2
List of stakeholders selected for personal interviews.

Reference in text	Stakeholder role	Affiliation
Amsterdam		
A1	Project manager	Municipality of Amsterdam
A2	Experiment organizer	Resident
A3	Junior program manager	Municipality of Amsterdam
A4	Senior designer	Municipality of Amsterdam
A5	Experiment participant	Resident
A6	Project manager	Municipality of Amsterdam
Munich		
M1	Policy maker urban mobility	City of Munich
M2	Experiment organizer	Local innovation platform to foster sustainable mobility
M3	Policy maker land use	City of Munich
M4	Citizens' initiative founder	Citizens' initiative
M5	Project manager public space	NGO
M6	Head of sustainable mobility and city councilor	NGO
M7	Business manager change	NGO

bedded and complex as that of urban mobility. For that reason, any evidence of a transition, regardless of its scale or magnitude, qualified as change.

Case studies

Amsterdam: weesperzijde testbed

As a response to an unmet demand for public space and an interest in the long-term effects of parking reduction (A1), 180 parking places totaling 2000 m^2 were freed up for alternative uses in the Weesperzijde neighborhood in the summer of 2019. This experiment stemmed from a niche development for Smart Mobility, which was implemented in the form of a European program called eHubs across a number of test cities. The Weesperzijde version included a 'shared mobility hub' with bike racks and electric (cargo-)bikes. In addition, parklet-style urban gardens and green street furniture were placed and paid for by active residents.

The aim of the Weesperzijde experiment was three-fold: reduce parking, increase alternative forms of mobility and improve public space (de Bruijn, 2019), which the residents were most interested in (A1). While from the outside it appeared as a collaboration between the Amsterdam East department of the Municipality of Amsterdam and active residents, these two parties had trouble aligning ambitions and efforts (de Bruijn, 2019). When residents attempted to organize a 'living street', closing the road entirely to traffic, they were denied by the Municipality on the grounds of insufficient funds, doubts about public support and the lateness of the application, which should have been submitted ten weeks prior to the start of the event (A1). As a response, the residents 'illegally' organized a communal lunch attracting more than one hundred people (see Fig. 3), for which they were reprimanded by the Municipality of Amsterdam (A1). In addition, residents also managed to find a loophole in the municipal system, applying and receiving temporary parking permits, typically used in the event of moving or construction, for a large number of spaces in the street. This chain of events stunted the building of a coalition between the two parties, which together ran the experiment as ultimately carried out.

Following the end of the experiment, an evaluation was made by the municipality municipality, specifically in order to better understand how the residents were able to apply for and receive the temporary parking permits (de Bruijn, 2019). This served as an important lesson for inter-departmental communication, leading to a new system for processing permits to prevent the recurrence of misuse that occurred during the experiment. Residents are still not satisfied with the current situation and are still searching for ways to clear the street of cars. In November of 2019, a group again applied for parking permits in the street, not to park their cars but to use as public space (de Boer, 2019).

Amsterdam: 'Living Street' Hugo de Grootkade

The Hugo de Grootkade, a typical residential street in Amsterdam West, was closed to motorized traffic for use as public space for a period of four weeks during the summer of 2016. The main objective was to implement and test the first-ever *leefstraat (*'living street') in Amsterdam. All cars were removed and temporary barriers were put up at both ends of the street. A blue carpet was laid down the middle of the street to highlight its new play and social function. Various objects, including picnic tables, benches, a hot tub and a temporary beach were installed. The experiment originated as a citizen-led project supported by subsidy funding from the local government in the neighborhood of Amsterdam West. The local government provided organizational support while residents voluntarily formed a small committee that was responsible for arranging permits, materials, scheduling activities and managing communication (A3).

While the local government initially planned to use the experiment as a chance to explore the solutions for the larger parking issue in the neighborhood, this goal was scrapped when the organization of the social activities proved to cost more time and money than expected, which was necessary in order to achieve all of the aims of the initiators (A2). The experiment was evaluated following its completion, however this feedback was not linked to any long-term policy development, nor did it address any long-term drivers or barriers of change (A2). Preparations for the experiment spanned over the course of four months, of which three were needed in order to receive approval for the plan from the municipality. In order to promote the activities, flyers were used, visual announcements in the form of large billboards were placed on the side of buildings, and residents were updated via a Facebook page that remained active following the completion of the experiment (A3). Local news outlets picked up the experiment, representing attention from the outside-in. Furthermore, the experiment's full-packed and visible program, with activities happening every day on the street, proved to mobilize residents to interact and participate.

Following the completion of the Hugo de Grootkade experiment, interview respondents noted an increased feeling of social cohesion in the neighborhood that was a direct result of the living street. A new and still active Facebook group continues to bring residents together today. The success of the Hugo de Grootkade led to its repetition a year later in the summer of 2017 and informed policy regarding other living streets in Amsterdam, which are budgeted for every year and available for those who wish to organize such an event (A2). While the street was returned to its original state, some furniture that was used during the experiment remains on the sidewalks.

Amsterdam: the 'cycling street' Sarphatistraat Zuid

The cycling street Sarphatistraat Zuid was transformed into a multimodal roadway featuring sidewalks, more greenery, a shared car and cycling path, and an improved tramline in 2016. The experiment included changing the asphalt from black to red, applying markings indicating the *fietsstraat* (cycling street) status, removing traffic lights and changing the maximum speed to 30 km/h. Plans to redesign the entire inner city ring (*Binnenring*) - of which the Sarphatistraat forms a section - began with a top-down motion from the political party GroenLinks and were carried out by the Municipality of Amsterdam.

The Sarphatistraat Zuid experiment was the first to be adopted within the larger structural plan, however the experiment was strictly aimed at improving the mobility flow and did not serve a range of uses beyond being a channel for traffic. It was an experiment in the strictest sense of the word: the municipality purposefully used it to test a possible future street design that would be implemented across the entire inner city ring and vowed to change the street back to its original state if unsuccessful (A4). While preparations lasted a year due to political discussions and the need to convince different departments within the municipality, the necessary resources were made available. As part of a larger citywide policy ambition, the Sarphatistraat experiment recognized barriers to long-term change and was assessed quite thoroughly before, during and after the experiment. This included polling residents, local business owners and passers-by about their opinions on user safety and traffic patterns. Interestingly, residents from surrounding neighborhoods were informed of the plans by way of a letter but there was no formal citizen consultation, which was noted by policy-makers as beneficial to the experiment's success as it made the process more feasible. The experiment received little backlash from local stakeholders and users adapted to the new scenario swiftly. Following the experiment, the number of cyclists using the street increased (A4) and eight out of ten respondents found that cyclists use the entire lane and 75 percent found that cars drive slower (Gemeente Amsterdam, 2016). Due to the improved safety revealed in the assessment following the experiment, the cycling street Sarphatistraat Zuid was kept, leading to a permanent alteration of the streetscape. The Sarphatistraat Zuid experiment further led to new relationships between the urban planning and traffic departments of the municipality. A shift in opinion from the traffic advisors and the politicians who were originally opposed to the idea paved the way for the further application of the shared cycling path model across the city under the policy Project Binnenring.

Munich: Umparken Schwabing-west

During the Umparken Schwabing-West experiment, which lasted four weeks, eight households exchanged their cars and parking spaces for public transport and shared mobility options while the leftover parking spaces were activated as public space. The experiment took place in the summer of 2020, during which the entire Hiltenspergerstraße was closed to motorized traffic and four parking spots were transformed into a modular parklet with a seating area, and bicycle and e-scooter parking to improve alternative mobility services in the area (M2). The experiment was an initiative of UnternehmerTUM, a center for innovation and business creation.

The Umparken Schwabing-West experiment featured a user-oriented approach to actively understand and reduce car ownership and was the first of its kind in Munich. While the experiment was not fully embedded in a strategy for long-term change, Umparken Schwabing-West was partially modeled after the popular shared mobility concept MaaS (Hensher, Mulley & Nelson, 2021). Organizers noted two challenges at the forefront of the experiment: first, finding test users for the mobility part of the experiment and second, understanding how the people living there want to use the space. In order to solve these barriers, the experiment conducted multiple citizen consultations. One included a neighborhood concert where possible participants for the mobility part of the experiment could be collected. Here an 'idea wall' was also constructed so that people could share their opinions on the use of the public space. Additionally, the organizers made use of a website for sharing information and an online survey to gather ideas (M2). During these preparations however, the experiment was almost canceled due to strong criticism from surrounding residents who were primarily worried about noise and the attraction of young people to the street at night (M2). Changes to the original plan (no benches in the public space) and support from the district committee allowed the experiment to continue.

The mobility behavior and user experience of the participants was closely monitored and assessed, although because the experiment was not linked to any long-term policy, it was used to mainly inform improvements for any follow-up experiments. To the surprise of the organizers, three of eight households permanently gave up their car (M2), signaling a behavioral change. Umparken Schwabing-West moreover ignited new cooperation among different stakeholders from the municipality, startups, and mobility operators who are continuing collaboration for a repeat of the experiment next year. The model of the Umparken Schwabing-West experiment will be improved and linked with the Summer Streets program (see below) and potentially brought to other cities (M2).

Munich: summer streets

Drawing from inspiration gathered during a visit to Stockholm, the city of Munich implemented its first 'Summer Street' pilot in two locations during the summer of 2019. The first street, south of Alpenplatz in Giesing, was closed to car and bicycle traffic, giving priority to pedestrians. The second, Schwanthaler Street, included a widening of the sidewalks for greenery and sitting areas (Landeshauptstadt München, 2019). Both pilot projects were implemented in order to identify a suitable process for temporary transformations of city streets on a larger scale. Due to the Coronavirus pandemic, the Summer Streets concept was expanded to the entire city in 2020, giving 10 streets traffic restrictions and designating four streets as play streets (M3). The main objective of the design was to provide outdoor space to citizens, without inducing crowds or gatherings (M3). The project was implemented in cooperation with the district committees, who together with citizens, requested to have summer streets and parklets in their district.

Summer Streets featured a streetscape redesigned for increased social interaction between users. Like its Swedish counterpart, it was an experiment connected to various programs and existing policies from the city, such as urban and mobility development strategies. In particular, the initiative was fed by discussions within the city council about the redistribution of public urban space, serving as a backbone for a mobility transition. The City of Munich worked very closely with the district councils to use available resources (existing furniture from the Building Department) to quickly respond to the demands of the pandemic (M3). The experiment was assessed using both qualitative and quantitative methods, where interview respondents noted that the physical aspect of the experiment was not particularly inviting. Because members of the district councils acted as representatives for users in the experiment, internal communication was limited. This was furthered by contact restrictions of the pandemic. Promotion of the experiment was gained in other ways, for instance through local news media outlets.

Following the closure of the experiment, users began to use the streets differently than before. A new professional relationship emerged within the City of Munich and the district councils, who had previously not worked together on such an issue. The Summer Streets experiment led to a resolution outlining the specific procedures to scale-up and repeat the experiment in 2021.

Munich: Piazza Zenetti

The 'Piazza Zenetti' experiment (see Fig. 4) was implemented for two months in the summer of 2018 and repeated in 2019 and 2020 (City2Share, 2020). Located in a district with high parking demands, Ludwigsvorstadt-Isarvorstadt, the experiment had two aims: test shared e-mobility alternatives and reclaim the unused parking spots as public space (Ibid., 2020). The experiment was a collaboration between citizens, the local government, and a landscape architecture firm under the umbrella research project, City2Share. The success of the experiment in its first year led to the start of a citizens' initiative who took over the project from City2Share.

Piazza Zenetti was the first of its kind in Munich. It actively addressed the issue of private mobility and transformed the leftover parking spaces into places for interaction and a 'living space in the street' (M4). A mini library was created and a bottle collector was also installed in order to keep the space tidy. Other programs included a meet-up for swapping clothes and yoga (M4). Initially, a small stage was installed as the 'Speaker's Corner' intended for people to use for speeches or music, however it remained unused and was therefore left out of the second design. The possibility to test these ideas was noted by the initiators as a direct benefit of experimentation (M4).

Piazza Zenetti was linked to broader programs, including European Mobility week in the first year, and the Summer Streets Program in the second and third years (M5). The fact that the experiment began under a formal organization was noted as contributing to its feasibility (M4). From the start, the local government intended to learn from the experiment (M1) and its impact on public space by way of monitoring and evaluation. Promotion of the Piazza Zenetti experiment was extremely thorough, which helped to gain support from local residents. Interestingly, a small sample of residents initially feared that the redesign of the square signaled a start to the gentrification of the neighborhood. In order to promote the experiment and gather support, experiment organizers made use of flyers, newspaper publications, a kick-off event with the mayor and representatives of the municipality during an 'action week' (M1).

Following the experiment, new interactions between residents grew and according to interview respondents, there was an awakened sense of community. This was, according to the organizer of the citizen's initiative, a direct result of the stimulating character of the square which prompted people to use the space. Half of the space used during the experiment was made permanent public space in 2018. The success of the citizen's initiative led to its formal adoption under the Summer Streets program in 2020 and the promise to repeat the experiment in the coming years.

Discussion of results

The case descriptions outlined above begin to illustrate the similarities and differences between the city street experiments. We now expand on these insights, answering the questions of how city street experiments create, build upon and exert their transitional capacity upon the urban mobility system.

Fig. 5 reports the results of the scoring of the experiments and their relationship to change. As stressed in the methodology section above, we use these scores as a heuristic guide, rather than a hard performance measure, in order to highlight emerging patterns and issues for further enquiry. We further do not claim any simple cause-effect relationships.

Based on our findings, it appears that there exists a broad relationship between the transitional capacity of city street experiments - measured by the five defining characteristics of transition experiments - and some degree of behavioral, organizational, institutional, or material change. In five of the six case studies, the Transition Score correlates to the Impact Score (see Fig. 9), confirming our working hypothesis that 'the greater the presence of the five characteristics, the greater change observed'. The highest scoring change dimension was individual change (1.3), followed by institutional (1) and material (1), and ending with organizational change (0.9) (Figs. 1, 6–9).

The *radical* nature of the experiments was a particularly strong component in all case studies, as they all featured a fundamentally different use and activation of the streetscape. The Sarphatistraat Zuid experiment, although the first of its kind in Amsterdam, was strictly mobility related and therefore less *radical* than the others. In the other cases, the removal of traffic and use of the street for socializing was regarded as one of the most positive aspects of the experiments and generally met with acceptance, even in the cases where residents were initially against the idea of having to move their cars (Weesperzijde testbed and Umparken Schwabing). The characteristic *radical* did not reveal any significant correlations with any of the dimensions of change (i.e. the more radical the project the more change observed) as suggested by the literature (Bertolini, 2020). *Radicality* was primarily mentioned by respondents in connection with that of *feasibility*; the more radical the project, the less feasible and vice versa. As a result of a too ambitious and therefore *radical* program, the Weesperzijde Testbed and Umparken Schwabing West experiments struggled to achieve their goals (A1, M2). These patterns suggest a potential trade-off between these two characteristics: in order to increase *feasibility*, the radical nature of projects may have to be lowered and vice versa.

The characteristic *challenge-driven* still appears to be emerging, despite shifts at the landscape level towards demand for more livability and less cars in cities, and an increased awareness for experimentation in both cities. Only three of the experiments (Piazza Zenetti, Summer Streets, Sarphatistraat Zuid) were connected to existing policies or programs. This confirms the propositions made by current literature regarding the disconnection of city street experiments from long-term strategies (Bertolini, 2020; Hipp et al., 2017). According to an interview respondent (A2), the local government dropped their original goal of exploring long-term parking solutions with the Hugo de Grootkade experiment in exchange for *feasibility* as the social program took more time and energy than expected. Furthermore, the Weesperzijde Testbed experiment proved to suffer from unclear goals related to its too-ambitious program (wanting to explore shared mobility, parking solutions and organize social activities) and confusion regarding roles and responsibilities. Interestingly, these experiments still revealed scores on the dimensions of change, despite the absence of this characteristic.

The *feasibility* of city street experiments varied across all case studies. As mentioned earlier, there appeared to be a trade-off between the *radicality* of the experiment and its *feasibility*. While all experiments garnered enough support and funding to be put on and completed, they likewise noted a lack of time and underestimation of the amount of energy required. Arranging permits proved to be the greatest culprit for experiments in both cities, an echo of the regime entrenchment of the automobile and relative novelty of such initiatives. In Amsterdam, this proved to be the case even for the Sarphatistraat Zuid experiment which was, solely organized by the municipality. Additionally, for the experiments that required a removal of cars, resistance from residents proved to slow preparations and prompted the alteration of plans according to interview respondents (M2). Active residents of the Weesperzijde testbed found (and continue to make use of) loopholes in the system to fast-track these processes: "It's good that they found a loophole, because they showed us that there was a weakness in our system and that shouldn't happen during such a project" (A1). Interestingly, resistance took on another form at the Piazza Zenetti, where some residents were wary of the experiment leading to gentrification. City street experiments have, until this point, been viewed as revealing positive benefits to current urban challenges. However, improvements to local economic situations (Littke, 2016) and livability could result in negative consequences in the form of exclusivity for certain groups, a risk also recognized in other contexts (Goossens et al., 2020).

The characteristic *strategic* formed a very weak point across all the case studies, confirming claims made by existing literature on city street experiments. In terms of assessment and monitoring, while most of the experiments were monitored, assessed and/or evaluated, the lessons generated were not used for the benefit of long-term change trajectories. This is an interesting point that relates to the literature stressing the importance of monitoring in connecting experiments to longer-term strategies (Sadik-Khan & Solomonow, 2017). The monitoring that occurred was mainly used to improve and learn from the experiment 'experience' itself, but was not extrapolated to wider, long-term plans, most likely because these experiments were not strongly embedded in long-term change trajectories to begin with. The possible lessons to be learnt from are therefore limited by the original framing of the experiment. Interestingly, the Umparken Schwabing-West and Hugo de Grootkade experiment scored very low on the characteristic *strategic*. This was matched in the former by a relatively low impact, yet the latter was the most impactful experiment in Amsterdam and the second most impactful of all case studies. One possible explanation for this divergence may be explained by the fact that the Umparken Schwabing-West experiment was initiated by a business accelerator and was the only case study that did not feature an active role from the local government. Conversely, the Hugo de Grootkade experiment featured a primary role from both the local government and the residents, representing a strong coalition between these two parties. The strength of this coalition and its role in achieving experiment goals, a component of the characteristic *communicative,* may have made up for the lack of *strategic* character.

The characteristic *communicative* proved a strong component in nearly all of the case studies. Street experiments garner momentum by way of building coalitions (reaching-out) and profiting from actor networks (reaching-in) that surround their niche development. As the initiator of the Umparken Schwabing experiment described: "It was only successful because we had good partners on board. We had the city… and we also had relevant partners and startups that were open to doing this project. Otherwise, it wouldn't have happened in such a short time frame. The project with its short planning and preparation phase didn't fit into the usual processes of the city of Munich at all" (M2). Initiators of the Piazza Zenetti experiment, mentioned new civic collaborations between citizens, the district committee and the city of Munich as a direct result of the project. Two nuances were revealed from our analysis. First, the type and intensity of communication strategies appears to vary depending on the aim of the experiment, and how *radical* it is. While the extremely *communicative* nature of the more interdisciplinary experiments combining mobility, social and public space goals, which was noted as the key to their success (Piazza Zenetti, Hugo de

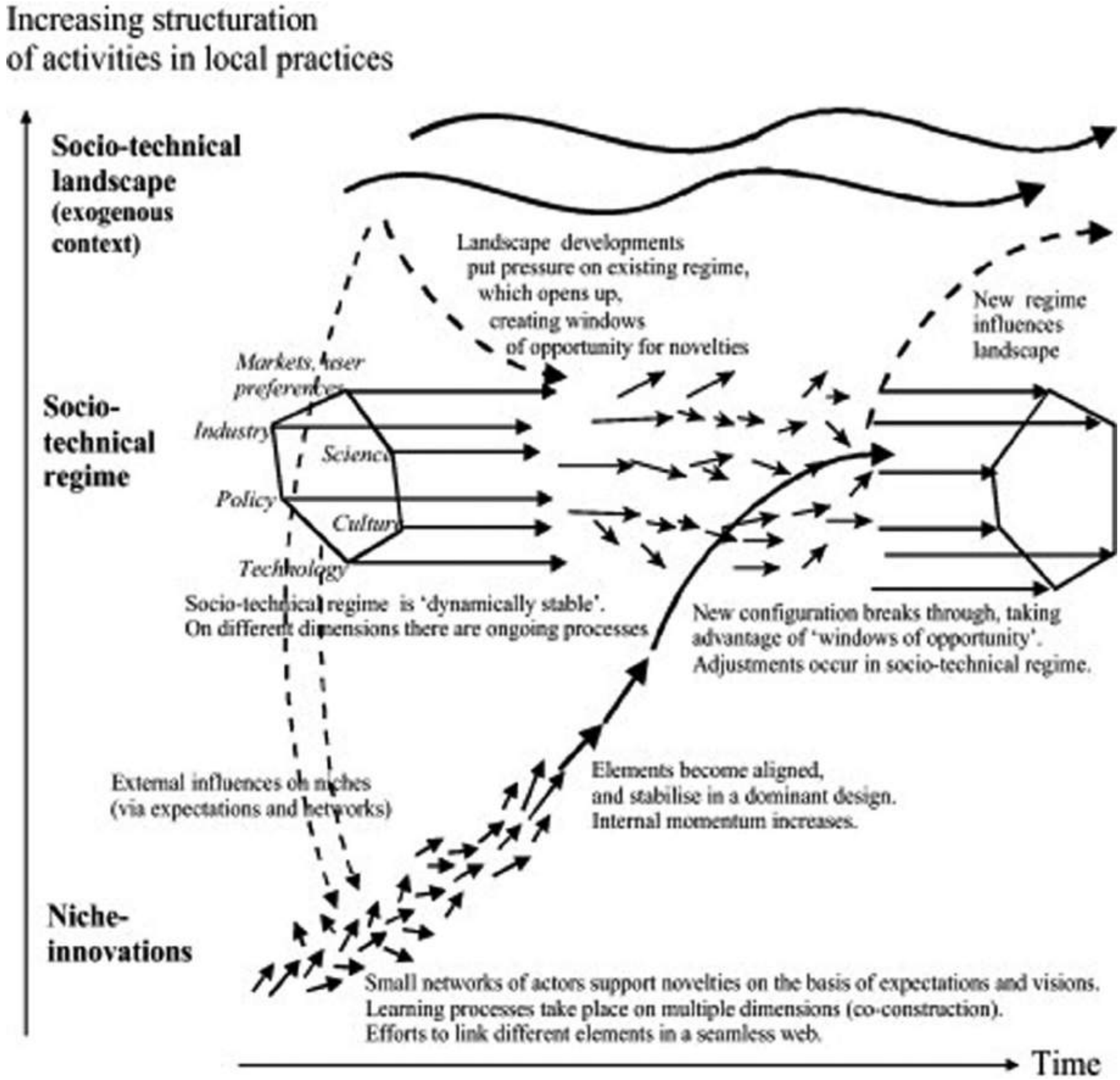

Fig. 1. The process of system change and innovation according to the multi-level perspective (Geels, 2004).

Grootkade, Summer Streets), the *absence* of a participation process in the Sarphatistraat experiment was noted as a factor in its success. This was likely made possible due to the lowered radicality of the experiment (solely mobility focused) and the promise to return the street to its original state if unsuccessful. This was also the case in the experimental and mobility-focused pop-up bike lanes in Munich from 2020 (M6). Secondly, while initiators of city street experiments can actively promote their experiments, the success of these efforts ultimately lies in the hands of their audience. A better understanding of the preferences of potential users and giving more time to 'warm-up' to the idea was noted as having been potentially favorable for behavioral change during the Umparken Schwabing-West experiment.

Reflection on the assessment framework and areas for improvement

As stated earlier, this analysis represents the first attempt to assess the transitional capacity of city street experiments. For the purpose of this explorative study, the assessment framework proved to offer valuable insights into the transitional capacity of city street experiments in relation to system change. It primarily acted as a stepping stone for the identifying of hypotheses for follow-up research. By scoring the individual characteristics and dimensions for each case study, we were able to single out specific patterns (e.g. trade-offs between characteristics) that would have otherwise been difficult to highlight. We therefore recommend the further use of this method, stressing its heuristic value and offering two points of improvement.

First, we defined material change as "evidence of a physical change in the composition of the streetscape following the experiment." Based on our analysis, this definition did not cover all forms of material change. Some examples of city street experiments are repeated due to their success but are not permanently implemented. Although the physical changes are only temporary, the Summer Streets and Piazza Zenetti experiments are now planned to occur every year and have proven to lead to a visible increase in the use of the street as a communal living space. We suggest that future assessments revise this component to include such 'temporary permanence' when scoring experiments on the material dimension.

Second, the framework assumed that change is positive (e.g. shift to sustainable mobility and active modes, increased social capital, com-

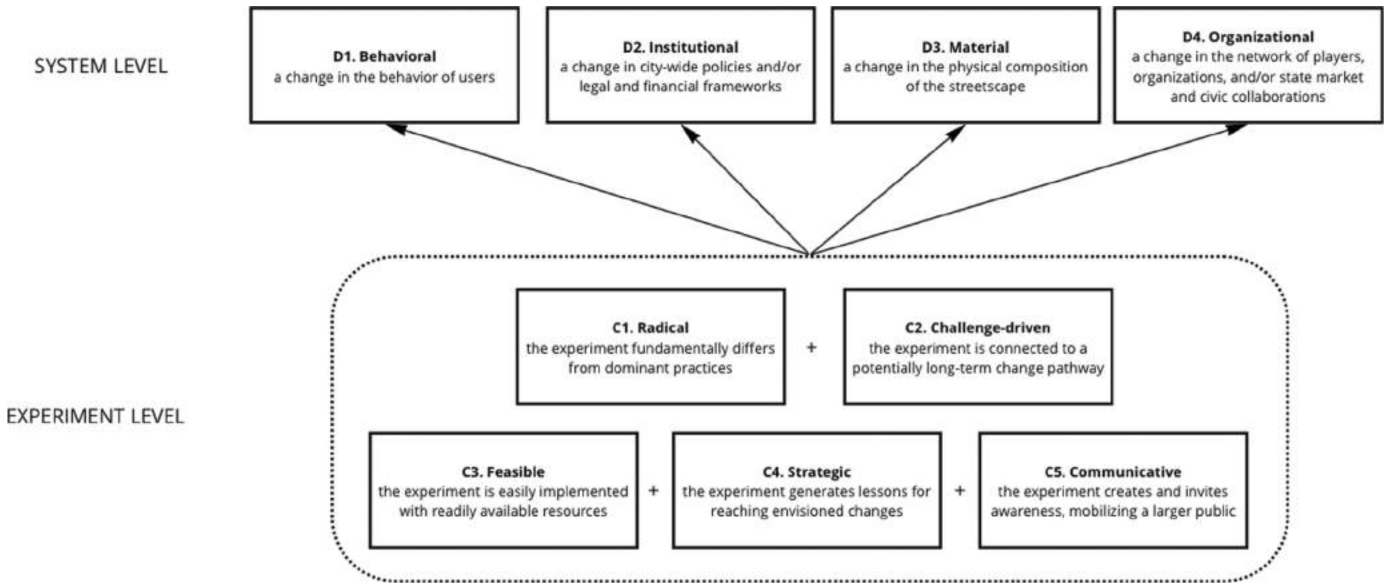

Fig. 2. Hypothesized relationship between the five characteristics of city street experiments (C1–C5) and the four dimensions of system change (D1–D4).

Fig. 3. Communal lunch in the Gijsbrecht van Aemstelstraat. Photo: Pieter Boersma.

Fig. 4. Children playing in the Hugo de Grootkade during the experiment. Photo: Authors.

Fig. 5. The red asphalt indicating the cycling street following the Sarphatistraat Zuid experiment. Photo: Floortje Opbroek.

munity building), however, this is not always the case, as shown by the Weesperzijde testbed. Here, social interaction increased, however it seemed to divide the neighborhood, the municipality and the residents, rather than unite them. In the Piazza Zenetti experiment, risks of gentrification were highlighted. This ‘dark side’ of social capital (Rydin, 2014) and the notion that change is not necessarily ‘good’ (on these and other aspects) should be explicitly considered when evaluating the transitional capacity of city street experiments and suggests the consideration of the possibility of negative scoring in future studies.

Conclusions

City street experiments are increasingly being implemented as ways to explore possible solutions to the challenges and tensions of contemporary urban mobility. This paper explored the extent to which such on-the-ground initiatives can trigger system change by developing and employing an assessment framework for their transitional capacity. The comparative nature of the assessment framework revealed how different capacity components influence dimensions of change, and how this process occurs across different experiments and contexts. Valorizing the qualities capable of causing change which are inherent to city street experiments reveals opportunities and barriers and provides novel insights for areas for improvement. In sum, our analysis highlighted the following patterns regarding city street experiments and their transitional capacity:

- There exists a broad correlation between the cumulative strength of experiment characteristics and overall dimensions of change.

Fig. 6. Preparations for the Umparken Schwabing West experiment. Photo: experiment organizers.

Fig. 7. Sign designating the beginning of the Summer Street experiment: 'Welcome to the Summer Street'. Photo: Authors.

- The characteristic *radical* holds a strong presence, however, appears to have no determining relationship with the dimensions of change.
- There is a clear trade-off between the characteristics *radical* and *feasible.*
- The characteristic *challenge-driven* is weak, however does not appear to have a determining relationship with dimensions of change.
- Institutional barriers, both formal (legal frameworks) and informal (automobility as a social norm) major constraints to the *feasibility* of experiments.
- The characteristic *strategic* is weak and appears to have no determining relationship with the dimensions of change.

Fig. 8. Piazza Zenetti in the summer of 2019. Photo: Johann-Christian Hannemann.

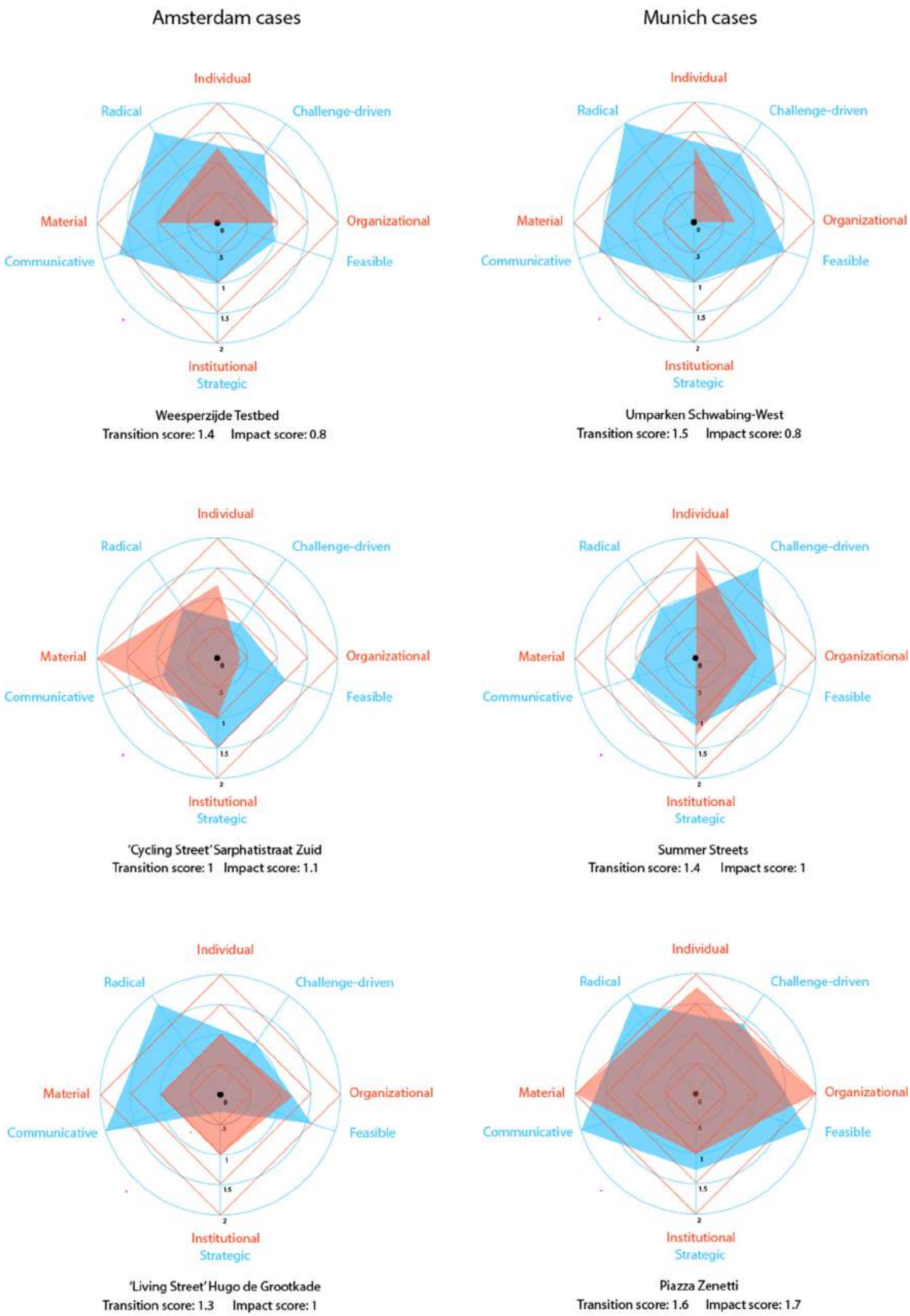

Fig. 9. Aggregated assessment of transitional capacity components and dimensions of change of six of city street experiments in Munich and Amsterdam (scale: 0 = weak, 1 = average, 2 = strong).

- *Communicative* is a strong characteristic and may be a necessary condition for the more *radical* projects. It could also act as the 'saving grace' for projects that are less *strategic*.
- The combination of (a) broad correlation between characteristics and change but (b) unclear individual correlations, opens the possibility that different mixes of characteristics, rather than across the board maximization should be pursued in order to deal with trade-offs and acknowledge contextual conditions, while still achieving change.

Our comparative analysis further revealed two important avenues for research and practice. First, the transitional capacity of city street experiments cannot be understood independent from the context and system in which they occur. Regardless of their strengths, experiments are influenced by shifts at the landscape level and dynamics of the mobility regime. The dominance of private mobility revealed a barrier for the city street experiments showcased in this study in several ways. First, the task of arranging permits for using the street as something other than for traffic proved to be the most time-consuming and posed a potential threat to the success of the experiments. Second, general opinions concerning such 'border-pushing' practices' (Bertolini, 2020) did not always align. Users who were not in favor of giving up parking spots resisted the implementation of the experiments. While city street experiments aim to change the local urban planning system, existing regimes, both formal and informal, have the potential to either limit or nurture them. One way to potentially combat this, would be for organizers to involve the local government and educate themselves on the conditions of the system they are operating within and for whom they are experimenting. For researchers, while this study specifically viewed this relationship from the perspective of the experiment, future studies would be advised to observe it from the position of the urban mobility system, analyzing its 'readiness' for such activities and own transformative capacity.

Second, while our study revealed a broad correlation between the five transition experiment characteristics and change, the results give us reason to explore the possibility that certain characteristics of city street experiments are non-negotiable while others are dispensable. This possibility might help address the trade-offs between different characteristics that also emerged, including that between *radical* and *feasibility* and also how certain characteristics interact with each other (e.g. more radical projects should be more communicative) If all five characteristics cannot be maximized, which combinations should initiators of street experiments then focus on? While the scope of this paper did not allow for a deeper assessment of the relationships between characteristics, we believe this to be an important next step in further understanding city street experiments and their transitional capacity.

Declaration of Competing Interest

No potential conflict of interest was reported by the author(s).

CRediT authorship contribution statement

Katherine VanHoose: Conceptualization, Methodology, Investigation, Formal analysis, Writing – review & editing, Visualization. **Ana Rivas de Gante:** Investigation, Formal analysis, Visualization, Writing – review & editing. **Luca Bertolini:** Conceptualization, Methodology, Supervision, Project administration, Funding acquisition. **Julia Kinigadner:** Investigation, Methodology, Formal analysis. **Benjamin Büttner:** Investigation, Formal analysis, Funding acquisition.

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Identifying, nurturing and empowering alternative mobility narratives

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ABSTRACT

Our mainstream mobility thinking is narrowly framed: it highlights the role of mobility in economic and urban growth, individual speed and system efficiency, but obscures its role in reproducing inequalities, and in driving unsustainable developments on a global scale. Critically, however, this narrative obscures our view on the increasingly problematic societal and environmental 'externalities' of mobility, such as its significant contribution to climate change, air pollution, social exclusion, deaths and injuries, public health issues and landscape degradation. With such high stakes for our common mobility futures, how can we identify seeds of emerging alternatives, nurture and amplify their potential impact and empower emerging alternative futures?

1. Introduction

Current mobility patterns are rapidly depleting individuals, cities, global resources and the environment – a situation requiring rapid and transformative change (McBain et al., 2021; Urry, 2008). To achieve such change, the wide-ranging negative impacts of mobility need to be fully acknowledged and swiftly addressed according to the principles of global and European policies, such as the Sustainable Development Goals, the COP26 pledges, the European Green Deal and the European Road Safety Charter. Despite the clear and urgent need to fundamentally change mobility patterns, infrastructures and technologies – as well as the institutions of policy, planning and innovation that shape them – little change is being achieved beyond cosmetic adjustments and so-called 'smart' techno-fixes informed by crude modernistic claims (see, for example, Ferreira et al., 2020; Qviström, 2015; Reigner & Brenac, 2019; van Oers et al., 2020).

The achievement of the much needed radical transformation of mobility systems presupposes a profound reimagination of the societal futures collectively accepted as desirable. Indeed, diverse and pluralistic imaginaries are needed so that the soaring dominance of smart futures is challenged (Bina et al., 2020; Couldry & Mejias, 2018; Ferreira et al., 2022). Breaking out of the current mobility systems requires, therefore, developing public awareness of the lock-in that confines both the physical world and human imagination inside a restricted space of possibilities. Such an awareness-building process entails recognizing the extent to which individuals became trapped in terms of the kind of future technologies they are capable of envisioning. It also entails recognizing the kind of values, worldviews and beliefs they are able to summon and adopt in their imaginings. Thus, if mobility systems are to be radically changed in the name of sustainability, we first and foremost need to challenge the way we think and talk about the world in general, and mobility in particular.

Mobility language, both technical and popular, is formed by a collection of stories, semantic rules and jargon used to describe and enact what mobility *is* and *what it is for* by individuals as professionals and or as travellers. This language is, by definition, a necessary representational simplification that allows individuals and organizations to approach complex phenomena, to share collective ideas about them, and to govern them (see Lakoff & Johnson, 1980; Morgan, 2006; Scott, 1998). Since it is a simplification, it is inherently limited, and the choices that are made in this simplification are often arbitrary. However, as we further discuss below, these choices lead to results that both mirror and perpetuate the simplifications made beforehand.

Thus, contemporary mobility language focusses our attention while limiting their imagination, which is both a wider characteristic of organizational decision-making, and a particular characteristic of mobility-

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related institutions (Bevir, 2011; Olin & Mladenović, 2022; Rindova & Martins, 2022; Ruhrort, 2022). The underlying choices that shape this language hold great power over individual thinking and organizational decision-making, that is to say, they hold power over which problems are identified and which are not, which solutions are invented and which are not. To unpack this framing process we use the concept of narratives, defined within research on socio-technical transitions as 'simple stories that describe a problem, lay out its consequences and suggest (simple) solutions' (Hermwille, 2016, p. 238). As we will discuss, a transition towards a mobility system that is radically different from the current one presupposes a move away from the currently dominant, strongly solidified and taken-for-granted narrative of 'mobility as disutility' (Ortúzar & Willumsen, 2011).

We agree with Holden et al. (2020) that mobility narratives should be 'understandable, attractive, motivational and possible, so [people] can believe in them and subsequently support them' (ibid., p. 1). However, we do not think that academics should aspire to develop on their own new mobility narratives and then 'convince all agents to believe in them' (ibid., p. 8). Transitions are societal, systemic and long-term processes; therefore, they ethically and politically require participatory and democratic processes of deliberation rather than the top-down imposed perspectives of societal elites. With this synthesis article we aim to position the importance of a collective search for new narratives, and we explore ways to do this by asking three interrelated questions:

1 How can the conceptual understanding of the relationship between mobility futures and narratives be enriched?
2 How can alternative mobility narratives be actively developed, refined and nurtured?
3 How can alternative mobility narratives be empowered?

Reflecting on the current practices of envisioning mobility futures and thus establishing a baseline claim, we first elaborate on why it is crucial to engage with 'deep leverage points' (Meadows, 1999) if fundamental changes in urban mobility systems are to be achieved (Section 2). Then, in order to answer the first research question, we elaborate on the relationships between narratives, thinking and language (section 3), as well as their powerful roles in the process of promoting fundamental changes in mobility systems (Section 4). In order to answer to research questions two and three, in Sections 5 to 7, we present a processual framework that consists of (1) identifying potential seeds for emerging narratives, (2) nurturing the promising alternatives in order to amplify their potential impact and (3) empowering a wider set of actors beyond technical experts, and especially citizens. We close the article by summarizing our argument as a whole and charting directions for future research involving collaboration across both transport planning practice and academic networks. Note that this article is not intended to provide a systematic literature review on all the relevant topics, but rather to present a well-reasoned and theoretically-informed position statement which offers entry points.

2. Why engagement with deep leverage points is needed for the achievement of fundamental change

Sustainability transitions are extraordinarily complex, future-oriented, abstract yet global processes (Geels, 2010). They are also associated with a variety of risks and ethical concerns to take into consideration (Shove & Walker, 2007). Similarly, mobility is so intertwined with fundamental human rights and the functioning of human societies that any initiative aimed at either increasing or reducing it inevitably leads to both positive and negative effects. The resulting 'mobility dilemmas' (Bertolini, 2017) make the promotion of sustainability transitions in the transport sector an intrinsically complex decision area for both policymakers and citizens. In terms of the multi-level perspective, a theoretical approach dominating a variety of debates on sustainability transitions, this complexity translates into dynamics on three analytical levels: landscape, regime and niche levels (Geels, 2005; 2010). The importance of narratives in these dynamics is already acknowledged in the literature on socio-technical transitions: 'landscape shocks will only create enduring pressure on socio-technical regimes if discursively prominent narratives become available that allow to translate the landscape shock into the socio-political environment of the respective regimes' (Hermwille, 2016, p. 240). In addition, the availability and use of alternative narratives that can enrich, challenge or replace 'a prominent narrative' can be a powerful tool for niche innovators to enter and reshape the regime level. In order to co-create and propose such alternatives we turn to work that deals with systemic transformations.

Meadows (1999), a prominent late scholar known for founding, together with others, systems dynamics modelling in the 1970s, offered a useful conceptualisation with which to further understand the dynamics of transformative change in complex systems (Fig. 1). She identified twelve leverage points with which to transform systems wherein the power to induce transformative change increases from the top (shallow leverage points) to the bottom (deep leverage points). However, the difficulty in mobilising leverage points also increases from the top to the bottom. Because of this, research and policies tend to focus on the shallower leverage points (i.e. feedback loops and parameters), which often fail to achieve the expected transformative change.

Meadows' conceptualisation offers a unique generic perspective that has four distinctive advantages for the present article concerned with inducing a transformative change in the transport sector (for further insights see Fischer & Riechers, 2019). First, the conceptualisation bridges the causal and normative dynamics of transformative change. Second, the conceptualisation explicitly acknowledges and enables the identification of leverage points with both low potency and high potency in relation to creating change. Third, it considers the dynamic interactions between leverage points with different potency levels as these points are interconnected through feedback mechanisms. And fourth, the conceptualisation acts as a methodological boundary object across different academic disciplines, and between academics and other stakeholders.

When intervening in mobility systems, policymakers often try to target its key parameters through instruments such as subsidies or taxes (level 12 in Fig. 1). Examples are subsidising electric cars in order to support a shift away from fossil-fuelled mobility (e.g. DG TREN's Green Car Initiative in the EU) and the ongoing discussions about introducing road pricing to fill the future revenue gap of decreasing fuel taxes. Other, more ambitious, interventions try to influence the material stocks and flows (level 10), for instance, by constructing new infrastructures that would enable different mobility patterns, such as the European investments in rail networks that intend to make sustainable European trade easier (te Brömmelstroet & Nowak, 2008). A current area of focus – for instance, in the EIT Urban Mobility programme – is the focus on 'solving the mobility challenges facing our cities' by facilitating and accelerating technological mobility innovations, which arguably targets deeper leverage points related to design (levels 6, 5, 4).

Such relatively shallow interventions will most likely not lead to transformative changes: 'the complex and systemic nature of mobility patterns means that linear interventions which launch single instruments for insulated problems often are either ineffective or produce problematic unintended effects' (Berger et al., 2014, p. 303). The history of mobility planning offers multiple examples of this, such as adding road capacity to reduce congestion which instead leads, in the long run, to the same levels of congestion being experienced by a larger number of users (see, e.g. (Cervero et al., 2006)); building park-and-ride facilities to reduce car travel which instead leads to more car trips (Mingardo, 2013); or straightening roads to reduce road danger which instead leads to riskier driving behaviour (Noland, 2003).

In summary, and as Abson et al. (2017) has underlined, focusing on shallow leverage points is not the answer. They called for a focus on the deep leverage points (i.e., those that deal with the design and intent of systems), thus increasing the pace of the systemic transformations required to achieve sustainable futures. Focusing on the deep leverage

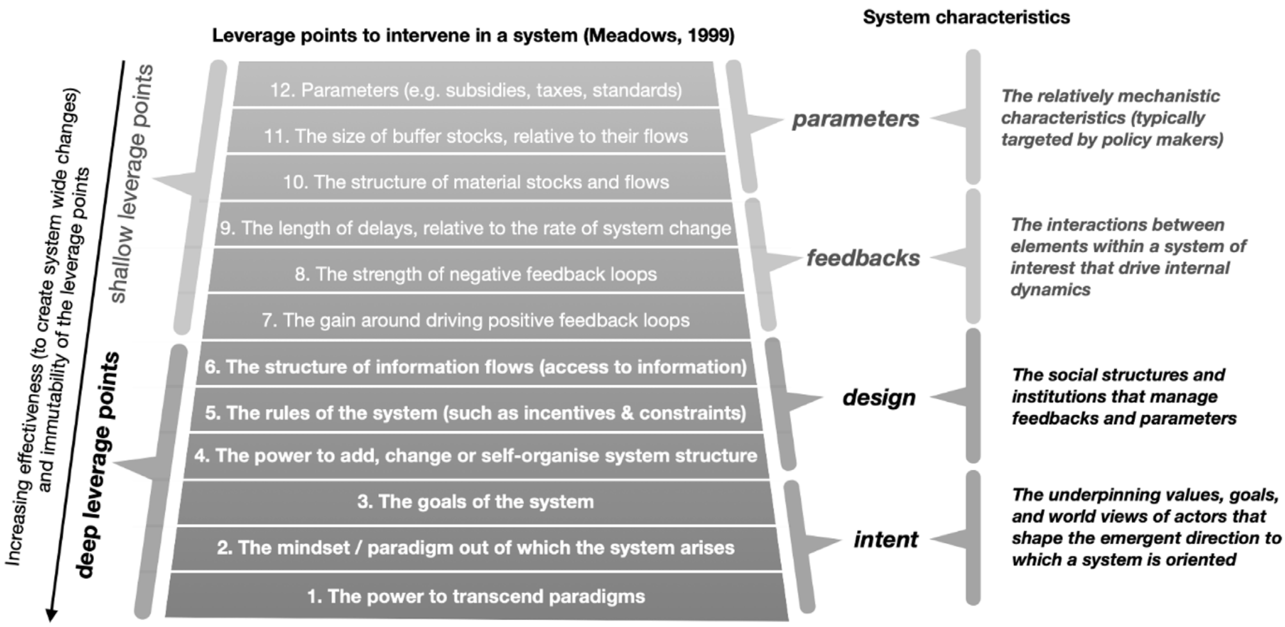

Fig. 1. Deep leverage points which can be used to intervene in a system (schematic adapted from that of Abson et al., 2017, p. 33).

points is required to create new metaphors and mental models, and to enable fundamental transformations in systems that are not achievable through a sole focus on shallow leverage points (Davelaar, 2021). Only through interventions at the deep leverage points can societies achieve transformational changes such as those called for in the mobility system (Mangnus et al., 2021; Miller, 2007).

In order to further operationalise the approach in order to influence deep leverage points, we turn to the concept of narrative, which helps connect language and thinking with the power to act.

3. How a narrative can help towards transformational change

In terms of everyday mobility practices, narratives relate to shifting experiences and identities, and are central to individuals' capacity to symbolise experience to themselves and others (Roberts and Roberts, 2019). Due to the everydayness of narratives, at first thought, the concept of narrative might be taken lightly. In fact, the narrative form is one of the most frequently occurring and ubiquitous forms of discourse (as argued, for instance, by Cortazzi, 1994). Similarly, in her seminal work on narrative analysis, Riessman (1993) observed that the popularity of the concept of narrative amongst politicians, marketeers and news anchors has resulted in it now being used in ambiguous and unspecific ways.

Here, we define a narrative as a story that provides consequential links between events or ideas and imposes meaningful patterns on what would otherwise be random and disconnected (based on the work of Riessman, 1993, p. 5). Narratives often intertwine a web of human and other-than-human actants, situated in particular places, involving various actions and affects over time. As such, they require a sophisticated understanding of the dynamics of events and the ideas within them while acknowledging their layered complexity (Inayatullah, 1998).

The power of collective narratives lies in the fact that they usually have a 'robust life beyond the individual [and are constructed by] groups, communities, nations, governments and organizations' (Riessman, 1993, pp. 5–6). We can turn to the events of the twentieth century to understand how narratives about mobility build path-dependence over time. It is in fact in the early twentieth century that the currently dominant mobility narrative emerged together with the mass introduction of car traffic in urban areas (Norton, 2011; Prytherch, 2018). Similar to lessons from the social construction of technology (see, e.g. Klein & Kleinman, 2002), historical analysis describes how the resulting pressure on the streets in the 1920s created a period of 'rhetorical flexibility' in which both the mobility desires of citizens and supply by industry and government played intricate roles.

While the wide social understanding of *the street* was relatively stable for millennia (as a space in which to play, trade, meet and travel), the new technology of the automobile was incompatible with it. This resulted in strong competition between two narratives: that of streets as places and that of streets as channels for vehicular throughput (Norton, 2011, p. 2). Following the period of rhetorical flexibility, in many places taking around a decade, a coalition of powerful politicians, industries and engineers achieved 'rhetorical closure'. Thus, the rhetorical flexibility collapsed due to the perception that the problem was solved or satisfactorily redefined. During the relatively short period of rhetorical flexibility, mobility was heavily debated throughout society from a variety of 'first-principle' perspectives: Is mobility a matter of justice? Order? Efficiency? Individual freedom? Closure was reached when the above-mentioned coalition managed to impose a dominant mainstream mobility narrative where concepts such as freedom and efficiency became utterly central (Te Brömmelstroet, 2020; Norton, 2011; Prytherch, 2018).

The power of narratives lies in the fact that they do not simply serve to describe entities or events. Narratives also shape perception and the nature of actions undertaken by individuals and organizations (Fischer & Forester, 1993). After the period of rhetorical flexibility and closure in the 1930s, the mainstream narrative solidified into traffic laws and rules, into design guidelines and handbooks, into institutions and models, and into asphalt, concrete and steel (Prytherch, 2018). Finally, all these development served to solidify the mainstream understanding and imaginaries of future mobilities (Mladenović, 2019; Mladenović et al., 2020; Te Brömmelstroet, 2020; Nikolaeva et al., 2019b; Pangbourne et al., 2020). These material and rhetorical solidifications form a reinforcing feedback loop that results in strong path-dependency.

According to Gössling and Cohen (2014), this path-dependency of thinking and acting is a prime reason for the lack of transformative change in mobility: 'belief systems comprising elements of technological innovation, (limited) market-based measures, and (voluntary) behavioural change, ultimately result in "path dependency" and social lock-in, i.e. a situation where (in)actions of the past condition future outcomes' (p. 198). Illich (1974) already warned about how this process of

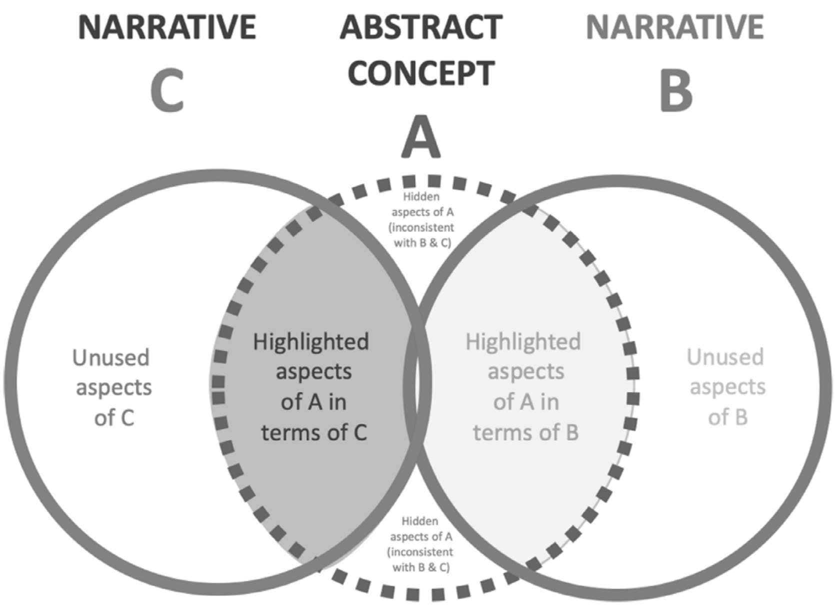

Fig. 2. *How narratives create distortions by highlighting and obscuring (based on the work of Te* Brömmelstroet, 2020*;* Morgan,2006*).*

solidification around car-based mobility leads to a 'radical monopoly': a system state that is so locked-in that 'it has frozen not only the shape of the physical world but also the range of behaviour and of imagination' (p. 66).

4. A Framework for developing alternative narratives

4.1. What could alternative narratives do?

Paraphrasing Morgan (2006, p. 5), the question becomes how policy-makers, technical experts, academics and communities can become *skilled in the art of developing and using alternative narratives, finding fresh ways of seeing, understanding and shaping the issues to be organised and managed*. This must not be done as a one-off exercise but as a continuous and iterative process. Here, we have to face the paradox of narratives; it is hard to reflect on them because they are simultaneously essential, ubiquitous and unnoticeable. A narrative is a *necessary* simplification of reality: individuals and organizations need such simplification to be able exchange thoughts and communicate with each other. In this process of simplification, choices have to be made (see examples of how this works in relation to metaphors in the work of Lakoff & Johnson, 1980; Morgan, 2006). The inherently arbitrary choices that are made in the development of a narrative become highly performative*;* especially once the narrative is no longer questioned and becomes taken-for-granted.

Narratives shape human thinking because they necessarily highlight certain characteristics of a complex phenomenon that fit with the narrative while obscuring others (see Fig. 3). For instance, the phrase 'time is money' helps individuals to see the construct of time as a tradeable commodity. However, it obscures the fact that time cannot be accumulated, as happens to money (Goodin, 2010). Crucially, here, the choices that underlie a narrative guide human actions: narratives do not only describe, but also create realities (Lakoff & Johnson, 1980). As Meadows (2008, p. 174) stated: 'The language of an organization is not an objective means to describe the reality – it determines what her members observe and which actions they take.' An important notion that can be observed in Fig. 2 is that each narrative – by definition – only offers a *partial* understanding of an abstract concept. Although some can be better in terms of how much they can describe, the key to developing a better understanding is the ability to use *different* narratives, a craft that Miller (2007) called 'futures literacy'.

As such, a dominant mobility narrative becomes a guide for the actions of all relevant agents – which can differ substantially based on the context, ranging from public administration, industry, civil sector and academia. These actions, in turn, reinforce the power of the narrative to make experiences coherent: the narrative becomes then a self-fulfilling prophecy. If in the efficiency narrative, *mobility* is described in terms of *disutility* (the aggregate cost of going from A to B, expressed through a measure that compounds the monetary expenses, time and discomfort required to perform the trip), transportation models and standardised cost–benefit analyses will solidify this notion by indicating that *reducing travel time* is a positive outcome (Ferreira et al., 2012). In practice, this means that plans and projects that intend to speed up traffic by default tend to trump plans for slower and safer streets. Congestion, or travel time loss, becomes the taken-for-granted key problem to be solved for agents in mobility planning (Marohn, 2021).

An alternative narrative can then help us to make visible what is obscured in the prominent one. To identify its potential to do so, Van Twist (2018, pp. 194–195) defined the power of an alternative narrative through its ability to:

1. Linger
2. Automatically invoke agreement
3. Start chains of thought
4. Seduce the opponent to step into the alternative narrative
5. Link to an undercurrent that has been pushed into silence
6. Rescue decision-makers from dilemmas (i.e. it covers more of the abstract concept in Fig. 2)
7. Create free air-time; due to the ability to inspire conversations or discussions, the frame gets ingrained and is harder to dismiss
8. Activate underlying values
9. Lead to a reversal of the burden of proof
10. Resist deconstruction
11. Force those who disagree with it to engage in offensive practices against the narrative.

4.2. How can alternative narratives be developed?

Critical futures epistemology (Ahlqvist & Rhisiart, 2015) offers a useful processual framework for activating and acting upon the deep leverage points explained above, although we recognize that similar ideas exist across urban studies and planning theory literature too. This framework consists of three horizontal and three vertical components with which narratives take on a processual meaning as *re-narrating futures*. The horizontal aspects include (1) providing seeds for alternative nar-

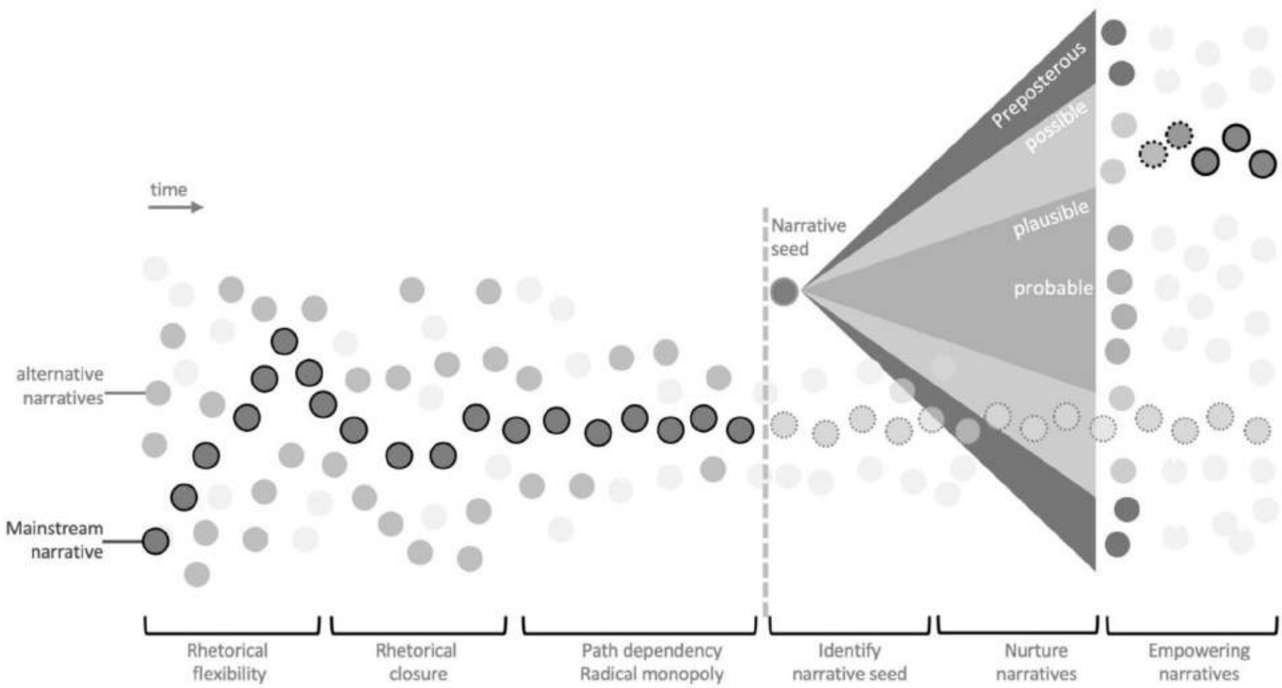

Fig. 3. The process of identifying, nurturing and empowering alternative-mobility narratives (based on the work of Sustar et al., 2020).

ratives by problematising the assumptions underlying the images of futures collectively held in the present; (2) scrutinising the concept of a desirable future through nurturing the promising alternatives; and (3) redefining roles and power across a wider set of actors in society. From a process perspective, the practice of re-narrating is dynamic, exists in a particular moment and place, is both distributed and collective, and is also mediated and contested (Davoudi, 2015).

In contrast, the first vertical aspect refers to *expanding the system boundary*. As Meadows (2008) stated: 'There is no single, legitimate boundary to draw around a system. We have to invent boundaries for clarity and sanity; and boundaries can produce problems when we forget that we've artificially created them' (p. 97). Therefore, we cannot solely focus on technological systems and not acknowledge interdependence on the wider environmental system, institutions, behaviour, norms, meanings and values. Moreover, the second vertical aspect refers to a *higher focus on imagination*. Here, our premise is that the exercise of imagination is a mental state, different from the belief that it is associated with a certain probability of events happening in the future (Kind, 2016; Oomen et al., 2021). This helps to think about futures that are probable, plausible, possible and preposterous (see the futures cone presented by Dunne & Raby, 2013). Similar to belief, imagination is a representational state that has intentionality (i.e. it is both about and directed at some object or state of affairs). Thus, imaginings have intentional content, but do not have to be true as one can intentionally imagine what could commonly be assumed as false. Without the constitutive connection to truth, imagining becomes a speculative, and often liberating, mental state (Pelzer and Versteeg, 2019; Hajer & Versteeg, 2019). As an essentially constructive but also speculative exercise, the act of using imagination involves a capacity to combine ideas in an unexpected and unconventional manner (Van Leeuwen, 2013). Finally, it is relevant to acknowledge that knowing and feeling are closely interrelated (Westin, 2016). Thus, the last vertical component relates to having higher empathy for participants in a planning process, for example in terms of developing genuine willingness to understand others' long-term struggles and experiences, both in the past and in the future.

Based on the above, the re-narration process has three distinct phases: identify narrative seeds, nurture them into full narratives and empower them as alternatives (see Fig. 3). Below we will go into each of those steps in detail, in separate sections.

5. Identify promising narrative seeds

In order to provide an example of some promising narrative seeds, this section briefly describes and reflects upon four possible candidates. They are all developed in relation to the current prominent mobility narrative. The non-inclusive, autocratic, technocentric and uncritical characteristics of the mainstream mobility narrative highlight the role of mobility in economic and urban growth, individual speed and system efficiency, but obscures its role in reproducing inequalities and driving unsustainable developments on a global scale (for more critical analysis of the dominant narrative and its underlying assumptions, see, e.g. Bonham, 2006; Harvey, 2012; Merriman, 2009; Metz, 2008; von Schönfeld & Ferreira, 2022). According to this narrative, individuals should be given the freedom to use their preferred mode of transport (e.g. the private car, which was presented as a technology of personal empowerment) in the most efficient transport network possible. On a collective level, mobility is presented as a derived demand – a mere means that allows people to do activities that are scattered across space (Banister, 2008). In economic terms, mobility is conceptualised as a *disutility*, a negative variable in the individualistic mind of the rational, egoistic, and utility-maximising Homo economicus (Ortúzar & Willumsen, 2011). These features lead to the understanding that reducing travel time is the ultimate policy goal, resulting in a focus on *ever-faster mobility* ('travel time savings') and an efficiently functioning infrastructure to *avoid delays* (which are seen as 'travel time losses').

The collective identification of relevant new narrative seeds is a crucial skill that should be performed with and by all relevant agents involved, as we discussed above. Therefore, the four narrative seeds that we describe below should be seen as illustrations that all have the potential to meet the three above-mentioned vertical aspects, namely, expanding the system boundary, a greater focus on imagination, and greater empathy. They represent starting points, inspirations, based on alternative lines of thinking about mobility (Mladenović, Geurs, Willberg & Toivonen, 2021). They should not be considered as exhaustive examples as we are aware of other narrative seeds that start from questions around health, global social inequalities or the meaning of *a good life* that have their own peculiarities across the world.

First, the narrative seed based on **mobility as individual play** is strongly linked to the concept of 'Homo ludens' (Huizinga, 1938). Streets become places for interaction, discovery and play. This makes mobility 'a valuable social and sensory experience in its own right' (Nikolaeva & Nello-Deakin, 2020, p. 313). Relatedly, being on the move can be seen as a way for individual intellectual development (Ferreira et al., 2012) and for experiencing positive mental states that may increase well-being and breed personal growth and transformation (Te Brömmelstroet et al., 2020).

Second, **mobility as social interaction** is a narrative seed that emphasises the street as the quintessential public place where people encounter others (Mehta, 2013). Being on the move provides exposure to societal diversity that has been associated with the growth of social capital, 'a sense of belonging' to a place and a community, and bridging social differences (Adey, 2010; Bissell, 2010; Sennett, 2012; Te Brömmelstroet et al., 2017). This seed is focused on the 'Homo urbanus' model for understanding human behaviour (Oberzaucher, 2017): people search for altruism, finding meaning in supporting each other, and are influenced by social norms.

The third narrative seed offers the possibility of understanding **mobility as a commons** rather than an individual right, as 'a collective good, paving the way for fairer mobility transitions' (Nikolaeva et al., 2019a, p. 346). It highlights the active and collective engagement that is required to give meaning to mobility as something humans make together: 'Commoning mobility can therefore be understood as a process that encompasses governance shifts to more communal and democratic forms while also seeking to move beyond small-scale, niche interventions and projects.' (Nikolaeva et al., 2019a, p. 346). Importantly, the 'mobility as social interaction' and 'mobility as a commons' approaches offer potential for a constructive critique and recalibration of smart innovations and business models that present themselves as opportunities for 'sharing', even though they are structured in the ways most likely to further commodify mobility while increasing social inequalities, social exclusion and the fragmentation of communities.

The fourth and last narrative seed to be mentioned here, one becoming increasingly relevant in the view of the current developments with the COVID-19 pandemic and the energy crisis induced by the war in Ukraine, is focused on notions such as low mobility, proximity and stillness (Ferreira et al., 2017). This seed offers a conceptualisation of mobility whereby the radical reduction of mobility patterns is not experienced as a detrimental or even traumatic experience, but as a form of social capital to be cultivated upon. During the COVID pandemic, individuals, communities and companies have had to experiment with continuing their activities while relying much less on physical mobility. While a privileged minority had the conditions to prosper in this initially unwelcomed state-of-affairs, many endured terrible experiences (Kokkola et al., 2022; Nikolaeva et al., 2022). In line with this, **mobility as unnecessity** is a narrative seed that highlights the need to promote conditions where stillness, low speed, and proximity-based social contacts and resources become (again) the object of positive attention and investment. Acknowledging that both the beneficial and the detrimental effects of immobility are unevenly distributed, this approach calls for further exploration and development in an inclusive manner.

6. Nurture narratives through inclusive futuring

How can policymakers, innovators and especially citizens be involved in holistic co-creation exercises that develop alternative narrative seeds towards alternative mobility paradigms? As noted by feminist scholars such as Monk and Hanson (1982), individuals structure both research and policy problems according to their values, concerns and goals, all of which mirror their personal experiences and subjective realities. The transport sector has been a field largely dominated by middle-class men, working in hierarchical organisations with a strong inclination towards positivist, technocratic and top-down decision-making approaches. As a result, mobility has to a great extent been shaped by such institutional settings and exclusionary worldviews (Ferreira, 2018). Although there are notable exceptions with some public engagement in transportation planning (Mladenović et al., 2021), the diversity of mobility experiences and needs related to, for example, gender and age have not been sufficiently addressed in transportation planning (Scholten & Joelsson, 2019). Perceptions of safety and comfort, the frequency and types of journeys, needs in terms of service provisions and so forth have all been proven to be highly varied among people.

Furthermore, transportation planning has systematically prioritised the needs of certain groups above others, with the experiences of women, children, people with disabilities, older adults and those with special mobility needs being rendered unaccounted for and invisible. While many scholars have been pleading for a more equitable distribution of accessibility (e.g. Martens, 2016; Pereira et al., 2017), we align with the mobility justice scholarship (e.g. Sheller, 2018) in shifting emphasis from the outcomes of transportation planning to the very politics of decision-making, including issues such as race or poverty. In other words, developing mobility narratives does not revolve around the needs of a non-existent average individual (which, in the minds of urban designers and traffic engineers, has been an able-bodied male by default) but around accommodating various needs, and it must start from nurturing narratives with a diversity of groups.

In addition to the above injustices, the approaches that use existing mobility narratives to either predict or assess the future of mobility (as done by Holden et al., 2020) are, therefore, necessarily problematic as they propose yet another way of shaping mobility futures in a top-down fashion instead of co-creating those futures through inclusive futuring processes.

Challenging this pattern requires engaging citizens in the process of co-creating future mobility narratives (Sustar et al., 2020). Similarly, sustainability transitions research maintains that citizens should be involved in the co-creation of knowledge for sustainability transitions through innovative participatory approaches and methods (Chilvers & Kearnes, 2015). Futuring – defined as the development of normative scenarios of alternative, desirable and sustainable futures as anchors to guide present-time decision-making – is common practice in sustainability transitions projects (Elzen et al., 2004). However, traditionally, these scenarios have been developed by and deliberated within expert groups. The public is left to bear the long-term consequences of policy decisions without being able to influence them. Thus, it has been argued that sustainability transitions need to be addressed by approaches in which not only different scientific disciplines are involved, but also other types of knowledge cultures, such as practice-based, tacit, lay and indigenous (Miller et al., 2008; Robinson, 2008; Sandercock, 2022). The inclusion of the general public in the development and deliberation of possible futures transition scenarios is not only a requirement for democratic policymaking but also crucial for the successful implementation of significant lifestyle and behavioural changes, particularly in the mobility domain (Banister, 2008). Considering how powerful the coalitions behind certain narratives of change, such as 'green growth', are, the more important it is to offer alternative versions of mobility transitions (Ruhrort 2022) and to critically analyse those that are currently promoted (Henderson & Gulsrud 2019).

In addition, the nurturing of alternative narratives is especially needed and even more feasible when, due to the mobility disruptions such as induced by the COVID-19 pandemic, opportunities for new meanings to mobility emerge. As mobility is slowed down, interrupted or prohibited at multiple levels, from global airspace to streets, we observe that new insights about the role of mobility in individual and community lives and in the functioning of economies are emerging, as well as new insights about unexpected possibilities for changing mobility practices (as alerted by Marsden et al., 2020). Some restrictions are more bearable or even benevolent than others for various people.

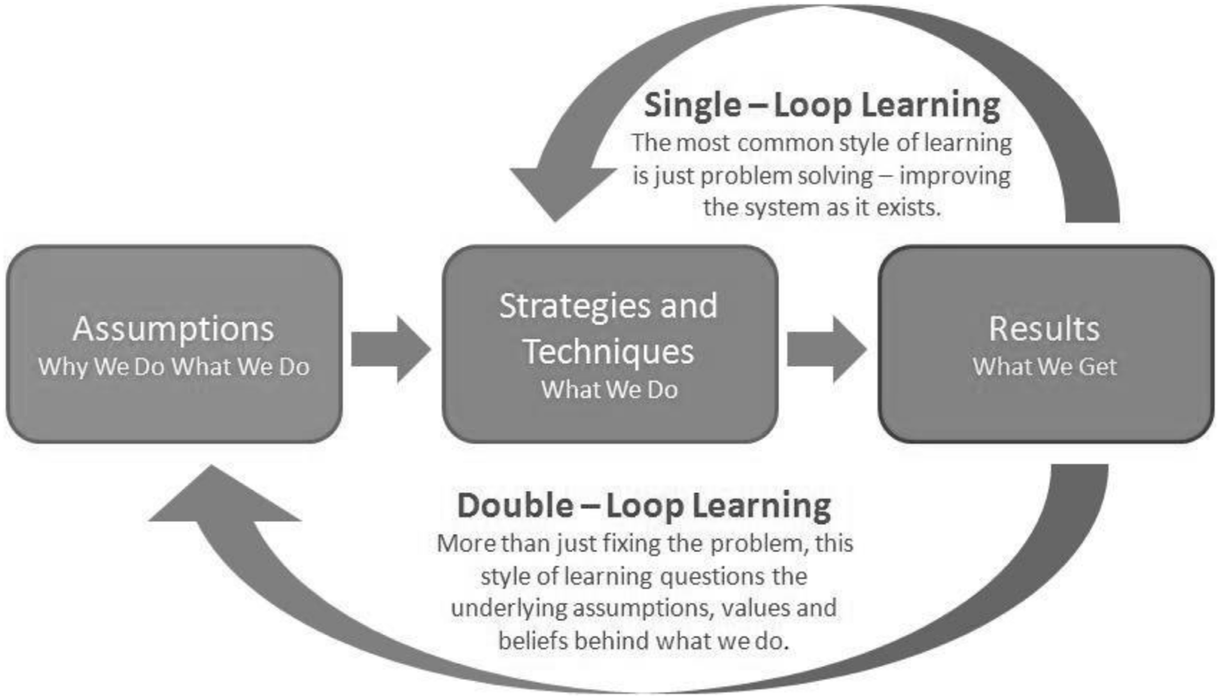

Fig. 4. Empowering double-loop learning (based on the work of (Argyris and Schon, 1978).

New inequalities emerge, but also new opportunities for re-imagining the mobility system around greener and fairer solutions.

7. How can experimentation empower narratives

To empower new narratives that come out of such a nurturing process, policymakers, innovation stakeholders and citizens need to go beyond single-loop learning, that is, acquiring knowledge, skills and data so that one can perform better within the existing frame of reference (Argyris, 1977). To create optimal conditions for transformative change (as discussed by Meadows, 1999; 2008), the frames themselves need to be questioned. In empowering **double-loop learning** (or *transformative learning*; shown in Fig. 4) and in recognising the importance of storytelling in innovation processes (Sergeeva & Trifilova, 2018), new narratives can be used to support actors in questioning their underlying assumptions, values and beliefs (Borup et al., 2006).

Even though both types of learning are critical for effective leadership, it is transformative learning which facilitates an individual or organisation to deal with new, highly challenging and unsettling circumstances as they emerge – particularly when these circumstances represent a threat to the status quo. However, transformative learning is also time expansive, meaning that individuals and organizations need to learn new knowledge as they generate it, as opposed to simply transferring it (Engeström, 2015). Expansive learning, together with power shifts, often implies a highly emotional state for all the actors in the affected networks. Thus, inter- and intra-organisational learning cannot lead to powerful changes if the need to cater for complex emotional states in these relational networks of people is neglected (Eräranta & Mladenović, 2021).

Using the European context as an example, the European international partnerships and organisations that bring together researchers, governments and businesses (e.g. the European Union and the United Nations) are particularly well-positioned to promote experiments with alternative mobility narratives. These experiments could contribute to steering societies away from the old normal by means of empowering alternative narratives through the way in which new technologies are developed, policies are promoted and streets are designed. On a local level, the urban innovation ecosystems – for instance, transition arenas – would be well positioned to become the co-creation 'nests' for the new narratives as they already bring together citizens, researchers, local policymakers and innovators (Dell'Era and Landoni, 2014). Many of the urban mobility-focused transition arenas and innovation hubs currently focus on creating smoother traffic or helping companies pilot new technologies. If that focus could be shifted towards the active exploration and exploitation of alternative mobility narratives, perhaps innovations that are now unthinkable and unimaginable would start emerging.

8. Conclusion

The dominant mobility narrative, which is deeply shaped by concepts such as utility, efficiency, speed, and cost-effectiveness, is limiting our individual and collective understanding of mobility phenomena. Ultimately, it is limiting the effectiveness of the vast majority of transport policy interventions and technological innovations in creating new urban mobility futures. This narrative dates back to historical facts from the eighteenth century and to policy choices made in the 1920s, and have since then solidified into common guidelines, models, laws and institutions; into concrete, steel and technologies; and into the limits of our imagination. Indeed, the domination of this timeworn narrative is most unlikely to contribute to the resolution of the following problems that were unthinkable when its seed was forcefully planted: the climate and energy crisis, biodiversity loss, and the emergence of zoonotic diseases such as COVID-19.

Unless we are able to collectively reimagine, challenge and add multiple alternatives to this narrative, we are unlikely to achieve the radical transformations that are called for. With high stakes for our common mobility futures, how can all agents identify the seeds of emerging narratives, inclusively nurture them and consequently empower emerging alternative futures?

Taking into account that a plethora of tools and methods for policy, planning, design and innovation are already available, we have outlined an overarching framework for holistic and future-oriented thinking about the process of narrative and system change – adaptable to particular contexts. To this end, we have distinguished four seeds for identifying, nurturing and empowering alternative narratives. These four potential candidates are: mobility as play, mobility as social interaction, mobility as commons and mobility as an unnecessity. They have been carefully selected as potentially among the most radical 'challengers' to the dominant mobility narrative, those which could serve as springboards for opening up new possibilities. Of course, we recognize that since these narratives draw from transport and mobility literature which is still dominated by Global North and Western focus, different potential radical narratives have to be looked for across the globe. Similarly, four narrative seeds are not an exhaustive number, as following the conceptualizations in futures studies, the number of possible futures is closer to infinity. In addition, we have argued that nurturing narratives, as a process, requires including all mobility-system agents and all types of knowledge cultures if new relevant meanings and aspirations for more justice in future mobility systems are to be created. Finally, we have argued that nurturing has to go hand in hand with empowering through a wider network of actors across institutions, which has to rely on both organisational learning and mutual empathy.

In line with Holden et al. (2020), this framework is intended to enable a process with which to achieve understandable, attractive, motivational and possible narratives. However, by deepening the conceptualisation of narrative in relation to deep leverage points, as well as the features of path-dependence, we have argued that we need a more comprehensive approach to understanding our mobility systems, more speculative imagination and empathy for all the actors involved. As such, we have aimed to move the discussion beyond the state of the art by providing reasons and means for the wider nurturing and empowering of alternative narratives that emerge outside of academic circles. Ultimately, although our description of the framework is mainly focused on *how* questions, we expect that its use in practice would also lead to more difficult *why* questions, which would further unlock potentials for transformative change (Bertolini et al., 2020). Such questions will need to go hand in hand with a further critical analysis of both the mainstream narrative and each alternative narrative.

The four seeds of alternative narratives that we presented are already much more informed by the focus on embodied and social nature of mobility emphasized by mobility scholars (Cresswell, 2006; Nikolaeva et al., 2019a) than the mainstream narrative. It would be valuable to further connect mobility practices as embodied and socially meaningful to the generation of alternative narratives, and the other way around, as well as to research the connections between the two. Studying experiments where mobility conditions are changed in real life can especially offer valuable platforms for such connections (Bertolini, 2020). Ultimately, the process of looking for new narratives, or 'dancing with narratives' (paraphrasing Meadows, 1999) would relate not only to built environments but also to organisational and governance cultures across mobility-related cross-institutional networks. We emphasize the point made by Gorman (2010) that these and other future activities ask for developing new kinds of interactional expertise attitudes across practices and academia.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Improving urban bicycle infrastructure-an exploratory study based on the effects from the COVID-19 Lockdown

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A R T I C L E I N F O

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A B S T R A C T

Introduction: During the COVID-19 lockdown significant improvements in urban air quality were detected due to the absence of motorized vehicles. It is crucial to perpetuate such improvements to maintain and improve public health simultaneously. Therefore, this exploratory study approached bicycle infrastructure in the case of Munich (Germany) to find out which specific bicycle lanes meet the demands of its users, how such infrastructure looks like, and which characteristics are potentially important.
Methods: To identify patterns of bicycle infrastructure in Munich exploratory data is collected over the timespan of three consecutive weeks in August by a bicycle rider at different times of the day. We measure position, time, velocity, pulse, level of sound, temperature and humidity. In the next step, we qualitatively identified different segments and applied a cluster analysis to quantitatively describe those segments regarding the measured factors. The data allows us to identify which bicycle lanes have a particular set of measurements, indicating a favorable construction for bike riders.
Results: In the exploratory dataset, five relevant segment clusters are identified: *viscous, slow, inconsistent, accelerating,* and *best-performance*. The segments that are identified as *best-performance* enable bicycle riders to travel efficiently and safely at amenable distances in urban areas. They are characterized by their width, little to no interaction with motorized traffic as well as pedestrians, and effective traffic light control.
Discussion: We propose two levels of discussion: (1) revolves around what kind of bicycles lanes from the case study can help to increase bicycle usage in urban areas, while simultaneously improving public health and mitigating climate change challenges and (2) discussing the possibilities, limitations and necessary improvements of this kind of exploratory methodology.

1. Introduction

The COVID-19 pandemic has fundamentally changed how movement and interaction take place in urban areas. As social distancing is the new norm in public spaces all over the world (De Vos, 2020) people change their transport behavior with immediate effect. Despite the rise of new formats of interaction and remote working, transport is and will remain a fundamental aspect of daily life (Brooks et al., 2020; Laverty et al., 2020). Nonetheless, new challenges are imposed on the way people move around cities, encouraging new and innovative solutions for major challenges such as urban health and climate change adaptation.

Many studies have shown that a strong immune system is an indicator for a mild course of infection (Taghizadeh-Hesary & Akbari, 2020). At the same time, Gupta et al. (2020) observe a positive correlation between air pollution and the lethality of a COVID-19 infection. Against the background of the global decrease in the use of public transport (De Vos, 2020; Tirachini & Cats, 2020) cities need to face the challenge of maintaining public health by adapting their urban transport infrastructure towards the needs of people. One main factor is infrastructural adaptation enabling individual traffic while reducing emissions at the same time. The lockdown during the first wave of the COVID-19 pandemic has shown that positive environmental effects are immediately visible when reducing motorized traffic (Kerimray et al., 2020).

One aspect of addressing this challenge is strengthening individual bicycle traffic in urban areas. Before the emergence of COVID-19 around the world, the level of physical commuting activity declined in many countries (Fraser & Lock, 2011). During the global lockdown, active transport (such as cycling) has increased as people can travel while keeping social distancing upright (Brooks et al., 2020). Teixeira and Lopes (2020) have shown that people started switching from the subway to bike-sharing possibilities in the case of New York

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City, but also other major cities have witnessed similar developments. De Vos (2020) frames cycling as a way to maintain public health while Hammami et al. (2020) highlight the importance of sufficient physical activity, especially during lockdown situations. An increase in bicycle traffic is, therefore, a possibility to face two challenges at the same time – mild courses of infection for COVID-19 patients and adaptation for climate change in urban areas – as this mode of transport does not only reduce emissions, improve air quality, and has environmental as well as public health benefits (Cole-Hunter et al., 2015), but cycling is also a vital part in building up a strong immune system to fight infectious diseases (Aman & Masood, 2020).

The situation caused by the pandemic needs to be framed as a public health opportunity (Brooks et al., 2020). It requires long-overdue infrastructural change, as infrastructure is a leading factor that influences individual decisions for cycling as a preferred mode of transport (Boss et al., 2018). As bicycles constitute an important part of a community's transportation system, the increasing pressure of individual transport (Dewulf et al., 2015) is an obstacle for cyclists, due to increased interaction with motorized traffic and associated safety concerns (Bagloee et al., 2016). Bao et al. (2017) argue that bicycle traffic has the potential to reduce the challenges imposed by too much motorized individual traffic. King and Krizek (2020) argue that changes in street design can rapidly increase access by individual modes of transport (Barros et al., 2020), but as financial means for such changes are usually limited they need a thorough evaluation to have the expected effect (Boss et al., 2018).

The global lockdown provided a test scenario with little individual motorized traffic in urban areas. Therefore, the aim of this exploratory study is the following: *How are bike lanes perceived from a bicycle rider's perspective and what do they need to look like so that increasing individual traffic (triggered by the COVID-19 pandemic) will shift towards cycling?* As cycling infrastructure should be based on the users' needs and not spatial constraints, such as existing road networks or limitations by buildings (Guerreiro et al., 2018) a rider-related approach is chosen. This may help to identify potential bike lanes that meet those demands and do not hinder the usage of bicycles as a sustainable mode of transport in urban areas. The exploratory case study was conducted in the city of Munich (Germany). Future COVID-19 policies will have a strong effect on the development of public spaces (Honey-Rosés et al., 2020) and the global lockdowns are an opportunity to change the previous state of traffic infrastructure (Laverty et al., 2020).

This paper is structured as follows: First, the lockdown is framed against (a) the background of 'Geographies of Health' with a special focus on air pollution development as well as the accompanying barriers to cycling at the same time and (b) the connection of bicycle infrastructure and bicycle usage. We document the exploratory methods used to identify types of bicycle lanes that enable cyclists to perform best and enjoy the ride at the same time and explain how their clustering was carried out. The case study investigates an exploratory dataset, that shows the analysis for a selected route in Munich. Based on this case study we discuss (1) aspects that revolve around what kind of bicycles lanes can help to increase bicycle usage in urban areas, while simultaneously improving public health and mitigating climate change challenges and (2) the possibilities, limitations, and necessary improvements of this kind of exploratory methodology.

2. Theoretical background & previous research

For this study, concepts originating from 'Geographies of Health' provide valuable insights into the analysis and choice of factors to identify how bike lanes need to be designed to enable the shift from motorized individual traffic towards human-scale individual carbon-neutral bicycle traffic. Health is not only about the absence of sickness in a person, but also the social and cultural construct of health, wellness, identity within the environment, and spatial experience (Giesbrecht et al., 2014). As societies will probably continue to face public health issues after the COVID-19 pandemic, knowledge about how cities can address those challenges needs to be deepened. Cities that encourage active transport can address such challenges more efficiently and profoundly (Giles-Corti et al., 2016).

Public transport systems are potential sources of infection, as social distancing cannot be upheld at all times. Long-lasting effects such as mistrust against public transport, as pointed out by Conway et al. (2020) can therefore be directly incorporated into the future planning of urban transport systems and be enriched by knowledge about other communicable or non-communicable diseases, e.g. cardiovascular diseases (CVD) (Giles-Corti et al., 2016). Many studies have shown a strong correlation between bicycle usage and health indices (e.g. Bagloee et al., 2016). Furie and Desai (2012) state that insufficient physical activity may result in CVD as well as obesity, diabetes, and blood-pressure-related health problems. Therefore, cycling is among the modes of transport that add to the daily amount of recommended physical activity (Panik et al., 2019). Celis-Morales et al. (2017) describe in their case study that 90% of active commuters meet the minimum of recommended daily physical activity which is a factor for a lower risk of CVD mortality. Additionally, even on a psychological level bicycle transport has positive effects: According to Avila-Palencia et al. (2017)) people who cycle to work experience positive effects for their self-esteem coupled with a positive environmental impact and significantly feel less stress. Those positive effects are among the motivations of people to use bicycles instead of other modes of transport – consciousness, pro-health, and the cyclist lifestyle (Biernat et al., 2018).

To incorporate those positive public health effects into individual daily schedules, Cole-Hunter et al. (2015) highlight the importance of urban environments to facilitate such changes. A proof of the positive development of less motorized traffic in cities was not the rise of bicycle traffic but the global lockdown situation that forced many people to work at home instead of daily commuting to work. Liu et al. (2020) have shown that during the lockdown and the following reduction in human activities there was a decrease of 8,8% in global CO_2 emissions (less individual motorized transport cannot account for this as a whole, but passenger transport accounts for 45,1% of all CO_2 emissions caused by transport (Ritchie, 2020)). In the 1940s up to 85% of trips in European cities were taken by bike, however, the development of cheap oil favored motorized individual transport (Larsen, 2017), although the distances are amenable to cycling: Rissel et al. (2013) state that for the case of Sydney 25% of distances traveled by car are below 2 kms and even half are less than 5 kms.

Many cities have experienced significant improvements in air quality during the lockdown. In Wuhan (China) the lockdown had a substantial effect on the ozone and nitrogen oxide (NO_x) concentration. As NO_x decreased by 53,3% the concentration of ozone increased by 116,6% (Lian et al., 2020). Kerimray et al. (2020) measured similar values for Almaty (Kazakhstan, −35% NO_x concentration). Forster et al. (2020) estimate that the global NO_x concentration decreased by approximately 30%. For the city of Munich, where the empirical study took place, similar observations were made, regarding the NO_x concentration in the city.

Fig. 1 shows the differences in the NO_x concentration in Munich for three different periods (2019, 2020 1st quarter, 2020 2nd quarter). The strongest difference is noticeable between the first and second quarters of 2020 when the lockdown was imposed, and traffic was significantly reduced. This figure backs up the findings of Laverty et al. (2020) investigating NO_x measures in urban areas and shows that transportation has direct and indirect impacts on public health. This is not only based on the decrease of NO_x but also less carbon dioxide and noise, resulting in higher air quality and a better urban atmosphere (Zambrano-Monserrate et al., 2020). Nonetheless, such developments might not be permanent: Chang et al. (2020) have shown for the case of Taiwan that post-lockdown the NO_x concentration rose between 5 and 12%, due to the shift from public transport to individual motorized transport – as a way to enable safe transport in pandemic times.

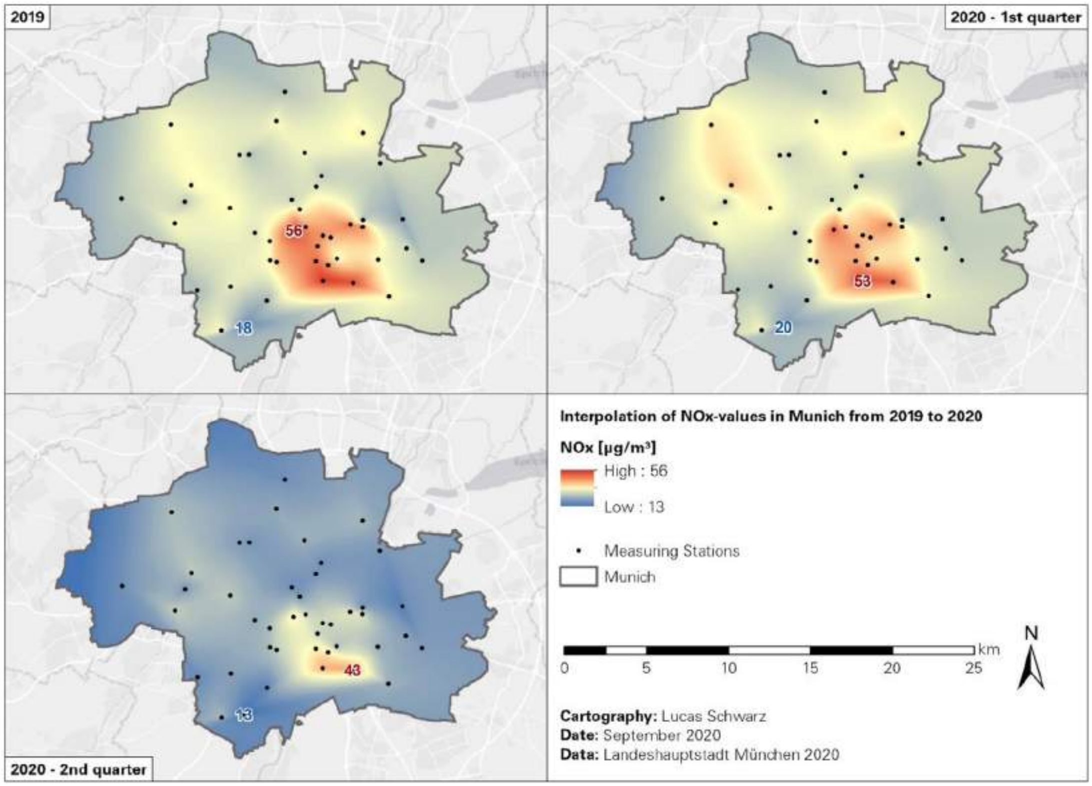

Fig. 1. Interpolation of NOx -values in Munich from 2019 to 2020 (1st and 2nd quarter), data derived from München (2020).

Conway et al. (2020) state, based on a US survey, that some behavioral changes initiated by the lockdown will persist, especially when it comes to cycling and walking more often. Although this study was carried out with highly educated US citizens only, the authors conclude that it is unlikely to fully return to pre-pandemic transportation habits. Especially health is a reason to frequently travel by bicycle but it is still outweighed by factors revolving around physical effort and the lack of a safe cycling network (Félix et al., 2019).

Although cycling already is the default choice of transport for many cyclists in urban areas (Kuhnimhof et al., 2010) there seems to be a connection between the individual choice to cycle and the built environment. Piras et al. (2021) provide an empirical example stating that there is a positive correlation between perceived cycling benefits, perceived comfort, and perceived importance of bicycle infrastructure and the propensity to cycle. In addition, they identified a connection between socio-demographic factors (e.g. age, gender), structures in urban areas, and bicycle usage and therefore conclude to focus on the built environment and behavioral and perceptional factors equally (Piras et al., 2021). Lanzendorf and Busch-Geertsema (2014) conclude that cycling is intertwined with infrastructural improvements. Buehler and Pucher (2021) reviewed the difference between urban traffic in the US as well as European countries but reach the same verdict: They explain differences in cycling and walking fatalities in Europe by better infrastructure and lower urban speeding limits.

Of course, infrastructural change has been intensely analyzed by scholars. Blitz et al. (2020) demonstrate by drawing from a case study in the German Rhine-Main Metropolitan Region that infrastructural improvements of bicycle streets have positive impacts, especially for frequent bicycle users. Nonetheless, they emphasize including individual urban travel behavior in future studies. Ghekiere et al. (2014) focused on cycling safety for children and conducted qualitative interviews about cycling infrastructure. They identified wide and even cycle tracks, a good overview of traffic, and traffic density as key factors for perceived safety. Although they reached those results by interviewing children, their findings seem to apply to a broader range of cyclists. For the German city of Münster, Schröder (2021) suggests that significant improvements of the built environment result in more safety, comfort, and shorter travel times. She demonstrates this by drawing from empirical evidence from improved bicycle streets. Further studies focused on barriers to using bicycles in urban infrastructure (e.g. traffic and too few bike lanes) (e.g. Dill & McNeil, 2016).

Although infrastructural improvement seems to be omnipresent in most studies, Assunçao-Denis and Tomalty (2019) name factors that cannot be influenced by infrastructural planning, such as cultural, demographic, or economic settings. Despite the importance, they emphasize the effect of local measures by expanding bicycle infrastructure. In a statistical study, Haustein et al. (2020) describe the model of perceived ease derived from cycling safety and security, autonomy, and priority in planning. This model explains 65% of the variance of the individual cycling perception (Haustein et al., 2020). Other authors analyze behavior and perception from different angles: Aletta et al. (2018) describe how the sound level is a factor to the cycling comfort but highly dependent on personal perception. van Cauwenberg et al. (2012) assign the personal perception of safety to gender differences and Pooley et al. (2011) draw attention to the individual perception of safety. In this context, Schwedes, Wachholz, & Friel (2021) support this thesis and state that safety cannot be understood as a number but needs to be analyzed from a qualitative point of view.

Abdai and Hurwitz (2018) analyzed the perceived level of comfort during a bicycle ride when overtaking truck loading zones as a factor to increase or decrease the share of cyclists. They analyzed ambient traffic (volume and truck traffic) as well as pavement markings and traffic signs as factors that influence the comfort during a ride, thus affecting future decisions to choose the bicycle as an adequate mode of transport. Other studies, such as Cho et al. (2009) argue similarly.

While Pooley et al. (2011) show that cyclists are especially concerned about risks that stem from interaction with motorized traffic), Dill and McNeil (2016) characterize four types of cyclists as not all cy-

Table 1
Comparison of Modal Split (Munich and Germany) in percent, data derived from BMDV (2019).

Modal Split	Pedestrians	Cyclists	Motorized Individual (Drivers)	Motorized Individual (Passengers)	Public Transport Users
Munich	24	18	24	10	24
Germany	22	11	43	14	10

clists have the same perception of safety, risk, or comfort. Nonetheless, not only the perception of cyclists is important but also of motorized vehicle users. Huemer and Strauß (2021) present an empirical experiment showing that car drivers feel more confident to overtake cyclists when those travel in lanes segregated by a marking.

As the presented studies have shown the analysis of behavioral and perceptional rider-related data (e.g. level of sound or level of comfort) in connection with bicycle infrastructure (e.g. type of bicycle lane) is necessary to expand bicycle infrastructure as a medium to combat health and environment-related crises. In the following section, we, therefore, present our exploratory approach for this case study.

3. Methods & case study

The case study is carried out in Munich, Germany's third-biggest city and home to one of the country's biggest car manufacturers. Cycling is a popular trend in the city, leading to an increase of cyclists in the modal split: While only 10% of inner-city travelers used bicycles in 2002, the share increased to 18% in 2017 (BMDV 2019). As Table 1 shows, the share of cyclists of all traffic participants in Munich is higher than the German average, while there is also comparatively less motorized individual traffic.

Drawing from literature and studies about behavioral, perceptional, and individual perspectives while cycling in urban areas, we use bicycle-rider-related data as a way to obtain data on how riders experience a route by bicycle and as a possibility to focus on multiple factors that influence a ride at the same time. This honors the critique formulated by Ryu et al. (2015). We include different aspects that depend on the rider, such as velocity or pulse as well as environmental data (temperature, humidity, and level of sound (as an indicator of nearby-motorized traffic and the traffic situation)). This data is held against the background of the status of the bicycle lanes, and segments are identified depending on their design (type of bike lane, interaction with traffic, structural condition) and qualitative evaluation of the rider's comfort after each ride (perceived safety, perceived quality of bike lanes, perceived comfort of infrastructure, perceived flow of the ride, perceived interferences with other traffic participants). To enable a comparison between different segments the data is spatially obtained: Most of the data is obtained using free apps on an Android smartphone fixed to the handlebar of the bicycle. The route is agreed upon beforehand and one bicycle rider carries out test routes. Table 2 gives an overview of the measurement devices and which apps are used to measure.

The bicycle trips are carried out on weekdays between 8 and 9 am during the morning commute and between 4 and 6 pm during the evening commute. All trips follow the agreed-upon route and all traffic rules are strictly obeyed. The chosen route consists of a cross-section of Munich from the West to the South-East and represents a commutable distance that is amenable to average bicycle users (6–10 km). Additionally, the route contains different kinds of bicycle lanes: segregated and shared lanes as well as no bicycle lanes; lanes that range from interaction with motorized traffic (in motion or parked) or pedestrians to no interactions; and bicycle lanes that have a high quality down to lanes that are consistently inter- or disrupted by sidewalks or other structural features. As the route is mostly flat (except for one short uphill segment, 300 m distance, elevation gain 14 m) the influence of altitude can be neglected.

To receive information on the identified segments a cluster analysis is carried out. Data was collected for defined time intervals (10 s) which concluded in 5.424 data points along the route, including all information mentioned in Table 2. A hierarchical cluster analysis is carried out as beforehand no structures were existent in the dataset (Janssen & Laatz, 2017). We select the squared Euclidean distance as a proximity measure and the Ward method as a merging algorithm to keep the variance within a group to a minimum (Backhaus et al., 2016; Bortz & Schuster, 2010). It is possible to simplify the multiple and complex relations between the single data points to detect spatial relations. To calculate the different clusters, we utilize personal (velocity, pulse) and environmental factors (level of sound). The environmental factors humidity and temperature are excluded from the analysis as they do not add to the differentiation of the clusters. As the case study is carried out in August, temperature and humidity do not significantly differ during the single rides. The decision for the exact number of clusters is made, using the elbow criteria as well as the dendrogram. The attribution of a feature to a cluster is made using standardized residuals. Additionally, we run a discriminant analysis to categorize waypoints that are lacking information due to measurement errors (Backhaus et al., 2016). In the last step, the spatial data is enriched by the information gained from the cluster analysis, and implications for bike lanes are derived.

4. Results

The cluster analysis sheds light on which type of bicycle lanes enables cyclists to perform best, move the most efficiently and safely between two destinations, and enjoy the ride at the same time. Those are the most important factors to decide for or against the usage of bicycles as a mode of transport (Bagloee et al., 2016; Félix et al., 2019). The following section presents the five identified clusters: *viscous, slow, inconsistent, accelerating,* and *best-performance*.

Table 3 shows the five different clusters along the personal and environmental factors used for the cluster analysis. The number in brackets indicates the standardized residuals. When the standardized residual is >2,0 it is interpretable and the higher it is, the stronger the attribute is linked to the corresponding cluster (Backhaus et al., 2016).

Fig. 2 represents the spatial distribution of the clustered segments, including the position of traffic lights along the routes. Three of the identified clusters represent data points that are characterized by non-optimal comfort of bicycle usage: *viscous, slow,* and *inconsistent*. The cluster *viscous* is characterized by a (very) slow velocity (<10 km/h to 10–15 km/h) and a (very) high pulse at the same time (115–130 to >130 bpm). The level of sound is ranging from quiet (75–80 dB) to normal (80–85 dB). The assigned bicycle lanes are usually intensely used by motorized traffic, such as cars or buses, and there is always plenty of interaction between all traffic participants. As the level of sound is quite low, motorized traffic is most of the time not in full motion but congested. Usually, bicycle riders can overtake but always have to be alerted to not cause any damage to cars (in motion or stopping) as well as not have any damage caused to themselves. *Viscous* segments usually have little to no coverage of bicycle lanes.

Another segment that is distinguished by a high level of interaction with other traffic participants is the *slow* segment. Bicycle riders cannot accelerate to a comfortable fast velocity as the segment is often disrupted by motorized vehicles or construction sites (although this is mostly a temporal phenomenon). Although the traffic lights are usually controlled to be in a series there are long waiting times to be expected as soon as a series is missed, resulting in a slow overall velocity. Based on all the forced stops the pulse is within a normal range (100–115 bpm).

Table 2
Overview of data measurement.

Factor	Sensor	Software/ App	Position	Type	Average	Minimum	Maximum
Spatial position	Smartphone	OSMTracker for Android™	Handlebar	Spatial	N/A	N/A	N/A
Trip time	Smartphone	see above	Handlebar	Time	20 min	16 min	35 min
Temperature	Psychrometer	–	Handlebar	Environmental	24,4 °C	15,1 °C	34,4 °C
Humidity	Psychrometer	–	Handlebar	Environmental	64%	28,5%	100%
Sound	Smartphone	Physics Toolbox Sensor Suite	Handlebar	Environmental	92,6 dB	69,8 dB	98,6 dB
Velocity	–	Derived from the spatial position	–	Personal	17,9 km/h	4,5 km/h	58,81 km/h
Pulse	Fitbit Charge 2™ fitness watch	Fitbit	Rider's wrist	Personal	114,6 bpm	71 bpm	160 bpm

Table 3
Results of the cluster analysis.

Factors/clusters		viscous	slow	inconsistent	accelerating	best-performance
Personal	*Velocity*	Very slow *(15,2)* Slow *(18,7)*	Very slow *(33,5)*	Slow *(2,3)* Very fast *(2)*	Fast *(2,4)* Very fast *(7)*	Normal *(7,4)* Fast *(10,5)* Very fast *(8)*
	Pulse	High *(12,8)* Very high *(7,2)*	Normal *(13,4)*	Very low *(12,9)* Low *(38,8)*	Very high *(38,7)*	Normal *(5,4)* High *(5,4)*
Environ.	*Sound*	Quiet *(4,1)* Normal *(2,8)*		Very loud *(2,1)*	Very loud *(2,6)*	

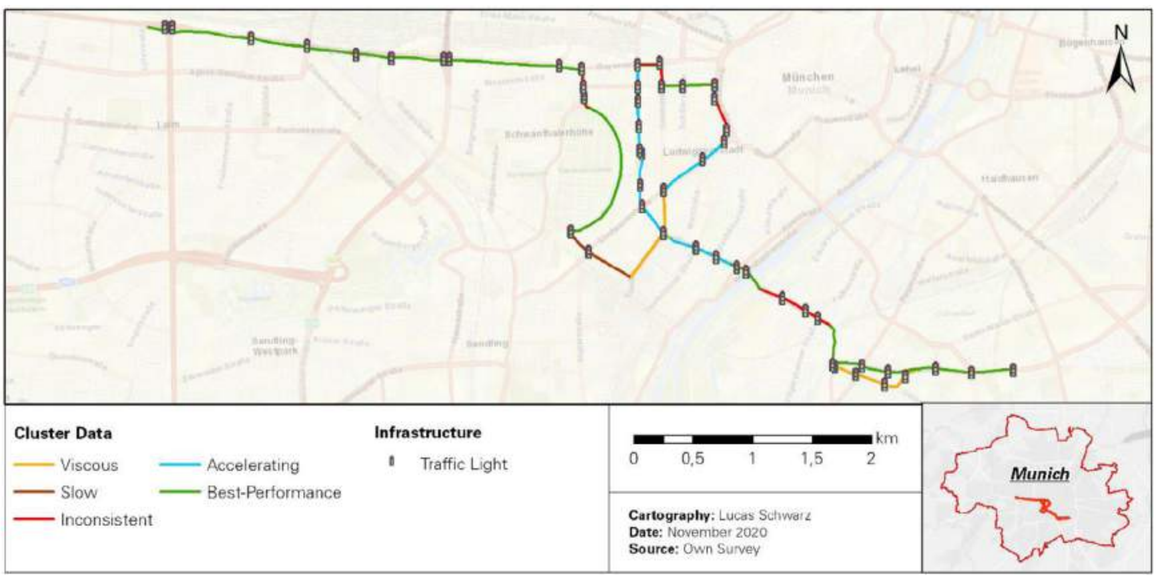

Fig. 2. Spatial distribution of clustered segments of the test dataset related to selected bike ride parameters.

The last cluster that is assignable to the non-optimal bicycle ride performance segments is *inconsistent*: The velocity ranges from slow (<10 km/h) up to very fast (>25 km/h) – this suggests a very uneven and non-consistent riding dynamic. Despite the fast velocity, the pulse is usually in a (very) low range. It is significant that the level of sound is very loud (>90 dB), which indicates that surrounding traffic is omnipresent, either accelerating or in full motion. Such segments tend to feature strong interactions with other traffic participants, e.g. motorized vehicles or pedestrians. The quality of bicycle lanes varies strongly from segregated lanes to narrow lanes that are embedded between shops and parked vehicles. The intensity of interaction varies accordingly by the time of the day.

The first cluster that is assigned to a more optimal riding and performance experience is *accelerating*. Segments that are marked *accelerating* can be traveled fast or very fast, resulting in a high pulse (>130 bpm). The level of sound is very loud which indicates traffic in motion in the vicinity of the segment. The traffic light is usually controlled to be synchronized but another factor responsible for disruptions and braking maneuvers are pedestrians and motorized vehicles. The main difference between *accelerating* and *inconsistent* is therefore the possibility of higher velocity on *accelerating* segments.

The optimal bicycle riding performance is possible on segments labeled as *best-performance*. The velocity ranges from normal (15–20 km/h) and fast (20–25 km/h) to very fast (>25 km/h). Accordingly, pulse ranges between 100 and 115 bpm (normal) up to 115–130 bpm (high). *Best-performance* segments offer the highest quality of bicycle lanes: wide, evenly paved lanes with little to no interaction with accompanying traffic. Along such lanes, some segments are even segregated through the construction of barriers, giving bicycle riders protection, and hindering interaction that would result in dangerous breaking maneuvers or physical injury. Besides, traffic lights are often in favor of bicycle riders, giving them the smoothest and most efficient bicycle riding experience of all identified cluster segments. Taking the research question into the account, what kind of bicycle lanes are needed to prevent the shift of individualization in urban transport towards motorized vehicles, lanes that fit the *best-performance* description are most likely to make people decide in favor of bicycles instead of cars. Those are the factors that result in positive associations with bicycle paths, as described

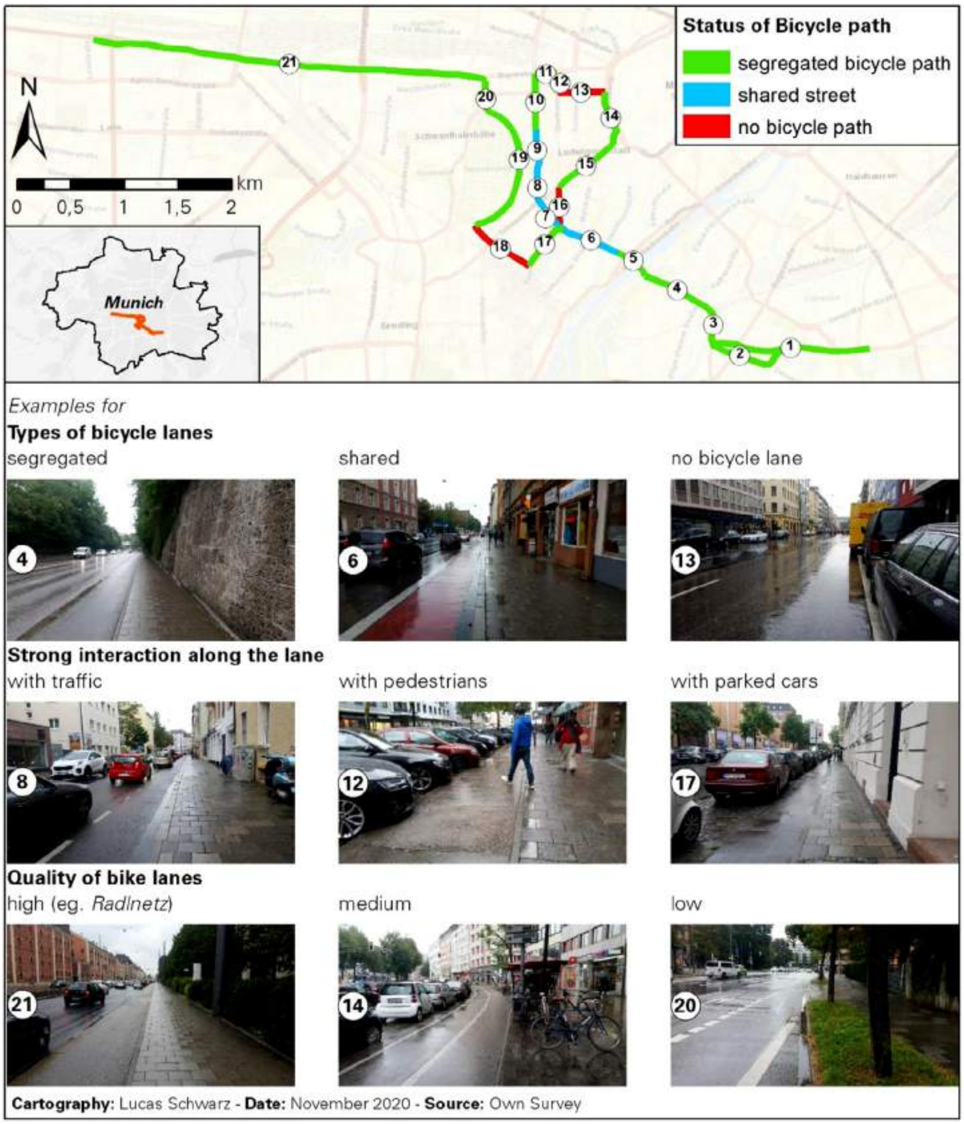

Fig. 3. Overview of bicycle paths on the test route related to pictures at selected sites – the numbers in the pictures correspond to the segments in the map above.

by Fraser and Lock (2011). Such segments are mostly found outside of densely used city centers towards residential areas where space is less contested (Fig. 2).

Fig. 3 compares the quality and the differences between the different bicycle lanes that occur along the route. The numbers in the pictures correspond to the segments on the map. Picture 21 is an example of the *best-performance* segment. There is no interaction with the traffic on the left side of the bicycle lane and no parking, shops, or any other source of possible interaction with pedestrians on the right side of the bicycle lane. Additionally, the bicycle lane is constructed differently than the pedestrian lane, adding up to the clear border, enhancing the safe usage for both cyclists on the left side and pedestrians on the right side. *Accelerating* segments are best represented by picture 8. The bicycle lane is quite narrow and motorized vehicles are often crossing into the bicycle lane as there is only an overlookable marking between the car and bicycle lane on this shared street. The non-optimal performance segment *inconsistent* is shown in picture 14. Parking is possible on the left side of the bicycle lane and shops are found on the right side. Additionally, there is the possibility to park and lock bicycles on the right side which is another possibility that bicycle riders will need to abruptly stop their bicycle. *Slow* segments are presented in picture 13, despite the difference that such segments are characterized by very dense traffic (mostly made up by motorized vehicles). Picture 17 represents an example of the *viscous* segment. The bicycle lane is quite narrow and there is a constant interference of the bicycle ride by opening car doors and people walking on the bicycle lane as the pedestrian lane is narrow. Additionally, people crossing the road are not easily spotted between cars, so bicycle riders on this *viscous* segment need to ride more carefully than on open bicycle lanes to avoid physical injury.

As the empirical survey was carried out in August the environmental weather conditions did not vary fundamentally. There was a slight difference in the daytime of the commute as the temperature was usually lower in the morning than in the evening, but no significant correlation was detected. For this study, it can be concluded that the influence of the environmental factors weather and humidity can be neglected for the summer months. This supports several studies' findings' (Bagloee et al., 2016; Félix et al., 2019): The main reasons to decide for or against bicycles as a suitable mode of transport is determined by the quality of bicycle lanes and the resulting implications for safety and comfort.

5. Discussion

We engage in two discussions: (1) What kind of bicycle lanes can help to increase bicycle usage in urban areas as means to improve public health in times of crisis and mitigating to climate change challenges? (2)

What are the possibilities, limitations, and necessary improvements of this kind of exploratory methodology?

5.1. Improved bicycle lanes as means to combat environmental challenges in urban areas

As the COVID-19 pandemic has shown, the prevention of crises is a cheaper solution than a cure. This applies to the climate crisis as well (Manzanedo & Manning, 2020). At the moment there are two scenarios for transportation in urban areas possible: business as usual or significant change to decrease the number of motorized vehicles in cities by either increasing the attractiveness of working from home (Hensher, 2020) or increasing the attractiveness of bicycles as a preferred mode of transport.

This exploratory study shows that only a share of all segments in an urban area meet the demands that cyclists have for *best-performance* segments. This supports the findings of Bagloee et al. (2016) as well as Parkin and Koorey (2012): The authors suggest that bicycle infrastructure cannot be simply added to an existing road network that is primarily used by motorized traffic but has to be promoted by separate networks. Although Cole-Hunter et al. (2015) suggest that bicycle lanes that are embedded in urban green areas are increasingly frequented, our findings cannot reproduce this correlation. This needs further differentiation as Aletta et al. (2018) focused on the relationship between the comfort of a bicycle ride and green areas contrasted by the perception of sound. In our case especially the separation as mentioned by Bagloee et al. (2016) and Schröder (2021) has a positive effect on the rider's perception of comfort and performance on the segment (see the comparison in Fig. 3). This also supports the findings by Ghekiere et al. (2014) although they focused on children's comfort while cycling.

The *best-performance* segment is characterized by an efficient mode of traveling by bicycle. This finding is in accordance with Dewulf et al. (2015) arguing that lost time is a major factor for dissatisfaction in commuters as well as Wild and Woodward (2019) stating that bicycle traffic can diminish transport-related uncertainties, such as congestions.

While the implementation of bicycle infrastructure that fits the characterization of *best-performance* segments seems necessary, there are barriers: Although the positive effects for urban health and climate change mitigation are obvious, urban developments have to be taken into account: Larsen (2017) argues that urban sprawl poses a threat to bicycle commuting as distances will not be amenable to most bicycle riders anymore, thus resulting in higher use of motorized vehicles and additional implications for the environment that cannot be subsidized by constructional improvements buy only by a strong link between public transport and bicycle usage. While this study only covered amenable distances between 5 and 10 km, further evidence from longer distances is necessary to generate reliable insights. This is especially necessary, as the course of COVID-19 infections remains unpredictable and the increase in individual motorized traffic continues to pressure urban transportation systems.

To promote cycling as one of the few carbon-neutral forms of urban transport (Fraser & Lock, 2011) while simultaneously increasing physical activity for public urban health (Perez et al., 2015; Zambrano-Monserrate et al., 2020), the cluster analysis shows, that infrastructure enabling such positive changes is already partly available in urban areas but needs further spread. It is essential to improve bicycle infrastructure in the sense of *best-performance* segments as they contain the highest perceived feeling of safety, which is necessary for the choice of transportation (Ghekiere et al., 2014; Marshall & Ferenchak, 2019).

5.2. Possibilities, limitations, and necessary adaptations of this exploratory methodology

We present a new approach for analyzing bicycle lanes in an urban area. Especially, the usage of bicycle-rider-centric data bears the potential of new insights for future analysis of bicycle networks. In addition, the qualitative identification of segments with similar perceptions of safety, comfort, interaction, and quality of bike lanes offers insights that are detached from purely quantitative approaches and therefore focus on the personal perception of bicycle riders.

To further consolidate the findings of this exploratory study a few improvements are necessary: As only one bicycle rider carried out the measurement rides and gave qualitative insights that led to the identification of segments, the perspectives of additional riders are necessary. Therefore, it is important to create a sample that covers a large share of the population, e.g. from younger to older people, all genders, as well as regular and irregular bicycle riders. Especially the latter is important to include the different types of cyclists as shown by Dill and McNeil (2016). By enhancing the sample of riders, personal effects can be bypassed, resulting in a more neutral and nuanced analysis.

Another point for improvement is the length of the study. Although this study was carried out in August, probably the busiest month for cyclists in German cities due to favorable weather conditions, cycling infrastructure will need to be sufficient all year long during all kinds of weather conditions (especially during colder seasons or rainy conditions). New analyses can focus on the effect of weather conditions on different kinds of bicycle lanes. For this sample, the weather conditions did not differ sufficiently.

While this study contains the most direct factors that influence a bicycle ride, an addition of qualitative urban data might generate interesting insights: For example, the proximity to urban green spaces (Aletta et al., 2018; Cole-Hunter et al., 2015), congestions (e.g. data from GoogleMaps), airflow within the city or shadow and direct sunlight situations can add to complex but more in-depth findings to the comfort and performance of bicycle riders.

As a novelty, this study used qualitative data to identify segments based on the perception of the bicycle rider. Although this is a new approach, it should be used directly within the cluster analysis, so that such effects can be directly compared to the average velocity and infrastructural occurrence on site. Finally, a comparison of different cities will be interesting. In Germany, Berlin can be an insightful example, as during the COVID-19 lockdown a lot of new pop-up bicycle lanes have been instated (Kraus & Koch, 2020, 2021).

6. Conclusion

This exploratory study raises several questions: *How are bike lanes perceived from a bicycle rider's perspective? How do they need to look like, that the rise in individual traffic (triggered by the COVID-19 pandemic) will shift towards cycling?* By using a bicycle-rider-centric approach, we can identify bicycle lane segments that fulfill riders' wishes for safety and efficient travel between two destinations in urban areas as well as a distinction between desirable and non-desirable bicycle infrastructure. The clusters *viscous, slow, inconsistent, accelerating,* and *best-performance* are identified and spatially applied to the empirical example of Munich. Following the study's result, we agree with Parkin and Koorey (2012) that cycling has to be treated as a distinct mode of transport instead of a side-product that can be added to existing road networks. Following Harms et al. (2014) we confirm that there is a need for a differentiated approach to analyze cycling infrastructure adequately. We conclude that the improvement of bicycle infrastructure bears the potential to tackle environmental or health-related challenges in urban areas, such as climate change or the spread of infectious diseases like COVID-19.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The datasets generated during the study are available at GitHub via the following link: https://github.com/schwal95/floatingbikedata

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(In)capacity to implement measures for increased cycling? Experiences and perspectives from cycling planners in Sweden

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ABSTRACT

This article seeks to explore and analyse the capacity of Swedish municipalities to implement measures for increased cycling. Through the concept of local capacity and against the backdrop of interviews with local cycle planners, the aim of the article is to gain deeper insights into cycle planners' experiences and perspectives on what the possibilities, obstacles and challenges are as regards achieving the aims of increased cycling. Although the interviews reveal that all capacity dimensions are important, financial and political capacity seem to be the most crucial dimensions. These two dimensions are also the ones that differentiate most between included municipalities, and thus also influence the local capacity. High staffing, earmarked funding, and a shift from the car to a sustainable mode of transport norm are all capacity-building measures. There also seem to be overarching difficulties in developing vertical linkages with the Swedish

Transport Administration to increase the municipal capacity. The authority's responsibility for funding, operating, and maintaining the national public cycle network, and a lack of will to find common solutions are perceived as challenging by many municipalities. Greater consensus and collaboration between municipalities and the Swedish Transport Administration must be achieved to fulfil national and local policy aims on cycling.

1. Introduction

International and national targets on sustainable development and reduced climate emissions require a substantial transformation of the current transport sector. Cycling is often seen as one of the most sustainable modes of transport, and increased cycling is often a goal when seeking to achieve a sustainable transport system (Raustorp & Koglin, 2019; Koglin, 2015a, 2015b; Buehler & Pucher, 2011; Banister 2019, 2008). Cycling also has the potential to contribute to implementation of the UN Sustainable Development Goals (UN, 2021). Nevertheless, to increase cycling, a well-developed infrastructure and planning that puts cycling first are required. However, as the allocation of funds to the development of cycling infrastructure is a political question, the budget for the improvement and maintenance of cycling infrastructure and cycling as a mode of transport has often been marginalised (see e.g., Koglin, 2018, Koglin, 2015a; Koglin & Rye, 2014; Aldred et al., 2019). Moreover, to plan for sustainability and to promote sustainable transport such as cycling is not always easy for planners. Research by Koglin and Pettersson (2017) has shown that planners in Sweden often lack the capacity to implement sustainable transport measures, due to lack of time or political support. Planners rather sometimes feel more like coordinators than planners and think they have lost power over planning, because this issue has become more complex over the past 20 years and more actors today are involved in the planning processes, both public and private ones (Koglin & Pettersson, 2017). Furthermore, cycling, especially in urban contexts, must be seen in connection to transport and urban planning. In Sweden, about 12 percent of all trips are made by cycle, and Sweden is also regarded as a country where cycling is a daily activity for many citizens (Trafikanalys 2015; Koglin 2020; Haustein et al., 2020) . Furthermore, the Swedish Transport Administration (2011) states that increased cycling brings great benefits to society, not least to the environment. Although the view of the Swedish Transport Administration could be seen as an important step towards achieving international and national targets on sustainable development, this has not always been the case. Cycling is still not prioritised and included in planning processes as research has shown (Niska et al., 2010; Aretun & Robertson, 2013; Koglin, 2015a, 2015b; Lindkvist Scholten et al., 2018; Emanuel 2012, 2020; Koglin, 2013; Koglin & Mukhtar-Landgren, 2021).

The way in which cycling infrastructure is planned and what is considered to be good or poor cycling infrastructure is context-bound and can differ between different municipalities. For example, on issues connected to the size of the municipality and its planning traditions. Over-

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all, a lack of safety for cyclists in relation to car traffic and infrastructure (such as signage and parking) is often cited as a reason why cycling is not more popular in Sweden (Koglin, 2013). The fact that motorists often park their cars on cycle paths, for example, makes access for cyclists even more difficult. Also, research conducted by Koglin (2018) and Balkmar (2014, 2018) has revealed an ongoing battle for space in Swedish cities and for space in traffic for cyclists, which can also be seen as a threat to increased and safe cycling. As Cox and Koglin (2020) highlight, cycling infrastructure is highly politicised, and against this background, a strategic cycling infrastructure must prioritise cycling over cars and be based on the needs of cyclists in terms of factors such as accessibility, safety, and directness. Hence, it is important to investigate how and in what way measures for increased cycling are implemented, what measures are considered to be good or bad, and the opportunities and challenges that may be encountered during the implementation process. But do municipalities have the capacity to achieve the aim of increased cycling? This article seeks to explore and analyse the capacity of Swedish municipalities to implement measures for increased cycling. Through the multidimensional concept of local capacity and against the backdrop of interviews with cycle planners in Swedish municipalities, the paper wishes to create deeper insights into cycle planners' experiences and perspectives on the possibilities, obstacles and challenges for achieving municipalities' aims of increased cycling.

The structure of the article is as follows. In the next section (section 2) we introduce the theoretical framework, drawing on the multidimensional concept of local capacity in order to develop the analytic tool for this investigation. This section is followed by section 3 on research methodology and context, which is focused on semi-structured interviews with cycling planners in Sweden. Thereafter, the empirical material is analysed against the backdrop of the concept of local capacity. Finally, in section 5, we provide the conclusions and discuss the findings' implications for practice and future research.

2. Local capacity

To fulfil this study's aim, we turn to the analytical concept of local capacity. Local governments' capacity (or lack of capacity) to carry out and execute public services has been analysed and discussed in previous research, and the concept of capacity has been discussed and defined by a range of scholars (Gargan, 1981; Franks, 1999; de Loë et al., 2002; Pirie et al., 2004; Ivey et al., 2006). Our definition is based on Ivey et al. (2006, p. 946) who suggest that capacity could be defined on the basis of a relational perspective which emphasises the ability of organisations and governments to establish and achieve their own goals and agendas. The concept of local capacity has a relational perspective (Gargan, 1981; Franks, 1999; de Loë et al., 2002; Pirie et al., 2004) and with regard to this study, all included organisations have developed strategic plans to increase cycling (often as a way to achieve other internal and external aims) but there might be differences and similarities in the ways the planners experience possibilities, challenges, and obstacles in realising these strategic plans and local objectives. Thus, to realise and implement the strategies and measures for increased cycling there needs to be a certain degree of local capacity within an organisation.

The concept of capacity is multidimensional (Gargan, 1981; de Loë et al., 2002) and even though different frameworks use different terminology, there seems to be a broad consensus that capacity includes aspects such as financial, human, managerial, and technical resources, while the institutional environment should also be included in such a theoretical framework (Grindle & Hilderbrand, 1995; Grindle 1996; Hamdy et al., 1998; Honadle, 2001; Ivey et al., 2004).

The approach used in this study draws to a great degree on the work of de Loë et al. (2002). They propose a conceptualisation of local capacity built upon five interrelated aspects: *technical, financial, institutional, political*, and *social capacity*, and while the importance of each of the aspects will vary from organisation to organisation, they are interrelated and influence each other, and will all to some extent influence the overall capacity of an organisation to achieve its objectives. We suggest that to achieve increased cycling, elements of all capacity dimensions must be present. The local capacity concept is used as an analytic framework to analyse Swedish municipal planners' experiences and views on possibilities and obstacles in realising the strategic aims and local objectives of increased cycling. The concept supports us in exploring what capacities municipalities have (or lack) to implement measures for increased cycling.

3. Local capacity to achieve increased cycling

3.1. Technical capacity

Municipalities' work for increased cycling could be defined as a *technical* activity. Infrastructure for cycling needs to be maintained and repaired in a proper way to facilitate an increase in the number of cyclists (Koglin, 2013). De Loë et al. (2002) state that the extent to which a municipality is able to undertake technical activities is an important measure of the capacity of the municipality, where the availability of educated staff with specialised knowledge plays a crucial role with regard to the technical activities of the municipalities. It is also of great importance that the staff have the capacity to interpret, and use information provided by external players, such as consultants.

3.2. Financial capacity

Moreover, in line with de Loë et al. (2002), we take a broad approach in terms of the *financial* aspects involved in capacity-building and define it as a municipality's resources available for working with cycling. Loë et al. (2002) suggest that the quantity of financial resources and their sources (e.g., the local tax base, tariffs, grants from external agencies) are crucial to trace in order to understand how capacity is built. Thus, the size of a municipality's budget is one element that affects how much the municipality can spend on cycling, and it also has significance for the way the work on cycling is funded. If a municipality relies heavily on grants and other temporary sources of revenue, this could impact its ability to function independently.

3.3. Institutional capacity

Loë et al. (2002) also suggest that *institutional* considerations are important for understanding how capacity is built in local governments, and they stress that institutional considerations impact institutional capacity on two levels. The first one is the institutional arrangements created by the municipalities, such as plans, policies and strategies. The second one is, according to de Loë et al. (2002), the institutional environment within which municipalities operate. An institutional environment is shaped by laws, rules, regulation, power relationships and procedures, and affects and influences explicitly and implicitly the capacity of the municipalities (Ivey et al., 2004; Pirie et al., 2004). One indication of the degree of institutional capacity, according to de Loë et al. (2002), is the extent to which regulatory and non-regulatory institutional arrangements exist within a certain area. With regard to this paper, the area is local cycle planning.

3.4. Political capacity

Political leadership is also a capacity dimension identified by Loë et al. (2002) as a key aspect of capacity in municipalities. They suggest that it is necessary to provide vision and direction and to be able to recognise and respond to changes. Another key political dimension for capacity-building, raised by de Loë et al. (2002), is the extent to which the political leadership is willing and able to form horizontal and vertical linkages within and beyond the organisation. Pirie et al. (2004) suggest that municipalities can overcome, or at least reduce, institutional obstacles through establishing vertical and horizontal linkages. A horizontal linkage is developed with one or several organisations operating at the same administrative level to accomplish a given task collectively. A vertical linkage is an agreement or partnership between different administrative levels of government, as a result of the sharing of information and/or resources (de Loë, et al., 2002; Pirie et al., 2004).

3.5. Social capacity

According to Loë et al. (2002), the level of *social capacity* and community awareness is partly a function of a municipality's ability to communicate with its inhabitants to create awareness in relation to a specific political issue: in this study, increased cycling. Measures used for this purpose can for example include public education and outreach programmes. But it is important that the community involvement goes both ways, which means that the municipality not only informs the inhabitants but also actively seeks consultation with them in terms of issues, needs, and goals, and involves them in the planning- and decision-making process to ensure that their interests are considered. Thus, the commitment and involvement of the municipal residents can improve a municipality's capacity. At the same time, opposition, or the fear of opposition from inhabitants, could result in a lack of capacity for the municipality to implement measures for increased cycling.

For our analysis we developed the dimension above into the five ones below in order to create a better analysis

1 Infrastructure operation and maintenance
2 Financial
3 Politics
4 Organisation and governance
5 Citizens

4. Research context and method

4.1. Institutional context

We carried out the empirical research in Swedish municipalities, which are lower-level local government entities. They are responsible for a large proportion of local services, including schools, water and sewage, and physical planning. In relation to the cycling network, municipalities have the responsibility for funding and maintaining urban and local roads, while national roads are owned and maintained by the Swedish Transport Administration. The national transport authority also has the responsibility for the development of the direction framework for long-term infrastructure planning, which is seen as an important step towards a modern and sustainable transport system. Municipalities' role within the institutional settings, together with their need to relate to state measures and policies, make the municipalities a beneficial context for studying the public effort on increased cycling in several respects. Firstly, the Swedish government has the ambition to become the world's first fossil-free welfare state (Ministry of Trade and Industry, 2018), and in 2017 the Swedish parliament agreed on a climate policy framework which sets out that Sweden shall have no net emissions of GHG by 2045. As part of achieving this objective, the Swedish government presented a national strategy for increased and safe cycling in 2017 which will contribute to a sustainable society (Ministry of Trade and Industry, 2017). Secondly, we note that Swedish municipalities have decided on climate policy objectives that are in many cases much more ambitious than both national and international aims. Thirdly, many Swedish municipalities have overarching aims to increase the bicycle's share of transportation, increase cyclists' status in planning practices, and have bicycles used for half of all trips shorter than five kilometres (Hållbar stad, 2016). Together, these three aspects serve as an interesting backdrop for our intention to deepen insights into capacities or lack of capacities in municipalities to achieve increased cycling.

Table. 1
Included municipalities.

Municipality	Inhabitants	Municipal asphalt cycling roads (km)
Halmstad	102 948	300
Karlskrona	66 609	N/A
Växjö	94 274	190
Gothenburg	580 667	540
Trollhättan	59 007	145
Skövde	56 529	134
Örebro	155 989	220
Karlstad	94 194	250
Eskilstuna	107 001	N/A
Sollentuna	73 939	120
Sundsvall	99 448	N/A
Umeå	129 231	228
Luleå	78 102	193

4.2. Method

Empirically, we have applied a qualitative research approach and conducted semi-structured interviews with cycling planners working in Swedish municipalities (see Table 1). Even though the challenges regarding increased cycling are general, many dimensions are local, such as the structure and size of the municipality, the quality of the road infrastructure, local political conditions, local traffic policies, urban planning agendas etc. Thus, conditions to facilitate increased cycling will differ from municipality to municipality. Therefore, to better understand the capacity or lack of capacity for initiating measures for increased cycling, we wanted to study cycling in several municipalities. However, we still wanted to keep some contextual aspects the same. We decided to carry out our research within the same national context while selecting several different municipalities for our empirical work. All 13 included municipalities are members of Swedish Cycling Cities – an organisation consisting of 31 municipalities and four regions, working consciously for increased and safer cycling. Overall, we contacted all 31 municipalities for a request of conducting interviews with planners who deal with cycling. The 13 municipalities who responded to our request where the ones we interviewed. We e-mailed the person who answered our request since the request was already forwarded to the planner who deals with these issues. After that we booked dates for the interview and conducted the interview via Teams with video and voice recording.

We interviewed one planner per municipality, resulting in 13 interviews. The interviews followed a semi-structured interview guide (see appendix) (Flick, 2006), where we included theory-driven questions inspired by the capacity framework, but still also providing opportunities for reflection and exhaustive answers. Thus, the interview guide focused on different dimensions of capacity that the planners experience in the implementation of local cycling plans and strategies. The interviews were conducted during May and August 2019 and lasted between 30 and 45 minutes. All interviews were recorded and fully transcribed, resulting in 99 pages of transcripts.

The semi-structured nature of the interviews allowed the interviewees to steer the discussions towards issues they found important. As the interviews were conducted, the answers, gradually became more and more repetitive. Therefore, a different kind of knowledge or new knowledge could not be gained by conducting more interviews. This is a very common aspect in interview studies (Maxwell 2004).

As an explanation of qualitative research, it can be said that the focus is on gaining a deeper understanding of complex social processes and that understanding builds on the interpretation of the answers. Thus, the goal of qualitative studies is to generate deeper insights into the analysed processes to develop an understanding of what has influenced the outcome, in this case the planning outcome and the planning processes. It can therefore be concluded that qualitative research generally aims at the understanding of processes and the relations that influence them and not at generalisations (Gubrium and Holstein 1997; Denzin and Lincoln 2000; Rubin and Rubin 2005; Cloke et al. 2004). We structured our analysis around institutional capacity theory in order to analyse what capacities the interviewed municipalities have for planning for and implementing of cycling infrastructure and what capacities are lacking.

4.3. Planners' experiences and views on capacity in municipalities

In this section, we will explore how planners in Swedish municipalities experience the capacity-building or lack of capacity to increase cycling. Emerging from our analysis were, as previously mentioned, the following themes that guided the analysis: *infrastructure operation and maintenance; financing; politics; organisation and governance*; and *citizens*. Although these themes undeniably overlap, we will here explore them separately to show how the planners in Swedish municipalities experience the issue of capacity-building.

4.4. Infrastructure operation and maintenance

Larsson et al. (2022) point out that ageing, structural interventions (e.g. digging to repair and/or change water and sewage pipes), and roots and vegetation, are the most frequent causes of problems on cycle paths. Thus, continuous operation and maintenance of bicycle infrastructure are crucial to avoid degradation, to prevent crashes, and to sustain the level of service and comfort for cyclists. The operation and maintenance of cycle paths in Sweden include activities such as re-paving, re-surfacing, removing roots and vegetation, fixing potholes and cracks (Larsson et al., 2022) and ploughing and sweep-salting during wintertime (Niska & Blomqvist, 2019). The operation and maintenance work are performed both by contractors who are awarded this work through public procurement processes but also by the municipalities. However, some planners state that there is a great lack of knowledge among the performers about what "good" operation and maintenance for bicycling is. This goes for both contractors' and municipalities' own operational management. Planners state that they have no cycling perspective when undertaking the maintenance and that there is a great need for education activities to develop their technical capacity.

Another issue is the access to technical equipment by the municipalities to maintain the infrastructure. This is most apparent in the metropolitan area of Stockholm, where there are in total 26 municipalities with much bicycling commuting crossing the municipality borders. Thus, the technical capacity (or lack of capacity) within a municipality could become very apparent for commuters as there could be a great difference between the municipalities in how well they are technically equipped. In addition, some planners state that there is a lack of personnel within the municipality to develop bicycle infrastructure and there are also problems within some municipalities in receiving tenders on decided cycling infrastructure projects. As a result, the projects are postponed, which could result in consequences for fulfilling bicycle plans.

Even though many planners highlight that maintaining cycling infrastructure is a year-round task, there is an emphasis in the interviews on winter maintenance, and this occupies many municipalities. All municipalities say that they need to take winter maintenance into account and state they have the capacity to perform this task. Municipalities located in the northern part of Sweden are, for obvious reasons, more used to undertaking and organising winter maintenance. Here, the planners see great possibilities in technical developments, and they embrace how technical innovation can make winter maintenance more effective. One municipality participating in an innovation project to develop technical capacity with regard to winter maintenance says that one of the main reasons for this is to obtain a certain degree of technical capacity and thus keep costs down. Of the main issues with regard to winter maintenance relates to what technique the municipalities use when removing the snow and clearing the cycle paths. Traditionally, conventional snow clearance through ploughing and gritting has been used in Swedish municipalities, but over the last few years, sweep-salting has become more popular for winter maintenance (Niska & Blomqvist, 2019). Although sweep-salting is a more costly technique, a majority of the planners state that they have the technical capacity to use it, although to varying degrees.

4.5. Financial

Although all studied municipalities are members of Swedish Cycling Cities, that does not automatically mean that internally, within their respective organisations, they have the financial support or capacity to work on measures to increase cycling. Many planners state that they are struggling with the financial situation. In some municipalities there could be a temporary financial cut due to the poor economy of the municipality, but in some it is more of an institutionalised situation where there is a limited allocation of financial resources to cycling. Consequently, they do not have the financial capacity to achieve the aim of increased cycling, and the lack of financial resources has the consequence that they do not have the possibility to implement measures in the decided strategies, or that the measures are postponed. As a result, an expansion of the bicycle network or mobility management measures could not be implemented. The lack of financial capacity for operation and maintenance of bicycle infrastructure is also emphasised by several planners. It is also important to underline that the structural design of cycle paths (choice of materials and techniques) differs from one municipality to another (Larsson et al., 2022). The general budget for operation and maintenance has been decreasing steadily in some municipalities. In relation to snow clearance the financial capacity is the greatest obstacle. One planner states that snow clearance is a huge cost for the municipality and highlights that with a greater budget they could have better winter maintenance, sweep-salt more paths, and thus increase make it possible for more people to bicycle during wintertime.

Some planners also highlight that they have tough saving requirements, and in such a situation it is virtually impossible to increase investment in cycling infrastructure. One planner highlights that you need to be innovative when there is a lack of financial resources, and the planner describes a collaboration with the Technical Services Department where they broaden cycle paths when the Technical Services Department dig up the road network for other reasons. In that way the municipality has both saved money and developed the infrastructure. However, the lack of financial capacity is described in some municipalities as an internal positioning and a battle of resources between different political areas and units. In some cases, it is also a battle between means of transport, where infrastructure for public transport has been and continues to be prioritised.

One way to increase the financial capacity of the municipalities is for them to gain access to external funds. It is highlighted by de Loë et al. (2002) that a strong dependence on grants or other external temporary funds could impact a municipality's ability to function independently. Some planners state that they rely to a large extent on external grants as their budget is limited. To increase the budget and keep a high staffing level some municipalities participate in research projects. Municipalities have also succeeded in increasing the budget with governmental funding over several years. This has been of great importance for strengthening the financial capacity. However, several planners call for an increase of governmental funding to achieve increased cycling, and state that the Swedish Transport Administration should allocate many more financial resources to cycling.

Although several municipalities are struggling with their financial capacity to work for increased cycling, some planners convey an image of a good financial situation within certain municipalities. One planner states that there is a political will to improve bicycling and that funding is ear-marked for it, which means that there are always assigned resources for cycling, regardless of whether the municipality has overall savings plans or not. Another planner highlights that they have a good budget for investment in measures and expansion of regional routes, and a descent budget for operation and maintenance. Moreover, the main problem for one municipality is not the financial capacity, where there are resources available for increasing cycling, but instead limited space is the greatest challenge. Space here refers to street space in the city and how that is allocated to the different transport modes. It is our understanding that taking street space from car traffic and giving it to cycling is often controversial and needs much political courage, because this would be a political rather than a planning question in the first place.

4.6. Politics

The issue of space has become apparent in relation to the political aspects of the capacity of municipalities to increase cycling. According to Loë et al. (2002) political leadership is a key dimension of the capacity of municipalities to provide vision and direction and also to recognise and respond to changes. For this article, political leadership means prioritising cycling to realise a sustainable transport system (Raustorp & Koglin, 2019; Koglin, 2015a, 2015b; Buehler & Pucher, 2011; Banister 2008, 2019). However, previous research has revealed an ongoing battle for space in Swedish cities (Koglin, 2018; Balkmar, 2014, 2018) and many planners say there is a great challenge with regard to the space issue. Planners state that there is a great will from the politicians, but it is problematic in existing urban space to meet all demands and wishes. The space is too small to implement optimal solutions for cycling infrastructure and there will always be a compromise between different modes of transport, not only in relation to the infrastructure for car traffic but also in relation to accessibility for public transport and access to green areas. The conflict between infrastructure for public transport and bicycles is mentioned by several planners – especially when it comes to raised cycle track-crossings and cycle parking close to commuter train stations.

However, although space is a challenging issue for many municipalities, a more difficult issue seems to be the reluctance of politicians to degrade car infrastructure in favour of bicycles. Many planners stress that prioritising cycling at the expense of the car is still not accepted and there is no political courage to make this kind of decision. In almost all studied municipalities there is no explicit aim and/or strategic document to limit and/or restrict car traffic, and many planners experience that the politicians do not want to risk not being re-elected by getting into conflict with motorists, who they believe are a large group of voters. One planner exemplifies the difficulties in changing the conditions between cars and bicycles with a planned measure to promote cycling. The cycling unit within the municipality wanted to close a central square with much parking space as a trial for one week. However, the political management refused because they did not want to mess with the business community and the merchants in the city centre. This was despite the fact that the unit had made inquiries showing that the majority of the revenues for the businesses derived from individuals using sustainable modes of transport, which also corresponds with previous research (Mingardo & van Meerkerk, 2012). However, the lack of vision and direction from politicians applies to a large extent only to existing space. When it comes to developing and planning new areas, the politicians have, according to many planners, found it easier to make decisions that benefit cyclists and limit car traffic.

A political dimension for capacity-building is the extent to which the political leadership is willing and able to form horizontal and vertical linkages beyond the organisation (de Loë et al., 2002). Municipalities have the possibility to overcome or at least reduce obstacles through establishing these kinds of linkages (Pirie et al., 2004). When it comes to cycling, the formation of horizontal linkages between municipalities is important to reduce the obstacle of having different standards of infrastructure and maintenance. A planner from a municipality in the metropolitan area of Stockholm states that there is great difference in the standards of infrastructure and maintenance between the municipalities, and there are different views on these matters. This could mean for example that some municipalities have more potholes, cracks, uneven cycle path surface and less maintenance during wintertime. Consequently, there has been a lack of political capacity to form horizontal linkages, and this has become very concrete for biking commuters crossing several municipality borders, who experience a range of different standards of infrastructure and maintenance. However, to a certain degree there exist horizontal linkages between the municipalities and there are common procurements in order to set a common standard. In addition, the organisation Swedish Cycling Cities is an example of the formation of an institutionalised horizontal linkage to achieve a common aim, where cycling planners from local authorities cooperate. Moreover, a horizontal linkage between municipalities has also been established to discuss measures and exchange ideas on how to increase cycling.

Within the municipalities' borders the cycling network consists of both local and national roads where municipalities have the responsibility for funding and maintaining urban and local roads while national roads are owned and maintained by the Swedish Transport Administration. Many planners describe the way the bicycle network is organised as a great obstacle to developing a coherent and comprehensive network. The main issue here for many municipalities is the difficulty in forming vertical linkages with the Swedish Transport Administration. Planners highlight that the national agency in theory should have the possibility to develop a good infrastructure, and one of the most important issues is to connect and standardise the local and national paths and develop a common view of what needs to be done. However, according to the planners, the national cycle network has many shortcomings and there is a lack of commitment from the Swedish Transport Administration, in terms of both financial and personnel resources. Some planners also experience long and costly processes when dealing with the national agency. In some municipalities, the greatest obstacle to increased cycling is that you cannot reach all smaller urban areas outside the city centre as there is a state-owned road network linking them and the Swedish Transport Administration are proceeding very slowly in their work on developing the national cycling paths. Thus, there is a disconnection between municipal and state-owned cycling infrastructure and there is a lack of vertical linkages between the municipalities and the Swedish Transport Administration, which has consequences for capacity.

4.7. Organisation and governance

The institutional capacity through institutional arrangements and through institutional environments influences the capacity-building in municipalities (Loë et al., 2002). When it comes to institutional arrangements, all studied municipalities have politically decided cycle plans or strategies. However, there seems to be a great difference between the municipalities with regard to content and in what way the municipality uses the strategy as a capacity-building instrument. Some plans/strategies include a defined objective for the proportion of cycling traffic by a certain year, while others only have an aim of increased cycling. One planner states that the cycle plan within the municipality is not that extensive and there is a great need for the planners to make their own interpretations and prioritisations, whereas another planner states that the municipality needs to revise the cycle plan to take a clearer stance on the role of the bike as a means of transport. In addition, in one municipality a planner states that there is no organisational consciousness about the strategy and thus there is a great challenge to get the whole organisation to work in the same direction. Similarly, a planner in another municipality states that there are steering documents within the municipality that are contradictory, which could lead to problems realising the objective of increasing the proportion of cycling.

There are also other plans and strategies within the municipalities that both explicitly and implicitly have an impact on the aim of increased cycling and the (in)capacity of the municipalities. One of these is the comprehensive plan, which is regulated by the Swedish Planning and Building Act and has a central role in the municipalities' work to formulate strategies for long-term sustainable development. One planner mentions the comprehensive plan as an important tool as it stipulates that the city should grow and densify within a 5 km radius from the large target points: the city centre, the university area, and the hospital area. This should reduce dependency on the car for the citizens and instead promote increased cycling. Thus, the comprehensive plan could impact the institutional capacity within the municipalities. However, in none of the studied municipalities is there a politically decided strategy for reduced car travel, and many planners mention car parking strategies and parking policies as great obstacles and as examples of how a lack of strategies and plans can reduce the local capacity. One planner states that at the cycle unit they have developed a travel policy for the whole municipality including municipally-owned companies and trusts which comprise many workplaces, although it is not their responsibility to do so. In one municipality they have even, according to the planner, developed a cycling parking guide and the guide has been distributed to property owners in order to develop and create good conditions for parking.

When it comes to the question of the institutional environment, the Planning and Building Act provides the municipalities with the opportunity to include not only cars in their parking policies but also bikes. And in connection to development of new housing this must be done "to a reasonable extent" (National Board of Housing, Building and Planning, 2020). However, one planner highlights that it is still accepted when building new housing with 100 apartments to develop a car parking garage with 80 parking spaces, but it would not be accepted to allocate half of the parking space to bikes. Another planner shares the view and states that none question parking for cars in the same way as they do for bikes. Among many planners, habits, norms, and strong interests within the municipality in connection to cars are highlighted as institutional obstacles to increasing space for bicycle parking, and these obstacles place great demands on the municipalities' capacity to work for increased cycling.

Within the municipalities, the way cycling is organised also has an influence on the institutional capacity of the municipalities. Within several included municipalities it appears that there is only one unit working on issues connected to cycling while the rest of the organisation to a large degree is decoupled from the issues and sometimes also lacks the will and knowledge to work on issues related to cycling. With only one unit engaging with the issues – and often with limited resources – it becomes difficult to implement the strategic plans. However, in some municipalities the planners state that there is a great deal of cooperation within the municipality and between the units and that the municipality has a long-term perspective on the cycle issues. It is also emphasised that there is a broad political consensus that the municipality should invest resources (personnel and financial) in cycling, and that the different units have become more co-operative in the organisation and know what the others are doing and what expertise is available.

4.8. Citizens

The commitment and involvement of citizens is highlighted by Loë et al. (2002) to improve the municipalities' capacity to realise and implement decided strategies and objectives. Measures that the authors highlight are communication, public education, and outreach programmes. Most of the studied municipalities are trying to increase their capacity through these kinds of measures. When it comes to communication, some municipalities state they have institutionalised forums to enable citizens to ask questions, comment, and get inspiration and knowledge concerning how the specific municipality and other municipalities are working to increase cycling. In one municipality it is also highlighted by the planner that they interviewed citizens as part of their process of developing a new cycling plan. Common to the different strategies is that they all seek not only to inform but also to involve the citizens, and seek their consultation on important issues concerning cycling, thereby increasing the social capacity.

The use of social media such as Instagram and Facebook is a common measure to create awareness about the positive outcomes of increased cycling. However, it is emphasised that it is difficult to find the right target group in a positive way. Posts on Facebook often result in a poor response, with many negative comments and complaints, whereas likes on Instagram do not go viral. One planner states that the overall cycle group in the municipality is small, is not that loud and does not have high demands. This contrasts with motorists in many municipalities that seem to have a relatively implicit influence on the local politicians. However, there are planners who stress that the municipality has engaged citizens who think it is of great importance that the municipality raises cycling issues.

In relation to public education and outreach programmes there is ongoing work to strengthen the social capacity through these measures. Cycle flea markets and auctions are organised to allow more citizens to have access to a bike. Many municipalities also seek to educate people – mainly through schools. The school is highlighted as an important space to create awareness and influence children about specific (cycling) behaviour at an early age. In addition, school personnel and parents are also highlighted as important target groups. Programmes including free access to different types of bicycles (electric bikes, long tail, cargo bikes, folding bikes, etc.) and projects directly targeted at the school personnel have been implemented. However, many planners experience difficulties in communicating with schools and find it challenging to get access to them. The possibility to initiate collaboration depends to a large degree on having a benevolent principal and the necessary will and engagement in the school. Moreover, in some municipalities there also seems to be great resistance from parents. Policy measures such as removal of car parking and car-free zones in connection to schools have been criticised. Thus, no interest in being involved in bicycle promoting activities has an influence on the municipalities' social capacity. In addition, there is a lack of resources within the municipalities to work on these kinds of issues, and they become questions only for the traffic unit and no other unit takes the responsibility. This of course also influences the municipalities' capacity to increase cycling.

5. Concluding discussion

This article seeks to explore and analyse the capacity in Swedish municipalities to implement measures for increased cycling. Regardless of the type of municipality or its location, it is important that municipalities – which often own much of the municipal road network and are responsible for drawing up overviews and detailed plans – work on improving and developing opportunities for cycling as a mode of transport. Overall, this study has given insights into a variety of possibilities, obstacles and challenges that cycling planners meet in their efforts to increase cycling in Swedish municipalities. Based upon our work, an overarching conclusion is that the capacity, or lack of capacity, differs from municipality to municipality. While some municipalities cover many (or all) of the capacity dimensions, others have great challenges, even though all municipalities are members of a network – the Swedish Cycling Cities – aiming for increased cycling. The differences between the municipalities touch upon all capacity dimensions proposed by Loë et al. (2002). However, the financial and political dimensions are the two most important dimensions dividing the municipalities – and both dimensions have a large impact on the municipalities' capacity to achieve the common aim of increased cycling. The size of allocated budgetary resources (large or small) and the fact that some municipalities need to obtain external funding in order to fulfil cycling plans and strategies are issues that certainly influence the local capacity. In addition, and with a close connection to the financial dimension, there is the political capacity, where a strong car norm still seems to be present. One example of this is the fact that improving and developing cycling infrastructure at the expense of cars in existing urban space is problematic. Also, measures to make it more difficult to drive through areas by using reduced speed limits, one-way streets, as well as car-free zones that would make it easier to cycle, are ways of prioritising cycling. However, for political reasons, such measures are unfortunately rarely implemented. Nevertheless, there are considerably better opportunities to prioritise cycling

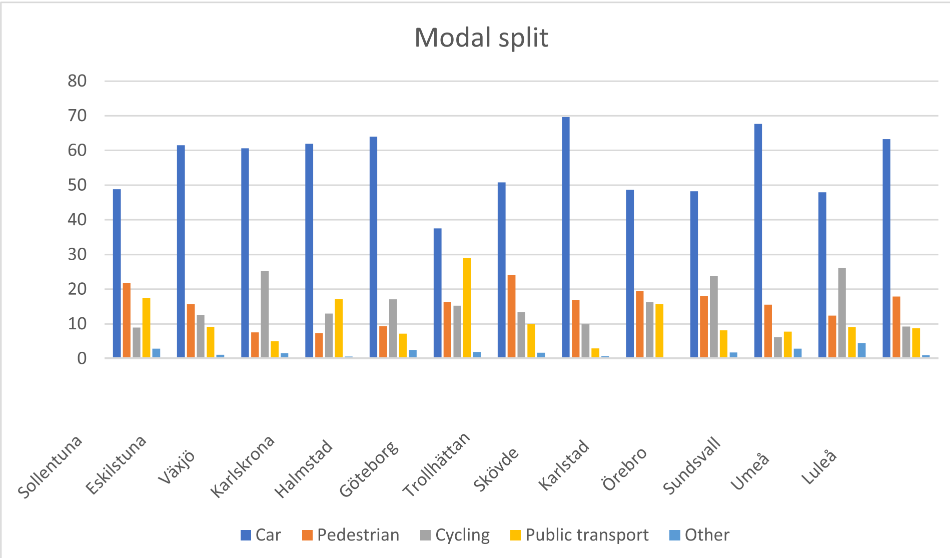

Fig. 1. Modal split of the investigated municipalities.
Source: National Travel Survey Sweden, 2019/2020

during new housing developments, as ingrained habits and routines that are difficult to change have not yet become established. This could be seen as an opportunity to improve the cycling infrastructure in Swedish municipalities, at least in new development projects.

The work of achieving increased bicycling is not connected to only one capacity dimension or only one municipal department. The work is much more integrated between the capacity dimensions and between the different municipal departments that have a responsibility for one or several areas (e.g. mobility management, strategies and action plans, operation and maintenance, financing, local traffic regulations) that are of great significance to achieve increased bicycling. Thus, there needs to be clear and integrated cooperation within municipalities and between bordering municipalities as well as with relevant actors at regional and national levels.

In many of the included municipalities there is a lack of political courage to implement policies that promote increased cycling, and additional financial and human resources are probably needed in those municipalities to improve the local capacity. This challenge has also been identified in previous studies by Koglin (2013, 2015b) and Koglin and Pettersson (2017). Planners and officials are often aware of the problem and of what is required to enable increased cycling or create a sustainable transport system. However, there is often a lack of political will. It became clear from this article that to develop and implement measures to increase cycling, the importance of cars needs to be toned down in strategic planning and policy documents, and there needs to be a sharper focus on sustainable transport, particularly cycling.

From this study it appears that municipalities located in metropolitan areas have a greater capacity to develop horizontal linkages with other municipalities as the cycle network is connected to a greater degree than in municipalities outside the metropolitan areas. Common procurements and sharing of technical equipment are examples of increasing the capacity, although there are still issues that remain to be dealt with to create a cycle network that is developed, operated, and maintained in a standardised way. The apparently great challenge for municipalities of creating vertical linkages and cooperation with the Swedish Transport Administration to create a coherent bicycle network is reducing municipalities' capacity. The Swedish public road network organisation with a divided responsibility for funding, operating, and maintaining the cycle network between municipalities and the Swedish Transport Administration creates challenges and obstacles for planners as they attempt to achieve local objectives. And with no (or a great lack of) institutional cooperation between the national and local levels, the aim of promoting increased cycling becomes difficult to achieve. Greater consensus and collaboration between municipalities and the Swedish Transport Administration must be achieved to fulfil national and local policy aims on cycling. This is particularly important in municipalities and regions in which the Swedish Transport Administration owns much of the road network.

We believe that many of the obstacles are not only occurring in Sweden, but also in other European countries. The planning systems in Europe are rather similar, although of course national differences exist. Thus, the results could also offer insights or at lease food for thought about the situation in other countries. Although cycling is a much more dominant mode of transport in Copenhagen, which is often considered to be more a bike-friendly city compared to many cities in Sweden, barriers for planning strategic cycling infrastructure exist. Barriers are often associated with the political courage and will to decrease car use, something almost all cities in Europe (and in fact the world) struggle with. In this sense, the results of this study are not really surprising but offer a deeper understanding of what is important in other cities outside Sweden. The fact that it is often easier to increase cycling as long as it does not interfere with car traffic is not only a problem in Sweden, but in many other countries as well (Henderson & Gulsrud, 2019; Koglin 2020; Freudendal Pedersen 2015a, 2015b; Koglin et al., 2021).

Generally, it can be concluded that this article shows that there is great desire, knowledge and understanding among planners and officials in Sweden in terms of how to create a strategic cycling infrastructure. These factors could form the basis of a strategic cycling infrastructure in Swedish municipalities that contributes to increased cycling and reduced car traffic, thereby bringing the transport systems one step closer to achieving a fossil-free transport system. However, the lack of political will to break free from the car norm is an important issue that planners alone cannot tackle. There needs to be a political and societal transition in mobility norms away from the car and towards sustainable modes of transport, not least cycling.

In terms of future research, we believe it is of importance to further look into the cycling mainstreaming of the different planning agencies, like national, regional, and local planning offices. More focus should also be directed towards the organisation and planning of cycling in semi-dense and rural areas as there has been and is an emphasis on cycling in the urban context. Moreover, more research on the dominance of automobile systems in our cities is needed in order to shed light on how that affects planning for cycling infrastructure. If we want to create sustainable transport systems it is of importance to decrease car use and the impact cars have on our societies for a proper transition towards cycling futures Fig. 1.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix Interview guide

0 Introduction to the Interview

This is a study where we conduct telephone interviews with the members of the organization "Swedish cycling cities", i.e., public organizations that themselves emphasize that they are at the forefront of the work with cycling in Sweden.

The purpose of the study is to investigate what you consider to be important measures to increase cycling, based on your knowledge, experience and perceptions. And, the three measures that you assess are the most important.

In the interview, we will therefore focus on important measures to increase cycling.

We also want to know which of these important measures for increased cycling that you in your organizations have previously implemented and which you are working on today, and plan to implement in the near future.

Finally, we also want to know what obstacles and opportunities you believe exist to implement these important measures, in the way, and to the extent that you believe are necessary for cycling to increase significantly.

Background issues

Education?

Age?

Gender?

How long have you been active in the organization?

Current post?

How long have you worked with cycling within the organization?

How is the work with cycling organized within your municipality / city / region?

What responsibilities, role and tasks around cycling do you have today?

Describe how you think the conditions for cycling are in the municipality / city / region? What are your strengths / weaknesses?

Does the municipality / city / region have a goal of increased cycling? What / which?

Important measures for increased cycling

What do you think are important measures to increase cycling? Justify why these are important.

List the different measures and motivate them one at a time. Take your time!

Which three of these measures do you think are the most important for increasing cycling? Rank from one to three (one most important, two second most important, etc.). Motivate!

Important measures for increased cycling that are worked on in the own organization

Which of the important measures - including the top three - that you have talked about have you previously implemented and / or are working with today in your organization? As well as planning to implement in the near future?

What important measures have you not implemented, nor do you plan to implement?

In your opinion, what governs which measures for increased cycling are selected and implemented, or not, in your organization?

Obstacles and opportunities to decide on and implement important measures for increased cycling

What obstacles and opportunities do you think exist in your organization to decide on and implement the important measures you have mentioned (theme 2)? And in that way, and to the extent that you consider it necessary for cycling to increase significantly?

Obstacles and opportunities, we believe, can be many different things, such as working hours, resources / budget, competence, political will, governing documents, legitimacy and priority within the administration, cooperation, and collaboration within and outside one's own organization, or other.

Obstacles & opportunities regarding:

A,

B,

C,

Etc.

(Review each of the key actions listed under theme 2)

Other

Is there anything else you want to address that you think we should know about issues and the work with increased cycling?

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Integration of shared transport at a public transport stop: mode choice intentions of different user segments at a mobility hub

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ABSTRACT

To create an integrated transport system that can compete with and reduce private car usage, we need a better understanding of the transport and user characteristics that relate to people's intentions to use shared and public transport at a mobility hub. For this purpose, this paper describes the results of a survey surrounding the case study of Leyenburg, The Hague in which a scenario of integrating shared mobility at an existing public transport stop is proposed. This study investigates the intention to use shared modes and public transport in a multimodal transport network and the factors and user characteristics that affect this intention. As digital technologies become important in the integration of modalities by offering digital planning and payment options, concerns regarding digital exclusion in transport services are growing. In this paper we developed a digital skills measure to reflects one's ability to perform tasks that are inherent to the digital services seen in the transport sector. Using an ordinal logistics regression analysis, the study has found that the intention to use shared transport is higher for people who are younger, have a high level of education and a high level of digital skills. In addition, having prior experience with shared transport in the past year and currently using multiple means of transportation during the trip are positively affecting the intention to use shared transport. The intention to combine shared transport with the bus or tram during a trip is similar to the intention to use shared transport and is related to similar characteristics, except for education. The intention to use the bus or tram is found to be mainly related to current transport usage and trip-specific factors and not to other user characteristics. For transport providers, the results provide evidence that offering shared motor scooters and bicycles would be an attractive option for young and highly-educated users who intend to combine the use of shared and public transport.

1. Introduction

The promotion of public transportation in its current form is seen as a way to address the sustainability impacts that are caused by high levels of private car ownership (Miller, de Barros, Kattan, & Wirasinghe, 2016). In addition, shared mobility is considered to be a promising new mobility system in the development towards sustainable transport, especially as it can address traffic congestion and CO_2 emissions (Rabbitt & Ghosh, 2016) (Taylor, et al., 2016). Furthermore, it is one of the measures proposed to reduce the parking need in urban areas (CROW, 2021) (Jorritsma, Witte, Alonso González, & Hamersma, 2021). Overall, developing and promoting public and shared transportation systems is considered as a way to address the issues regarding the ownership and usage of private cars.

Extracting the potential sustainability benefits of shared mobility requires an understanding of how to integrate shared mobility into the existing urban transportation system and improve its efficiency from social, environmental, and economic perspectives (Machado, De Salles Hue, Berssaneti, & Quintanilha, 2018). Nevertheless, combining the offering and promotion of shared mobility services with public transportation is seen as a way to address the growing pressure on urban transport systems as the various transport modes can together serve as a substitute to the private vehicles (Kamargianni, Li, Matyas, & Schäfer, 2016). Such an integrated system should offer more variety of transport by adding shared modalities while being better able to integrate them within the existing urban transportation by building upon the foundations of public transport. Yet, past studies have shown that shared modalities compete with public transport, walking, and cycling without reducing the use of the private car (Esztergár-Kiss & Lopez Lizarraga, Exploring user requirements and service features of e-micromobility in five European cities, 2021).

For car sharing, the study of Ruhrort (2020) showed that station-based services lead to a net reduction of car ownership. Shaheen, Cohen and Zohdy (2016) found that free-floating services contribute to a reduction of cars on the road, while Hülsmann et al. (2018) found

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that free-floating car-sharing does not negatively affect public transport use, but also does not reduce user's car ownership or transport-related CO_2 emissions. Two studies regarding bicycle sharing in the Netherlands showed that shared bicycles are often used as a substitute for the bus, tram, metro, walking, using a private bicycle (Jorritsma, Witte, Alonso González, & Hamersma, 2021) or even the car (Ma, Yuan, Van Oort, & Hoogendoorn, 2020). Hence, it is important to ensure that shared and public transport complement each other in order to serve as an attractive alternative to private vehicles.

The integration of multiple transport modalities can be divided into a digital and a physical component (Zeng, Hidalgo, Mackie, & Schleeter, 2014). The digital integration encompasses the building blocks of information and fare integration, which are often aimed to be manageable by both service providers and passengers via digital information systems on a real-time basis (Esztergár-Kiss, Kerényi, Mátrai, & Aba, 2020). The integration of infrastructure and operations of public transport and shared modalities is referred to as "the physical" integration (Zeng, Hidalgo, Mackie, & Schleeter, 2014). A physical location that enables, at a minimum, the physical integration of different means of transport is often described as a mobility hub. One of the general definitions of mobility hubs is: "recognisable places with an offer of different connected transport modes supplemented with enhanced facilities and information features to both attract and benefit the traveller" (CoMoUK, 2019). Creating hubs will require space, which is very limited in urban areas. However, the availability of alternative transport at mobility hubs is expected to lead to the reduction of privately owned vehicles which will offset the initial space it costs to create a hub (Witte, Alonso-González, & Rongen, 2021).

In addition to the technical and organisational difficulties of digital and physical integration, this study considers the user perspective as it requires a significant shift in people's behaviour to start using new or different means of transport. The ambition is that the integration of public and shared mobility services can make both services more accessible and useful to a larger user group. However, literature published on this topic notes that this can only be achieved if the barriers of making an effective scheme of shared mobility are accounted for during the integration process (Alonso-González, Hoogendoorn-Lanser, van Oort, Cats, & Hoogendoorn, 2020). Some of the important factors in addressing these barriers are inclusiveness, accessibility, equity in terms of fair distribution of cost, and a citizen-oriented approach where the users' needs are central (Machado, De Salles Hue, Berssaneti, & Quintanilha, 2018).

Various studies have recently attempted to determine factors that relate to people's decisions to use various modalities. These factors include user characteristics, such as age and education, and transport system characteristics, such as performance and the required effort to use it (Jahanshahi, Tabibi, & van Wee, 2020). The relationship between user characteristics and people's intention to use means of transport will contribute to understanding the potential of the various means of transport at a mobility hub and help identify possible limits of the systems in terms of, for example, inclusivity. Regarding inclusivity, people's digital skills can be an important user characteristic to consider as it describes people's ability and willingness to operate connected devices, regardless of their access to these devices (Durand & Zijlstra, 2020). Differences in the level of digital skills will especially be an apparent issue for accessibility and inclusivity of multimodal transport systems when the digital integration component becomes more important (Shaheen & Cohen, 2018).

This study aims to determine the intention of potential users to use shared mobility and public transport when offered in an integrated transport system. With this aim, the study contributes to both policy makers' and transport providers' attempts to create integrated transport systems that increase the use of shared and public transport. The research questions are defined as follows:

- What is people's intention to use the shared car, shared bike, and shared motor scooter when they are offered at a mobility hub together with the public transportation (bus and tram) and how does this compare to the existing transport usage?
- Which user and transport characteristics are related to people's intention to use any of the transportation offered at the mobility hub and affect the potential uptake of the multimodal transport system?

A survey is conducted within the catchment area of the public transport stop "Leyenburg" in the Dutch city of The Hague in collaboration with the city's public transport company (HTM). The remainder of this paper is structured as follows. Section 2 presents past literature on determining people's intention to use different means of transport and the factors that can be related to this intention. Section 3 provides more details about the methodology, including the case study, survey, and data analysis. In section 4, the representativeness of the analysis is discussed, and the study's results are presented. Finally, sections 5 and 6 provide a discussion and concluding remarks, including future research directions.

2. Literature review

The concept of shared mobility and its effect on existing transportation has increasingly been addressed in academic literature. The integration of public transport with shared transport in a multimodal system has also received growing attention, especially concerning the concepts of mobility hubs and digital integration of transport. Regarding this study's aim, a review will be provided of the literature in these domains covering the understanding of people's intention to use means of transport and the characteristics of these potential transport users.

2.1. Intention to use a new transport system and the related factors

Determining the potential uptake of the multimodal transport system requires an understanding of the public's acceptance or rejection of this system (Jahanshahi, Tabibi, & van Wee, 2020). In the case of this study, the desired behaviour modification is to get people to use one of the multiple means of transport at the mobility hub or to conduct trips that combine multiple modalities. To understand what makes people modify their current behaviour, different researchers have studied theories and tried to develop models that could describe people's acceptance or rejection of ideas (Jahanshahi, Tabibi, & van Wee, 2020). In recent years, the Unified Theory of Acceptance and Use of Technology (UTAUT) model developed by Venkatesh, Morris, Davis and Davis (2003), Venkatesh, Brown, Maruping and Bala (2008), and Venkatesh, Thong and Xu (2012) is adapted and applied in the transportation research domain. The models contain various factors that are considered to influence people's intention to use a system.

Adapting from these original models and the methodology of Jahanshahi, Tabibi and van Wee (2020), as this is one of the most recent studies to apply the UTAUT model in a transportation context, the theoretical framework in Figure 1 presents, among others, these factors. The theoretical framework contains adaptations of the original UTAUT constructs of *Performance Expectancy, Effort Expectancy, Social Influence, Facilitating Conditions, Price Value*, and *Perceived Safety* to suit the purpose of this study. They are referred to as the general barriers to use transport. As such, the relation between the transport barriers and the intended user behaviour can be evaluated in this study. Travel time and number of transfers are used as transport barriers adapted from the UTAUT construct of *Performance Expectancy*. From the *Effort Expectancy,* multiple payment methods and ease of use are considered as factors. The remaining UTAUT constructs are adapted to the transport barriers of the opinion of others, facilities at public transport stops, travel costs, and feeling safe.

In addition, various user characteristics are considered in UTAUT models for transport such as age, gender, income, and education (Jahanshahi, Tabibi, & van Wee, 2020) (Venkatesh, Morris, Davis, & Davis, 2003) (Venkatesh, Thong, & Xu, 2012). Travel behaviour is added in this study as an adaptation of the experience variable found in the

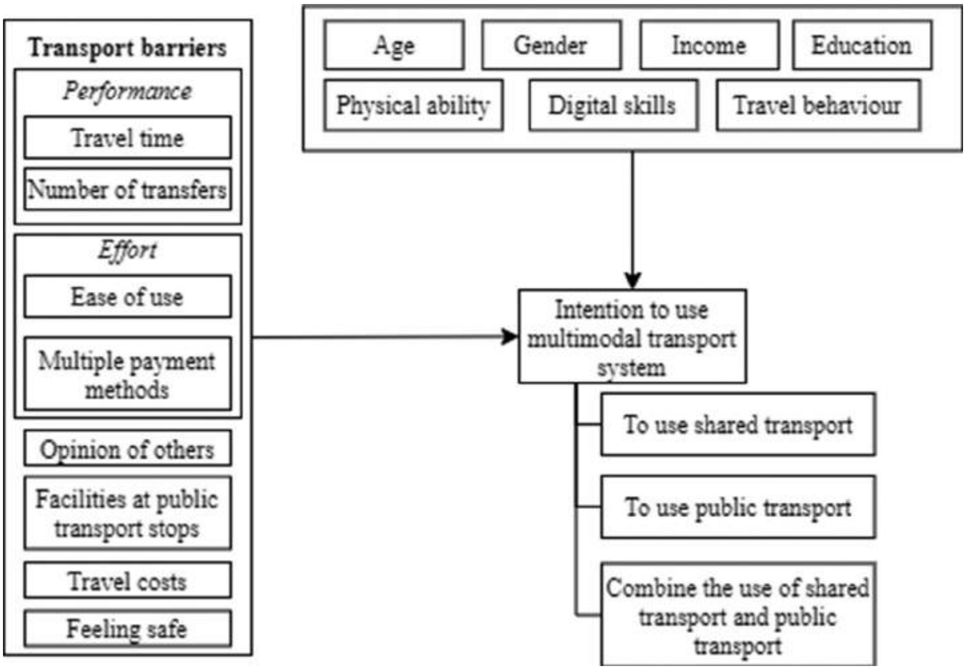

Figure 1. Theoretical framework adapted from the UTAUT models presented by Venkatesh, Morris, Davis and Davis (2003), Venkatesh, Thong and Xu (2012) and Jahanshahi, Tabibi and van Wee (2020).

original UTAUT models. It encompasses the experience with transport such as cars, public transport, and existing shared means of transport. Finally, based on the importance of an individual's capabilities to being able to access transport systems, two additional user characteristics are considered. Physical abilities are included as people with limited physical abilities can experience certain types of transport as less accessible and inclusive than others, compared to people without these limitations (Kett, Cole, & Turner, 2020). The final variable is that of personal digital skills.

2.2. User characteristics of shared transport users

Following the user characteristics from section 2.1, we review past literature that tries to determine their effect and relation in the domain of shared and multimodal transport systems. The success of new modalities and transport systems is influenced by the usage of the systems, which has led to a significant number of research aiming to characterise the users. Studies on bicycle sharing in five cities across the United States, Canada, and Mexico City in 2012 and 2013, showed that, in comparison with the general population, people that use shared bicycles tend to be wealthier, higher educated, younger and more often male (Shaheen, Martin, Chan, Cohen, & Pogodzinski, 2014) (Shaheen, Cohen, & Zohdy, 2016). A more recent study in The Netherlands, looked at the impacts on modal shift by comparing station-based and free-floating bicycle sharing systems (Ma, Yuan, Van Oort, & Hoogendoorn, 2020). It showed, for example, that male and multimodal commuters are more likely to use free-floating bicycle sharing. Another study in the Netherlands showed more than half of the Dutch car sharers is between 31 and 50 years old and slightly less than one-third is younger than 30 (Jorritsma, Witte, Alonso González, & Hamersma, 2021). It also found a relationship between a higher shared car usage and single-person households or households without children. In addition, the study found that primarily young people, males, and highly educated people use the shared bicycle.

Besides characterising users of these shared modalities, people that use multiple modalities during a single trip are also characterised in studies. Based on data from 2015 till 2017, research of KiM (2019) in the Netherlands determined that the use of multiple modalities in a single trip is higher for people aged between 18 and 30 years, with a higher income, with higher education, and for people that face a lower car availability. In addition, the level of urbanisation and trip motive affect people's decision of using multiple modalities in a single trip rather than one (KiM, 2019).

2.3. Digital skill as user characteristic affecting travel behaviour

The digitalisation in transport services, among which the mentioned aspects of digital fare and information integration, provides various advantages to multiple parties (Durand & Zijlstra, 2020). For travellers, the digitalisation in transport means instant access to travel information and increased levels of customisation and flexibility. However, at the same time, the increased use of such digital technologies creates new rules which impose new requirements on (potential) users. Examples of such rules are the smart public transport cards and the central role the smartphone has taken in the last decade (Durand & Zijlstra, 2020). Not everyone can or wants to follow the pace of these digital developments in transport services. Durand and Zijlstra (2020) show that this digital inequality is a complex and gradual process in transport services. Besides the access people have to electronic devices and an internet connection, the range of what they are able and willing to do with them also matters and is not directly dictated by their material access (Zhang, Zhao, & Qiao, 2020).

Online travel information makes it easier to access and possibly understand information that was previously unavailable or hard to find (Durand A., Zijlstra, van Oort, Hoogendoorn-Lanser, & Hoogendoorn, 2021). With this reasoning, digital services can reduce the resistance to use transport services, especially for inexperienced users. However, people with a lack of knowledge on how to operate a smartphone and use features applied in online travel information services have, in general, a higher likelihood of having restricted access to this travel information (Zhang, Zhao, & Qiao, 2020).

The digital skills that are needed in transport services can be described as two types: medium- and content-related skills. Medium-related skills are the skills that relate to operating a digital medium. They are required to successfully develop content-related skills (Van Dijk & Van Deursen, 2014). Content-related skills relate to skills such as searching, finding, processing, and critically assessing information (Van Dijk & Van Deursen, 2014). In transport, if the experienced difficulty of selecting the right piece of travel information is too high it can result in people abandoning their journey (Lamont, Kenyon, & Lyons, 2013).

The digitalisation that is linked to the integration of shared and public transport will increase the necessity of digital skills to be able to use these types of transportation. Therefore, having a low level of digital skill becomes an additional barrier to transport and people with reduced digital skills might see their mobility options remain the same or even shrinking (Durand & Zijlstra, 2020). Following this trend, there is a risk of polarisation due to the digitalisation in transport services, which could result in transport-related social exclusion (Durand & Zijlstra, 2020).

Even for general purposes, Non, Dinkova & Dahmen (2021) concluded that around 23% of the Dutch respondents do not possess a basic level of digital skills based on a survey of the OECD (2013). Based on Eurostat measurements collected from self-reported measures of the ability to perform tasks, around 20% of respondents aged 16 to 74 years in the Netherlands did not possess at least the basic level of digital skills in 2019 (Eurostat, 2021). From the same data, however, around half of the respondents from the Netherlands did possess an “above basic” level of digital skills in 2019, compared to the 33% average in the European Union (CBS, 2020a).

In addition to measuring the level of digital skills, studies have tried to link digital skills to certain demographic variables. The study of Non, Dinkova and Dahmen (2021), using the data of the OECD (2013), shows that individuals with low digital skills are generally older, lower educated and more often female. Additionally, Durand, Zijlstra, van Oort, Hoogendoorn-Lanser and Hoogendoorn (2021) conclude that older people with lower income and education and those who are part of minority groups are more vulnerable to digital exclusion from transport services.

2.4. Research gap and contribution

Summarizing the literature, most studies have focussed on understanding the modal shift caused by shared transport and the characteristics of the users of these new shared mobility systems. KiM (2019), which is our closest prior art, has found characteristics of people that use multiple modalities during a trip, but this characterisation is not linked to specific modalities. To understand the benefits of integrating shared and public transport, both physically and digitally, this paper focuses on investigating which factors influence the intention to use modalities in the system, including public transport, and how these factors compare for the various modalities.

In addition, with the development of shared transport, the digital component in transport is growing as some of the shared mobility systems offer only digital options to plan and pay for a trip with a vehicle (Durand & Zijlstra, 2020). However, as seen in our literature review, various levels of digital skills exist, and a lack of these skills can result in transport-related social exclusion. Hence, this paper will study if digital skills affect people’s intended use behaviour of transport modalities to get a better understanding of the possible extent of this transport-related social exclusion. In addition, the digital skill measures found in literature would only partly represent the presence of skills needed to operate the developing digital platforms for transport services. Hence, this study will develop a digital skill measure that reflects one’s ability to perform tasks that are inherent to the digital services seen in the transport sector. This measure allows evaluating the potential digital exclusion that can be caused by the digitalisation in transport, as seen in multimodal transport systems.

3. Methodology

To study this intention to use shared transport modes at a mobility hub, a survey is conducted concerning a theoretical mobility hub based on an existing public transport stop. The mobility hub is defined as a location that combines the offering of the bus and tram together with the transport means of shared car, shared bicycle, and shared motor scooter.

3.1. Case study

To conduct our survey, a case study has been developed in collaboration with HTM, a public transport company in the city of The Hague. The case study concerns the public transport stop Leyenburg in The Hague. Figure 2 provides an overview of the stop and its surrounding area. This stop includes the transport modes of bus, tram, and HTM’s ‘HagaShuttle’, a self-driving minibus. It is also located next to a drop zone for the ‘HTM fiets’ and shared motor scooters from various providers can be used in the area surrounding the stop. The ‘HTM fiets’ is a bicycle sharing system using more than 215 designated drop zones where the bicycles can be picked-up or returned (HTM, 2022). The use of these bikes is facilitated purely by the means of a separate app. Currently, a significant amount of these drop zones is located close to or at public transport stops (van Marsbergen, 2020).

The public transport stop Leyenburg classifies as one of the 20 busiest stops for HTM (HTM, 2021). It serves as a connection to the public transport network for people living in surrounding neighbourhoods and the people travelling to or from the hospital ‘het HagaZiekenhuis’. In addition, the stop is used by travellers to switch between different vehicles in the public transport network, for example from bus to tram. Overall, this variety of characteristics, such as being an important public transport connection for a neighbourhood, facilitating transfers between public transport modes, while also serving an important destination in the form of a hospital make this stop a suitable case to include people with a variety of travel behaviours in this study.

3.2. Survey

To collect the data required to address the paper’s research questions, a survey has been developed that targets the following three groups of either current or potential users of the public transport stop:

- The public transport users currently travelling from, to, or via the stop Leyenburg.
- The visitors of ‘HagaZiekenhuis’.
- People living in the vicinity of the stop Leyenburg.

The latter two groups are a mix of public transport users and non-public transport users. Both a paper and a digital version of the questionnaire were used to reach the three target groups. A flyer was created with a QR-code and weblink that both direct to the digital questionnaire made using Qualtrics software. The paper version of the questionnaire consists of four pages and its English version is made publicly available at https://doi.org/10.17632/gr2fn7b7yw.1.

The digital questionnaire was open from June 21st, 2021, to August 1st, 2021. During a period of two weeks, starting at June 21st, flyers and the paper version of the questionnaire were distributed among the three target groups. Finally, the digital version of the questionnaire was also shared on the website and social media page of HTM and on the internal platform for employees of the hospital. In total around 4290 flyers have been distributed of which 2910 flyers were received by households in either their mailbox or by handing it to them in person (103 of the 2910 flyers) in the area surrounding the Leyenburg stop. The remaining flyers were distributed to people at the public transport stop and outside of the HagaZiekenhuis. In addition, 146 paper questionnaires have been handed to people that indicated they preferred the paper version of which 131 were handed out at the public transport stop in front of the HagaZiekenhuis. The other 15 were handed to people from households that were approached in person in a selected area in the neighbourhood based on the characteristics of age, income, and type of housing obtained from a CBS data set of 2017 (CBS, 2017). Overall, 710 responses were collected of which 48 responses were received

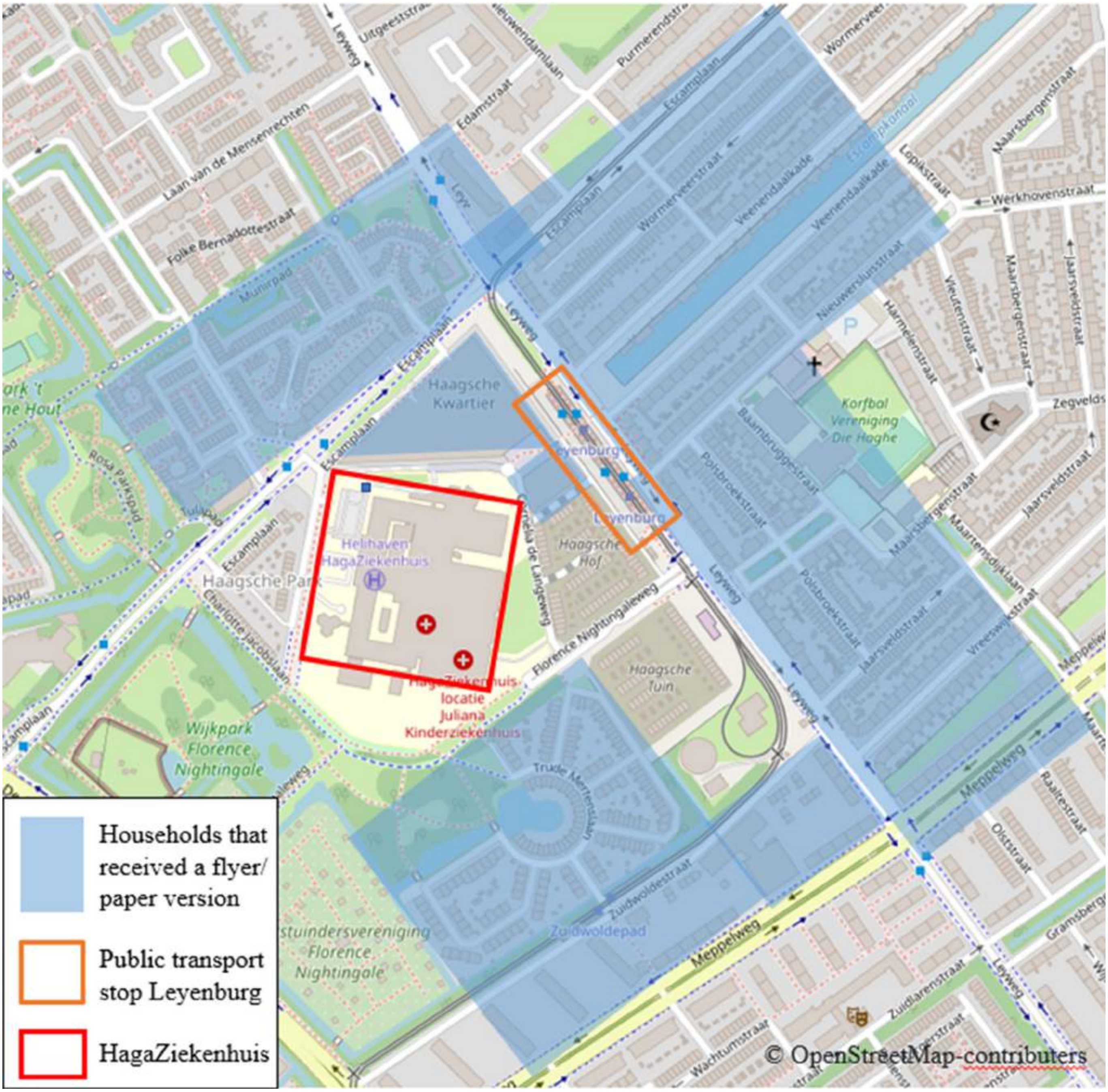

Figure 2. An overview map of the case study area. The top of the map corresponds with the north direction.

on paper. The other 662 responses were collected via the digital questionnaire, where 348 respondents indicated that they had been made aware of the survey through the distributed flyer. The remaining 314 digital respondents got to the digital questionnaire via one of the other distribution methods or did not specify how they were made aware of it.

Both the digital and paper version of the questionnaire were available in English and Dutch. In our survey, a person with a migrant background is considered someone of which at least one of the parents is born outside the Netherlands (CBS, 2021). During the development of the questionnaire, it was tested and read in advance by a committee of 10 members, consisting of employees of HTM and researchers from the University of Twente.

The content of the questionnaire consists of four parts:

- 1 - Personal experience in travelling and digital activities in the past year
- 2 - Importance of the transport barriers
- 3 - Travelling to/from Leyenburg and the intention to use transport in the mobility hub scenario
- 4 - Personal information

Parts 1,2, and 4 contain questions concerning the factors and user characteristics included in the theoretical framework that might be related to people's intention to use certain means of transport in the multimodal transport system at the hub. All questions were asked using likert-scales or multiple answer options, except for the age of the respondents which was asked as a question with an open answer. For a more detailed overview of the questions, see the publicly available paper version of the questionnaire at https://doi.org/10.17632/gr2fn7b7yw.1. For the digital activities, the questions ask about the frequency of performing activities that relate to the components of information/planning and payments on a smartphone using a likert-scale.

These digital activities are used to measure people's level of digital skill relevant for app-based transport services based on the following self-constructed scale. Except for the first category, which will represent persons with no relevant digital skills at all, the categories will represent different levels of content-related skills. The frequency of performing activities related to the components of planning and digital payment is used in the digital skill scale consisting of four categories with the following labels:

- Level 0 – No skills at all – No access to a smartphone, so not even general medium or content-related skills have been developed.

A person in this level did not have any access to a smartphone in the past year.

- Level 1 – Low level of skills – used a smartphone but not frequently performed planning activities via an app.

A person in this level has used a smartphone in the past year.

- Level 2 – Medium level of skills – used to plan a trip using an app but less used to do digital payment activities via an app.

A person in this level has also, in addition to the above, planned a trip with either his/her own transportation or PT using an app at least *often*.

- Level 3 – High level of skills – used to do both planning and payment/reserving related activities via an app.

A person in this level has also, in addition to the above, used an app to transfer money to someone at least *often*.

Part 3 of the questionnaire covers people's intention to use various means of transport, which is asked using likert-scale questions. The respondents are asked about this intention by sketching a scenario in which they would repeat a previously executed trip when shared mobility would be present together with the existing public transport near the origin of their trip. All people that indicate to have never travelled within the boundaries of the case study in the past year will skip part 3 and proceed to part 4 of the questionnaire. For all other respondents, if they started their trip in the vicinity of the public transport stop Leyenburg, this was specifically mentioned as the location where the shared car, bicycle, and motor scooter would become permanently available at a fixed location close to the existing public transport (bus and tram). As the choice of mean of transport is often determined at the origin of the trip, people that indicated the area of Leyenburg to be the destination of their trip were provided with a slightly different scenario. Here, the created scenario described the situation where the shared modalities would be permanently available at a public transport stop near their home. The statements related to the intention to use transport were asked for a future trip from the respondent's home to their destination in the area of Leyenburg. Regarding the digital integration of the modes, it was stated that a trip could be planned, reserved, and booked using an app on a smartphone.

3.3. Data analysis

The survey resulted in N=710 usable responses for the analysis after removing the empty responses and the responses of people indicating to be younger than 18. Using these responses, various descriptive statistics are obtained for the variables that contribute to the understanding of the respondent's user characteristics, including digital skills, and the intention to use shared and public transport. To analyse the relationship between variables of intention to use a certain means of transport and the factors like the transport barriers and the user characteristics, a subset of responses is used containing N=538 cases. These cases are retained because they contained answers to at least one of the questions related to the intention to use means of transport. The study's main result will originate from an ordinal logistic regression analysis aimed to determine the influence of the independent variables of user characteristics, transport barriers, and other trip-specific factors on the dependent variables of intention to use types of transport in the multimodal transport system.

The analyses were executed using the software SPSS statistics. For the ordinal logistics regression analyses, the assumption of proportional odds is considered by using the test of parallel lines, where the assumption is upheld if the test is not significant (Liu, 2009). Additionally, the collinearity diagnostics of SPSS Statistics are used to ensure that there is no multicollinearity among the independent variables. Here, tolerance values less than 0.1 (Menard, 1995) and VIF values greater than 10 (Myers, 1990) are considered to indicate an issue of collinearity among the independent variables.

An ordinal logistic regression analysis was executed three times, once for every ordinal dependent variable listed in Table 1 that refers to people's intention of using a certain mean of transport or combining the use of shared transport with the bus or tram. For each of the analyses, the same set of independent variables is used, as presented in Table 1. The Kendall's Thau correlation values among the ordinal independent variables do not exceed $\tau= +/-.35$. Hence, none of the independent variables is omitted because of strong correlations between them. The results of the ordinal logistic regression analyses will show whether or not an independent variable is able to significantly predict the dependent variable. For each of these significant independent predictor variables, the relationship with the dependent variable is described using the b-value and the odds ratio (exp(B)) resulting from the analysis. This odds ratio is crucial for the interpretation of logistic regression (Field, 2018). With categorical predictor variables, the odds ratio represents the change in odds caused by a unit change in the predictor variable (Field, 2018). If it is greater than 1, it indicates that as the predictor increases with one step, the odds of the outcome occurring increase. The other way around, if the value is less than 1, it implies that as the predictor increases, the odds of the outcome occurring decrease.

To satisfy the requirements of the ordinal regression analysis, three dummy variables are created for the nominal variable of household composition as it contained more than two categories. The dummy variables are created for the categories of *single parent, two persons without child(ren),* and *two-parent*, with the category *single person* being the reference category. For people's current travel behaviour, three variables are extracted from the questions; one indicating if someone used a car at least weekly, one indicating if someone used public transport (train, bus, tram or metro) at least weekly, and finally, a variable indicating if someone had any experience in the past year with either the shared car, shared bicycle, or shared motor scooter. For people's level of education, the multiple-choice answers based on the Dutch education system are converted to terms of a low-, middle-, and high-level of education in accordance with the definition as used by the national statistics office CBS (2019). In addition, the people without any education have been assigned to the lowest of the three levels.

Additionally, multiple independent variables are obtained by combining the results of several questions in the questionnaire. First, using a Principal Component Analysis (PCA) and Cronbach's alpha (α) it is checked if the questions for the transport barriers related to Performance Expectancy (PE) and Effort Expectancy (EE) can be combined into their respective higher-level constructs. The PCA analysis was conducted with the four transport barriers of which two were designed to relate to PE and two relate to EE. The results showed that when two factors were retained, they represented the PE and EE constructs as designed after the initial four transport barriers were loaded onto the factors using oblique rotation (direct oblimim). The eigenvalue of factor 1 (PE) was 1.89 and that of factor 2 (EE) was 0.92. However, only for the factor PE did α

Table 1
List of variables included in the model for the ordinal logistic regression analysis.

Independent variables	Dependent variables	
Frequent Car User	Country of birth	Intention to use shared transport
Frequent PT User	Limited physical ability	Intention to use bus or tram
Shared transport experience	Household composition	Intention to combine use of shared transport with the bus or tram
Digital skills	Transport barrier (TB) – Performance Expectancy	
Frequency of trip	TB – Ease of use	
Location of trip	TB – Multiple payment methods	
Origin/destination of trip	TB – Facilities at PT stops	
Nr. of transport means used during trip	TB – Feeling safe	
Gender	TB – Travel costs	
Age	TB – Opinion of others	
Education		

support the variable's ability to describe the results of the two transport barriers related to it, with $\alpha = 0.64$. For EE, the question related to ease of use and the question related to having multiple payment methods for transport were not found to measure the construct of EE sufficiently, with $\alpha = 0.43$ supporting this. Hence, both these questions are kept as individual variables in the model for the ordinal logistic regression analysis. Secondly, the dependent variables describing people's intention to use means of transport include the results for both mobility hub scenarios used in the questionnaire. In addition, the questions related to the intention to use a shared car, shared bicycle or shared motor scooter in the mobility hub scenarios are used to construct a new variable indicating the intention to use any of these shared means of transport. The highest response on any of these three questions is transferred to the new variable which then contains the same ordinal scale of disagree, neutral, agree.

A final important note regarding the methodology is that household income is not included as an independent variable in the model because of the low number of useful responses on the related question. Only 354 out of the 538 responses for the regression analysis were useful for the income variable. A Kendall's thau correlation analysis shows a moderate and positive correlation of a person's income with the education variable (τ=.29, p<.001) for the 354 useful responses. Hence, the level of education will be used as an indicator of the level of household income to be able to consider this variable in further analyses and conclusions in line with the study's theoretical framework.

4. Results

The first two sub-sections will describe characteristics of the respondents, among which their representativeness compared to larger populations. Hereafter, the focus will be on the mobility hub scenario and the analysis of people's behavioural intention towards the use of means of transport in a multimodal transport system. This includes, in the final sub-section, the results of ordinal logistic regression analysis concerning the model as detailed in the section above.

4.1. Socio-demographic characteristics and representativeness of the sample

The socio-demographic characteristics of the respondents are explored and compared with larger populations to check the representativeness of the collected data. Table 2 provides an overview of these characteristics and the distribution of all the respondents among the different categories.

The main comparison is made between the survey's respondents and the population of the municipality of The Hague, as most of the respondents live in The Hague. The data of the population is obtained from the Municipality of The Hague (2021) and CBS (2020b), the Dutch national statistical office. As can be seen in Table 2, the data from the survey has a higher response from females (59%) compared to the almost equal distribution of males compared to females as is present in the population of The Hague. For the different age classes, a bias can be noted towards more people of age 55-74 years and fewer people of age 18-54 years compared to the population of the Hague. In addition, the respondents of the survey contain more highly educated (48.3%) and less low educated people (16.0%) compared to the general population (32.1% and 31.5%, respectively). Finally, for the household composition, the significant difference can be found in having fewer one-person households and more multiple-person households without children compared to the municipality statistics. Overall, these biases towards more female and higher educated respondents are not unexpected for a survey. In addition, the strong representation from older age categories is explained by the distribution strategy and might be caused by the hospital visitors among the respondents.

Finally, comparing the respondents from the paper questionnaire with the digital respondents based on their age and digital skills shows that there is a significant difference in characteristics. 75% of the paper respondents (N=44) are older than 65 years, where this is 20.3% for the digital respondents (N=497). For digital skills, 88.1% of the paper respondents qualified for level 0 or level 1 digital skills, whereas only 30.7% of the digital respondents have these low levels of digital skills. Based on these characteristics, a significantly different audience is reached with the two types of questionnaires.

4.2. Descriptive statistics

In addition to the socio-demographic characteristics of the respondents, other moderating variables such as the travel behaviour and digital skills are considered to possibly influence people's intention to use means of transport. The results are summarized below to gain a better understanding of the measured variables before they are discussed in the context of the regression analysis.

4.2.1. Frequencies of transport mode use

Figure 3 shows the frequencies of respondents' transport mode usage from July 2020 to July 2021. Comparing the use of public transport and the car among the respondents, 87.5% of the respondents has used the bus, tram, or metro at least once in the past year compared to 77.7% for the car. Overall, 94.8% of the people have not used a shared car in the past year.

For the regression analysis, the variables of *frequent car user* and *frequent public transport user* are applied, referring to people that use these means of transport at least once per month. From all respondents with relevant answers (N=649), 18.2% qualify as both a frequent car and public transport user. 26.2% are not a frequent car user but use public transport frequently, whereas 37.1% are a frequent car user but not a frequent user of public transport. Finally, the remaining 18.5% does not qualify for either frequently using the car or public transport. To better understand the distribution, only around a third of the frequent car users, use public transport frequently.

4.2.2. Digital skill scale

To understand the variation of digital skills among the respondents, Figure 4 shows the distribution of the respondents (N=698) among the

Table 2
Socio-demographic characteristics of the survey's respondents and corresponding percentages for the population of The Hague (Municipality of The Hague, 2021) (CBS, 2020b).

Gender	Sample Survey N=575	Population The Hague	**Household composition**	Sample Survey N=556	Population The Hague
Male	40.3%	49.8%	One person	33.9%	47.1%
Female	59.0%	50.2%	Single parent	7.3%	9.3%
Other	0.7%		Two person without children	33.7%	22.6%
Age	N=557		Two-parent	24.7%	21.0%
18-24 years	9.9%	11.5%	**Income household**	N=385	
25-34 years	17.2%	19.4%	< 25,000 euros	19.2%	
35-44 years	12.7%	18.2%	25,000-45,000 euros	45.7%	
45-54 years	16.0%	17.7%	> 45,000 euros	35.1%	
55-64 years	19.4%	14.7%	**Country of birth**	N=563	
65-74 years	17.4%	10.9%	The Netherlands	88.3%	
≥ 75 years	7.4%	7.6%	Outside of the Netherlands	11.7%	
Education level	N=574				
Low	16.0%	31.5%			
Middle	35.7%	36.4%			
High	48.3%	32.1%			

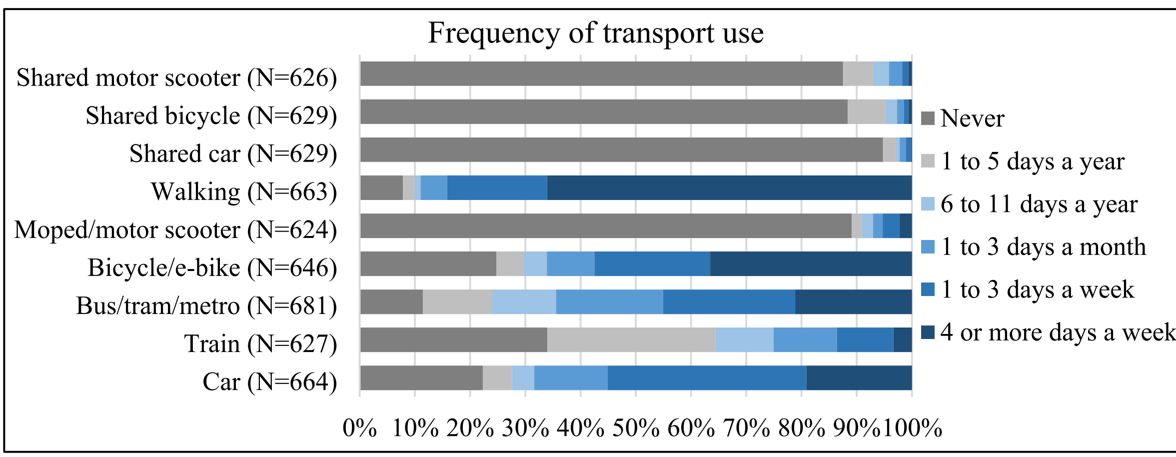

Figure 3. Frequencies (in percentage) of the respondent's use of different means of transport in the past year.

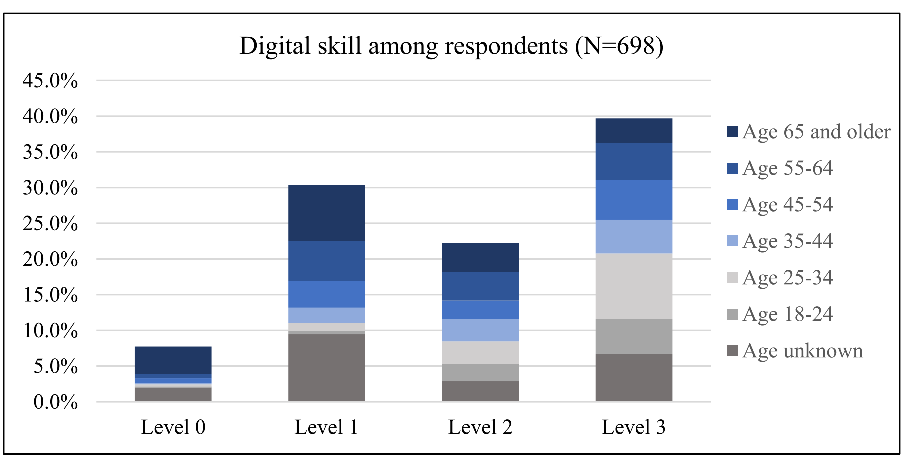

Figure 4. The distribution of the four digital skill levels (explained in section 3.2) among the respondents of the survey (N=698) and the age distributions within these levels.

four levels of digital skill as defined in section 3.2. First, 7.7% has never used a smartphone in the past year (level 0) and thus possesses no relevant digital skills for the app usage in the transport domain. Level 1 is a significantly larger group (30.4%) which represents the people that had access to a smartphone but not frequently used it for transport-related planning activities. 22.2% of the respondents have used a smartphone and used it frequently to plan a trip (level 2). The highest level of skills (level 3) is possessed by 39.7% of the respondents and they have also frequently performed payment-related activities on their smartphones in addition to the planning activities.

In the theory of digital skills, relations were noted between age, education, and a person's digital skills, among others. In this study's analysis, a significant and a moderate to relatively strong correlation is noted between the digital skill measure and people's age (τ=-.333,

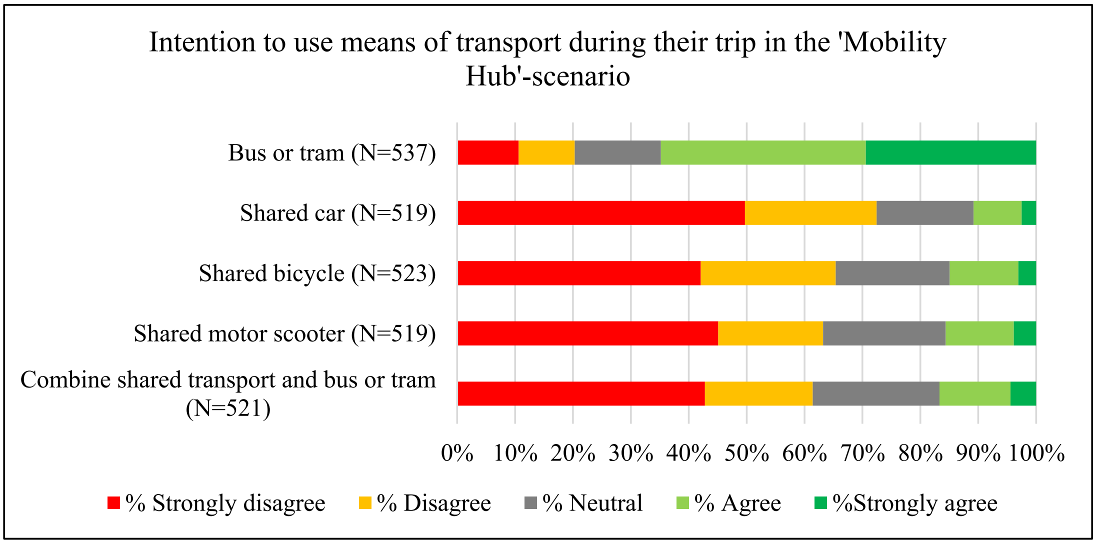

Figure 5. Response to the statement 'I want to use a … as (one of) the means of transport during this trip'.

p<.001) and a slightly more moderate correlation with people's education (τ=.193, p<.001). Among the other variables, a weak but statistically significant correlation is noted between digital skills and frequent car users (no/yes) (τ =-.089, p=.031) and frequent public transport users (τ=.098, p=.016).

4.2.3. People's intention to use means of transport and their current use

To get an understanding of the overall intention to use the various means of transport included in this study, the results for these variables will be discussed below. First, Figure 5 shows that, for all three means of shared transport, less than 20% of the survey's respondents agreed or strongly agreed with the statement that they would intend to use the shared means of transport during their most frequent made trip in the past year, if these were made available at a mobility hub nearby. Only 10.8% of the respondents intend to use the shared car compared to 15.0% for the shared bicycle and 15.7% for the shared motor scooter. Finally, the majority (64.8%) of the respondents intend to use (agree and strongly agree) the available public transport at the mobility hub during their trip.

Table 3 below, shows that people's age and level of education relate significantly to whether someone belongs to one of the two groups of people. When comparing Table 3, to the characteristics of all respondents (summarized in Table 4), it can be noted that the two groups are generally younger. Interestingly, people with no prior experience but with the intention to use shared transport have a higher distribution in the age category of 18-24 years compared to the group that has prior experience but no intention to use shared transport. The latter group consists of more people in the group 35-44 years. Based on Table 3 and Pearson Chi-square results, it can be noted that the people that do not intend to use shared transport, even though they have experience, are more likely to not use the car on a weekly basis (not frequent). The people that intend to use shared modalities, but have not used them before, show a significant relation with the number of means of transport they currently use during their trip and their digital skills.

4.2.4. Comparison of potential users of shared cars, bicycles, and motor scooters

Among the shared means of transport, the people that intend to use the shared motor scooter tend to be younger and slightly lower educated than the potential users of the shared bicycle and shared car. The correlations between age and the intention to use each of these shared modes are significant (p<.001). However, for education there is no significant correlation (Kendall's thau) between the intentions to use shared car, shared bicycle, or shared motor scooter. The distributions of people that use a car and/or public transport frequently or not differ among the three means of shared transport, see Table 4. However, only for the shared scooter (τ=.091, p=.034) and the shared car (τ=.105, p=0.016) is the correlation with current car use significant. The current public transport usage only correlates with the intention to use shared motor scooter (τ=.134, p=.002) and not with the intention to use the shared car or the shared bike. From the people that intend to use a shared motor scooter a slightly higher percentage are frequent car and frequent public transport user. Finally, the finding that people that have the intention to use a shared mean of transport are generally using more means of transport during a single trip seems to be the most apparent for the shared bicycle.

4.3. Results of ordinal regression analysis – intended use behaviour

This section will present the results of the ordinal logistics regression analysis for three dependent variables: intention to use shared transport, intention to use the bus or tram, and intention to combine the use of shared transport with the bus or tram. We note that no multicollinearity exists among the selection of variables. Further assumptions and quality of the models will be discussed for each of the analyses individually in the sections below.

4.3.1. Intention to use any means of shared transport

The results for the analysis of the model with the dependent variable 'the intention to use shared means of transport' and 21 independent variables are described below (N=423). Table 5 shows an extract of the ordinal logistic regression analysis for the dependent variable of the intention to use shared transport. Here, only the independent variables with a significant, or almost, significant relation (p<.05) are shown. As the Wald statistic and related significance can contain inaccuracies (according to Field (2018)) the likelihood ratio Chi-Square statistics are also obtained for each predictor variable as a whole. When necessary, the significance values from these results will also be highlighted. Based on these results, digital skill is a significant predictor of the intention to use shared transport, as well as the experience with shared transport. The other two variables related to travel behaviour, the frequency of car and public transport use, cannot be marked as having an influence on someone's intention to use shared transport. Hence, whether someone uses a car frequently, or means of public transport does not affect their intention to use shared transport, based on these results.

Table 3
Pearson Chi-square test results of significantly related characteristics of two different types of people regarding their previous use and intended use of shared transport.

	People without experience, but with intention to use shared transport		People with experience, but no intention to use shared transport	
	%	χ^2	%	χ^2
Age	N=71		N=41	
18-24 years	25.35%	χ^2=29.841 p<.001	14.63%	χ^2=18.126 p=.003
25-34 years	19.72%		24.39%	
35-44 years	19.72%		29.27%	
45-54 years	15.49%		12.20%	
55-64 years	11.27%		17.07%	
≥ 65 years	8.45%		2.44%	
Education level	N=72		N=42	
Low	4.17%	χ^2=9.651 p=.008	9.52%	χ^2=8.722 p=.013
Middle	33.33%		19.05%	
High	62.50%		71.43%	
Frequent car user	N=72		N=42	
No	41.67%	χ^2=0.494 p=.482	61.90%	χ^2=4.973 p=.026
Yes	58.33%		38.10%	
Nr. of transport means during TRIP	N=72		N=42	
One	56.94%	χ^2=6.759 p=.034	54.76%	χ^2=0.388 p=.824
Two	12.50%		26.19%	
Three or more	30.56%		19.05%	
Digital skill	N=72		N=42	
Level 0	1.39%	χ^2=18.894 p<.001	2.38%	χ^2=3.861 p=.277
Level 1	13.89%		23.81%	
Level 2	20.83%		19.05%	
Level 3	63.89%		54.76%	

Table 4
Percentage distribution of answers among potential user characteristics for all respondents and the three groups that intent to use three means of shared transport.

		Intent to use:		
	All respondents	Shared bicycle	Shared car	Shared motor scooter
Gender	N=575	N=75	N=56	N=81
Male	40.3%	36.0%	42.9%	35.8%
Female	59.0%	64.0%	57.1%	64.2%
Other	0.7%	0.0%	0.0%	0.0%
Age	N=557	N=75	N=55	N=81
18 -24 years	9.9%	17.3%	23.6%	25.9%
25-34 years	17.2%	33.3%	29.1%	34.6%
35-44 years	12.7%	12.0%	9.1%	16.0%
45-54 years	16.0%	12.0%	14.5%	9.9%
55-64 years	19.4%	17.3%	14.5%	11.1%
≥ 65 years	24.8%	8.0%	9.1%	2.5%
Education level	N=574	N=75	N=56	N=81
Low	16.0%	9.3%	7.1%	7.4%
Middle	35.7%	29.3%	33.9%	40.7%
High	48.3%	61.3%	58.9%	51.9%
Household composition	N=558	N=75	N=54	N=79
One person	33.9%	34.7%	29.6%	25.3%
Single parent	7.3%	8.0%	9.3%	10.1%
Together without children	33.7%	26.7%	37.0%	26.6%
Together with children	24.7%	30.7%	24.1%	36.7%
Other	0.4%	0.0%	0.0%	1.3%
Country of birth	N=563	N=75	N=55	N=81
The Netherlands	88.3%	90.7%	87.3%	92.5%
Other	11.7%	9.3%	12.7%	7.5%
Frequent car user	N=664	N=75	N=55	N=79
No	44.9%	45.3%	40.0%	40.5%
Yes	55.1%	54.7%	60.0%	59.5%
Frequent PT user	N=687	N=75	N=55	N=80
No	53.9%	45.3%	56.4%	45.0%
Yes	46.1%	54.7%	43.6%	55.0%
Experience with shared transport	N=622	N=69	N=50	N=75
No	78.3%	55.1%	62.0%	49.3%
Yes	21.7%	44.9%	38.0%	50.7%
Nr. of transport means during trip	N=573	N=78	N=56	N=81
One	55.1%	42.3%	51.8%	46.9%
Two	22.9%	17.9%	16.1%	19.8%
Three or more	22.0%	39.7%	32.1%	33.3%

Table 5
Parameter estimates of ordinal regression analysis with dependent variable: Intention to use shared transport (N=423).

	b	Std. Error	Wald	Sig.	Exp(B)	95% CI for odds ratio	
						Lower	Upper
Threshold							
[Intention to use shared transport = disagree]	-3.718	1.363	7.440	0.006	0.024	0.002	0.347
[Intention to use shared transport = neutral]	-2.349	1.356	3.003	0.083	0.095	0.007	1.341
Location							
Digital skill = level 0	-1.593	0.621	6.571	0.010	0.203	0.062	0.664
Digital skill = level 1	-0.879	0.301	8.516	0.004	0.415	0.228	0.755
Digital skill = level 2	-0.409	0.270	2.292	0.130	0.664	0.390	1.131
Digital skill = level 3	0a				1		
Experience with shared transport = No	-1.393	0.277	25.201	0.000	0.248	0.143	0.432
Experience with shared transport = Yes	0a				1		
TB - Ways of paying = not important	-1.028	0.404	6.487	0.011	0.358	0.162	0.791
TB - Ways of paying = a bit important	-0.748	0.412	3.294	0.070	0.473	0.209	1.071
TB - Ways of paying = fairly important	-0.477	0.386	1.528	0.216	0.621	0.292	1.317
TB - Ways of paying = important	-0.382	0.348	1.202	0.273	0.683	0.345	1.351
TB - Ways of paying = very important	0a				1		
Frequency of trip = 1 to 5 days a year	0.537	0.422	1.624	0.202	1.712	0.744	3.935
Frequency of trip = 6 to 11 days a year	-0.386	0.491	0.618	0.432	0.680	0.265	1.745
Frequency of trip = 1 to 3 days a month	-0.775	0.381	4.133	0.042	0.460	0.215	0.988
Frequency of trip = 1 to 3 days a week	-0.064	0.259	0.061	0.805	0.938	0.566	1.556
Frequency of trip = 4 or more days a week	0a				1		
Nr. of means of transport during trip = 1	-0.498	0.269	3.427	0.064	0.608	0.355	1.040
Nr. of means of transport during trip = 2	-0.842	0.324	6.768	0.009	0.431	0.228	0.813
Nr. of means of transport during trip = 3 or more	0a				1		
Trip origin/destination = HagaZiekenhuis	0.406	0.223	3.313	0.069	1.501	0.966	2.333
Trip origin/destination = other	0a				1		
Age class = 18-25	2.267	0.514	19.459	0.000	9.649	3.441	27.056
Age class = 25-34	1.433	0.431	11.071	0.001	4.192	1.786	9.838
Age class = 35-44	0.898	0.450	3.986	0.046	2.454	0.995	6.052
Age class = 45-54	0.781	0.439	3.156	0.076	2.183	0.908	5.245
Age class = 55-64	1.019	0.404	6.371	0.012	2.770	1.238	6.198
Age class = 65 and older	0a				1		
Education = low	-1.246	0.428	8.473	0.004	0.288	0.125	0.664
Education = middle	-0.261	0.244	1.150	0.284	0.770	0.480	1.236
Education = high	0a				1		

Only the selection of (almost) significant variables are shown.
Link function: Logit.
a. This parameter is set to zero because it is redundant.

For digital skills, the odds ratio of 0.203 for level 0, indicates that the odds of someone in level 0 to intend to use shared transport (answered agree) rather than not is 1/0.203 = 4.926 times smaller than that of someone with digital skill level 3. In the same way, with the odds ratio of 0.415 for level 1, the odds of someone with digital skill level 1 intending to use shared transport rather than not is 2.410 (1/0.415) times smaller than that of someone with level 3 digital skills. For level 2 digital skills, the prediction value with respect to level 3, is not significant.

Moreover, having prior experience with shared means of transport significantly increases the odds of intending to use shared transport in the proposed mobility hub scenario (p<.001). The odds of someone with shared transport experience intending to use shared transport again in the future (answered agree) rather than not is 4.032 (1/0.248) times larger than someone without any experience with shared transport.

Based on Table 5 it can be said that two of the four tested categories of the transport barrier about the necessity of having multiple ways to pay for public or shared transport show a significant relation based on the Wald statistic. However, the predictor as a whole, based on the Chi-Square likelihood ratio, has a significance of p=.115. The same applies to the variable of frequency of trip, even though one category shows p<.05, the overall variable seems not to have a significant prediction value to the dependent variable.

The number of means of transport used during a trip is a significant predictor to the intention to use shared transport. However, the first category shows a significance just above p=.05. From the odds ratio, the odds of someone using two means of transport during their trip being intended to use shared transport rather than not is 2.320 times smaller than that of someone using three or more means of transport during their current trip.

Finally, the age and education of a person are also determined to be significant predictors based on Table 5. For the complete variables, this is confirmed by the significance of the likelihood Chi-square ratio with for age: $\chi^2(5)=23.488$, p<0.001 and for education: $\chi^2(2)=9.234$, p=0.010. For age, the odds ratios are relatively equal for ages 35-44, and 55-64. For the younger groups, the odds ratio is large and shows the decrease in odds of intending to use shared transport rather than not as age increases.

Several independent variables from the model are not included in Table 5, as they do not have a significant role as predictor to the dependent variable of intention to use shared transport. This includes the location of the trip (whether the trip only takes place within The Hague or not), country of birth and physical ability. The latter is interesting because of the active modes of transport included in shared transportation.

4.3.2. Intention to use the bus or tram

Next, the results of the second ordinal logistic regression analysis with the dependent variable being the intention to use the bus or tram will be discussed. For this analysis, N = 424. The model's prediction ability is at a similar level as that of the previous model for the intention to use shared transport. The test of parallel lines of SPSS statistics results in p=.784, indicating that the assumption of proportional odds is met for this analysis. The results are presented in Table 6.

4.3.3. Intention to combine the use of shared transport with the bus or tram

For the last analysis, the ordinal logistic analysis was executed with the dependent variable of the intention to combine the use of shared transport with the bus or tram (N=421). The model fit is proven by

Table 6
Parameter estimates of ordinal regression analysis with dependent variable: Intention to use the bus or tam (N=424).

	b	Std. Error	Wald	Sig.	Exp(B)	95% CI for odds ratio Lower	Upper
Threshold							
[Intention to use bus or tram = disagree]	-2.650	1.645	2.595	0.107	0.071	0.003	1.808
[Intention to use bus or tram = neutral]	-1.598	1.641	0.948	0.330	0.202	0.008	5.138
Location							
Digital skill = level 0	-0.353	0.595	0.353	0.552	0.702	0.225	2.193
Digital skill = level 1	-0.837	0.320	6.826	0.009	0.433	0.230	0.815
Digital skill = level 2	-0.410	0.312	1.721	0.190	0.664	0.359	1.229
Digital skill = level 3	0a				1		
Car user = non-frequent	0.560	0.266	4.427	0.035	1.750	1.031	2.971
Car user = frequent	0a				1		
PT user = non-frequent	-1.799	0.293	37.574	0.000	0.166	0.092	0.296
PT user = frequent	0a				1		
TB - Facilities PT = not - fairly important	-0.127	0.363	0.123	0.726	0.880	0.430	1.801
TB - Facilities PT = important	-0.622	0.283	4.829	0.028	0.537	0.306	0.941
TB - Facilities PT = very important	0a				1		
Frequency of trip = 1 to 5 days a year	1.588	0.494	10.334	0.001	4.893	1.909	12.546
Frequency of trip = 6 to 11 days a year	1.675	0.551	9.255	0.002	5.339	1.851	15.400
Frequency of trip = 1 to 3 days a month	1.082	0.410	6.976	0.008	2.951	1.301	6.695
Frequency of trip = 1 to 3 days a week	0.632	0.291	4.728	0.030	1.881	1.059	3.344
Frequency of trip = 4 or more days a week	0a				1		
Trip origin/destination = HagaZiekenhuis	-0.648	0.252	6.613	0.010	0.523	0.319	0.858
Trip origin/destination = other	0a				1		

Only the selection of (almost) significant variables are shown.
Link function: Logit.
a. This parameter is set to zero because it is redundant.

the Chi-Square, Pearson, and deviance statistics, and results of the R^2 measures confirm the prediction ability for the model. The final consideration is the assumption of proportional odds. The test of parallel lines indicates that this assumption is met as p=.236. Table 7 shows an extract of the analysis, containing all six independent variables that show a significance of p<.05 for at least one of their categories.

We note that only the first category, age between 18 and 25 years, has a significance below p=.05. Finally, people who currently use one or two means of transport during their trip are less intended to combine the use of shared transport with the bus or tram than people who are currently already using three or more means of transport. Hence, someone's existing experience and behaviour regarding the use of multiple means of transport during a trip is a significant predictor of their intentions to combine shared transport and the bus or tram during a trip. This effect is stronger than for the intention to use shared transport, where the b-value was smaller and the category of using a single mean of transport during a trip was not significant.

From the independent variables not included in Table 7, and thus not being a significant predictor to the dependent variable, education is considered to be interesting. From the first analysis, someone's level of education influences someone's intention to use shared transport during a trip. However, from this analysis it results that education does not have an influence if someone intents to use this shared transport together with the bus or tram during the same trip.

5. Discussion

In this section, the results will be put into perspective by discussing the implications of certain decisions made regarding the survey and the data analysis as well as the implications of the sample characteristics.

5.1. Implications of sample characteristics

The variables of age and education were both shown to affect people's intention to use shared transport. These are the variables that have shown a slightly different distribution among their categories when compared to the socio-demographic statistics of the municipality of The Hague and the neighbourhood surrounding Leyenburg. As both age and education were found to influence people's intention to use certain means of transport, the sample characteristics have implications on the study's result. An underrepresentation of younger age group has likely caused the intention to use shared transport to be lower on average in this study than it would be for the population of The Hague. On the contrary, the overrepresentation of highly educated people in this study's sample will have caused the intention to use shared transport to be higher for this sample than it will be in reality. Similar effects might be the case for people's level of digital skills based on the correlations found between digital skill and people's age and education.

The comparison of the public transport users of the sample with bus and tram users of HTM showed that the sample was underrepresented in younger public transport users. Hence, when interpreting results regarding frequent public transport users, similar cautions should be taken. This underrepresentation could have caused the percentage of public transport users who intend to use shared transport to be lower than it would in reality be for users of HTM's busses and trams. For the shared bicycle users of the study's sample, no implications are expected as only their gender differed significantly from the HTM's shared bicycle users and this variable is not found to influence people's intention to use any mean of transport.

Finally, a limitation of this study is its inability to sufficiently compare the sample with The Hague's population based on the percentage of people with a migrant background. This is caused by the fact that the variable of people's country of birth does not accurately reflect whether people have a migrant background. Hence, the study was not able to determine if people's migrant background affects people's level of digital skills and their intention to use the multimodal transport system. As Durand, Zijlstra, van Oort, Hoogendoorn-Lanser and Hoogendoorn (2021) noted a relation between ethnicity and digital skills, future research should try to better include respondent's migrant background by determining their parents' country of birth.

5.2. Consideration of case study and survey characteristics

This study provides an insight into the potential of a collective offer of existing public transport options with the included shared modalities and the characteristics of the potential users via the data collected with

Table 7
Parameter estimates of ordinal regression analysis with dependent variable: Intention to combine the use of shared transport with the bus or tram (N=421).

	b	Std. Error	Wald	Sig.	Exp(B)	95% CI for odds ratio Lower	Upper
Threshold							
[Intention to combine shared transport & bus/tram = disagree]	-2.685	1.399	3.685	0.055	0.068	0.005	1.018
[Intention to combine shared transport & bus/tram = neutral]	-1.290	1.393	0.858	0.354	0.275	0.019	4.059
Location							
Digital skill = level 0	-1.339	0.691	3.757	0.053	0.262	0.068	1.015
Digital skill = level 1	-0.711	0.324	4.820	0.028	0.491	0.258	0.935
Digital skill = level 2	-0.622	0.286	4.712	0.030	0.537	0.308	0.937
Digital skill = level 3	0a				1		
Experience with shared transport = No	-1.062	0.270	15.527	0.000	0.346	0.203	0.589
Experience with shared transport = Yes	0a				1		
TB - Ways of paying = not important	-1.310	0.430	9.267	0.002	0.270	0.114	0.642
TB - Ways of paying = a bit important	-0.508	0.417	1.484	0.223	0.602	0.261	1.385
TB - Ways of paying = fairly important	-0.417	0.389	1.149	0.284	0.659	0.308	1.410
TB - Ways of paying = important	-0.293	0.343	0.730	0.393	0.746	0.376	1.482
TB - Ways of paying = very important	0a				1		
TB - Opinion of others = not important	-1.242	0.595	4.349	0.037	0.289	0.091	0.921
TB - Opinion of others = a bit important	-0.973	0.636	2.341	0.126	0.378	0.110	1.305
TB - Opinion of others = fairly important	-1.185	0.648	3.345	0.067	0.306	0.087	1.075
TB - Opinion of others = important	-0.782	0.701	1.245	0.265	0.457	0.116	1.808
TB - Opinion of others = very important	0a				1		
Nr. of means of transport during trip = 1	-0.676	0.274	6.088	0.014	0.509	0.296	0.875
Nr. of means of transport during trip = 2	-0.998	0.339	8.652	0.003	0.369	0.189	0.718
Nr. of means of transport during trip = 3 or more	0a				1		
Age class = 18-25	1.615	0.528	9.375	0.002	5.030	1.774	14.264
Age class = 25-34	0.843	0.467	3.254	0.071	2.323	0.945	5.709
Age class = 35-44	0.607	0.489	1.537	0.215	1.834	0.705	4.775
Age class = 45-54	0.432	0.476	0.824	0.364	1.540	0.614	3.865
Age class = 55-64	0.759	0.445	2.907	0.088	2.136	0.907	5.028
Age class = 65 and older	0a				1		

Only the selection of (almost) significant variables are shown.
Link function: Logit.
a. This parameter is set to zero because it is redundant.

the survey. However, the sketched integration scenario used in the survey certainly affects the relationships with the intended use behaviour found in this study. Hence, some of the results will be put into perspective. First, the integration scenario proposed in the survey emphasises the digital integration for the shared means of transport and does not specifically mention the need to plan and pay trips with the bus or the tram via an app. Therefore, the relation between digital skills and the intention to use the bus or tram, which showed a weak to almost no prediction value, is not a sufficient reflection of constraints on accessibility for people with low levels of digital skill when digitalisation increases for bus and tram transport. Further research is needed to understand if low digital skills would limit someone to take a trip with public transport if planning and paying should be done via an app.

It is interesting that the variable of trip origin or destination (whether the HagaZiekenhuis or not) affects the intention to use the bus or tram. People travelling to the HagaZiekenhuis have a lower intention to use the bus or tram. From previous research, trip motive is seen to affect mode choice, however, this has not been evaluated in this study. Nevertheless, the significance of the HagaZiekenhuis as origin or destination would imply that it is useful to further investigate the relation of trip motive with the intention to use a multimodal transport system. Going to the hospital is quite a unique trip motive in itself and, as employees of the hospital were also invited to participate in the survey, the trip motive of work could also be an underlying contribution to this significant relationship.

Another possible limitation is the effect of the COVID-19 pandemic, the related restrictions, and people's change in travel behaviour on people's perception of future transport use and their current use of transportation. The year for which respondents indicated their travel behaviour was affected by COVID-19. Hence, the noted differences between current use and intended use behaviour of the multimodal transport system could theoretically be smaller for, for example, public transport as people are using public transport less during the pandemic. For the intended use behaviour, it is uncertain to what extent people have considered the pre-COVID-19 circumstances or one of the various situations seen during the COVID-19 pandemic. Depending on the circumstances at the time, COVID-19 might also affect the conversion of intended use behaviour to actual use behaviour when a multimodal transport system is implemented.

Regarding the factors affecting people's intention to use means of transport, the importance people assigned to most of the transport barriers was not found to have a significant prediction value. The original UTAUT models from which these transport barriers were constructed are commonly used on new but existing systems or services, whereas this study evaluates a possible future scenario that is not implemented. Hence, the lack of a relation between these transport barriers' importance and the intended use of the multimodal transport system should not lead to neglecting these constructs or UTAUT models in future research. Especially not as research on this topic evolves towards more pilot-based performance assessments.

5.3. Managerial implications

For transport providers, the case study of Leyenburg has shown that the intention to use the shared bicycle and shared motor scooter are higher than the intention to use the shared car. Similar user segments as those who intend to use shared transport are intended to combine shared and public transport. Hence, offering shared bicycles and shared motor scooters at a hub thus has a higher potential as this is a larger group with similar characteristics to those who want to combine these shared modalities with public transport. In addition, the intention to use public transport at the mobility hub is higher (64.8%) compared to the current use (57.2%) during trips to, from, or via Leyenburg. Following the analysis of the intended use behaviour, it is seen that there are significant differences in the factors affecting the intention to use shared transport or the bus or the tram. To target new users that intend to use shared transport, transport providers should consider an audience that is young and highly educated. The intention to combine the use of shared and public transport is affected by similar factors as the intention to use shared transport. This shows that as more of the potential shared transport users are captured, the group of people that wants to combine shared transport with public transport also grows. Hence, having these types of mobility hubs as recognizable places where shared transport modalities are placed such that an easy transition to public transport is possible, will facilitate the uptake of public transport. For further growth of shared modalities, the people who are older and less educated are an interesting group as they currently express a significantly lower intent to use shared mobility. Besides the consideration of digital skills, other barriers to using shared transport for these groups of people should be discovered. Regarding long-term transport policies, the people's intention to use the various means of transport supports policies related to the development of mobility hubs as a mean to promote the use of public transport.

Another managerial implication concerns the digitalization. The various levels of digital skill characterised in this paper can predict the intention of using shared transport. Helping to improve people's digital skills, especially, in the context of the transport domain, would therefore contribute to the improvement of the potential uptake of the shared modalities. In addition, it emphasises the impact of digitalisation in transport that has helped grow the interest in shared and multimodal transport on the intended use of potential user groups. For transport providers working on ways to integrate their own modalities, or potentially integrate modalities of different operators, it is recommended to consider the potential digital exclusion that can occur among existing users or potential new users. Offering different digital and non-digital options to plan and pay for trips would reduce the danger of digital exclusion. Involving the potential user in the development process of digital applications and mobility hubs could lead to a better understanding of how to deal with the various levels of digital skill. It could be useful to understand to what extent alternatives to application usage, such as dedicated machines/pillars at hubs for planning or paying, improve the intended use of transport for people with lower levels of digital skill. The latter suggestions to avoid digital exclusion also apply to future policies in this transport domain. Hence, long-term policies regarding the development of MaaS should include considerations of accessibility for people with low levels of digital skills to ensure that the benefits are more equally shared among different potential user segments. As stated for transport providers, other barriers to using shared transport and mobility hubs should be discovered in time as specific measures could be included in transport policies to ensure the accessibility of these types of transport.

6. Conclusion

In this paper, the intention to use shared and public means of transportation in a multimodal transport network was studied by means of a survey within the case study of Leyenburg, The Hague (N=710). User characteristics, among which digital skills, and transport-related characteristics were evaluated for their potential influence on people's intention to use shared transport and the bus and tram when they are physically integrated at the existing public transport stop.

When shared transport is offered at the existing public transport stop Leyenburg, 15.0% of the respondents intend to use the shared bicycle, 15.7% intend to use the shared motor scooter, and only 10.8% intend to use the shared car. Of the 131 people who intend to use any of the shared means of transport, 72 people have not used any of them in the past year. Capturing the latter group would result in an increase in shared transport usage. Of the 343 people who have no intention to use shared transport only 42 have used shared transport in the past year. From the survey, 64.8% of the respondents intend to use the bus or tram during their trip when shared transport is offered at the stop Leyenburg. This is higher than the 57.2% of people who expressed a current use of the bus, tram, or metro during their trip, indicating a potential increase in the number of bus or tram users. The results show that around a quarter of the people who do not intend to use the bus and tram when integrated with shared transport are currently using the bus, tram, or metro during their trip. However, from the larger group of people who intend to use the bus or tram (64.8%), around a quarter are currently not using it during their trip.

The study has determined several factors which influence the intended use behaviour of shared and public transport when they are integrated at a mobility hub. This supports the characterisation of people that are currently already a potential user of the different means of transport at the mobility hub and it highlights the characteristics of the people that currently have no intention to use certain means of transport. The intention to use shared transport is found to be higher for people with higher levels of digital skill, prior shared transport experience, who are younger, highly educated and those who used multiple means of transport during their trip. Largely the same characteristics are related to the intention to combine the use of shared and public transport, with only the influence of people's education not being significant for this intention. Nevertheless, in accordance with past literature, people's age and education are found to correlate to people's level of digital skills and hence education cannot be neglected as a relevant user characteristic to determine this intention. Finally, one category of the transport barrier of having multiple ways to pay for transport was significantly related to the intention to combine shared and public transport. This might imply that having multiple ways to pay for travelling with multiple of these modalities supports its potential uptake. The other transport barriers are not found to be related to people's intention to use any of the types of transport. The intention to use the bus or tram is found to be mainly related to current transport usage and trip-specific factors. The intention is higher for both people who used public transport more than once a week and people who used cars less than once a week in the past year. In addition, people who performed the trips to, from or via Leyenburg less frequent and those who did not travel to the HagaZiekenhuis had a higher intention to use the bus or tram.

With these results, this paper has contributed to the understanding of the intended use behaviour of multimodal transport systems for different user segments. Besides these user needs, the potential of integrated transport systems at hubs could also be considered in future research by studying the impact of adding or removing means of transport at a hub on the actual usage of the different transport types. This would also further contribute to transport providers' considerations regarding the benefits and costs of mobility hubs. Finally, with the use of pilot studies, future research should attempt to evaluate the actual use behaviour of both public and shared transport when these are integrated. Comparing the actual use of the means of transport with the results of this study might help understand what factors are key in the maximization of the potential uptake of transport at a mobility hub.

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Lessons learned from setting up a demonstration site with autonomous shuttle operation – based on experience from three cities in Europe

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ABSTRACT

The interest in operating autonomous vehicles is growing and several demonstration sites using automated shuttles have been established all over the world. Major work is involved in setting up an automated shuttle operation that involves more than identifying the relevant site, including adhering to current regulations and obtaining approval, as well as a considerable amount of preparation and commissioning required at the site. The shuttle must pass relevant national vehicle regulations, and the operation site has to undergo a site assessment. This paper is based on lessons learned achieved from setting up automated shuttle operations in three different areas in Europe: Brussel (Belgium), Linköping (Sweden) and Turin (Italy). The focus is on the practical aspects of operation. Through the experience we have gained of setting up demonstration sites at three locations in Europe, we have identified the need to summarise the lessons learned from preparing AV shuttle operation sites in order to facilitate the implementation of other operation sites. Hence, this paper aims to consolidate lessons learned during preparation and implementation of automated shuttle operations in near urban environments and to identify the path toward future implementation The three sites operate different brands and number of shuttles, different types of infrastructure and varying local conditions. The focus here was on generic lessons learned and not to understand differences between brands and operators. It is clear that further development of the AV shuttles is vital to ensure that they operate smoothly in complex traffic situations considering lane and road width, shared spaces, snow, dust, rain, leaves, birds, etc. Adapting the road infrastructure to enable the shuttles to run in the autonomous mode should be avoided, instead the shuttle development should prioritise fitting into the existing traffic environment and eco system. Mitigation areas have been identified covering: road infrastructure, weather dependant operation, season dependent operation, improvement of localisation, digital infrastructure, design and working conditions, and citizens' user experience.

1. Introduction

The interest in operating autonomous vehicles is growing and several demonstration sites using automated shuttles have been established all over the world (Iclodean et al., 2020). The authors foresee a positive impact of these vehicles on public transportation once they have been rolled out large-scale. To date, the driving force for demonstration and operation with automated shuttles is primarily technical and innovation based (Skogsmo & Anund, 2021). The demand for an open, socially constructed process for automated vehicle (AV) development has become apparent and research must not only address the technical, but also the societal dimension of transitioning to AVs (Milakis & Müller, 2021). Oldbury and Isaksson (2021) point to a need to develop a more clearly articulated policy and planning agenda which clarifies the long-term public vision for automation in infrastructure and transport planning. Regarding governance arrangements around smart mobility solutions a tendency towards a transfer of roles has been observed, whereby bus operators will gain a new and influential role in smart mobility in public transport. This has created a need to think critically about the ways in which roles, relations and responsibilities may be shaped and reshaped

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in collaborative governance. Currently, the main findings about safety operators and barriers to autonomous vehicle adoption are synthesised in two recent literature reviews (Alawadhi et al., 2020; Bezai et al., 2021).

An issue often raised in relation to automation, is that users, the passengers as well as the safety operators, are generally not kept in the loop during the design and development of automated solutions in general (Anund et al., 2019). Studies often focus on user feedback of an existing service. A study of the user perspective in general in the Baltic Sea area showed that across all cities, the feedback from passengers is remarkably positive with regard to personal security and safety onboard (Bellone et al., 2021). In addition, the importance of safety operators was highly rated.

Despite the clear statement in the UN Sustainable Development Goal 11.2 (UN, 2021) about providing access to safe, affordable, accessible and sustainable transport systems the aim of automated operations is, to the best of our knowledge, in general not being developed as a mobility solution accessible and available for all. It can be seen in the literature that automated shuttle usage has been studied in relation to age, gender and income, but rarely in relation to user groups with special needs Zubin et al. (2020). Instead, Zubin et al. (2020) concludes that research gaps are found in infrastructure and network design as well as the topic of how to remove human personnel on automated shuttles. In a paper by Nesheli et al. (2021) more than 25 ongoing operations were reviewed and lessons learned were summarised. The paper was however not dealing with the operators' own perspective and insight into planning and solving daily issues to keep them up and running. Three key dimensions were focused looking at deployment locations, service characteristics of the shuttles, and stakeholders in 19 operations on going in US (Haque & Brakewood, 2020). The paper focus is on where they are up and running and the type of service they provide and what stakeholders that was involved or responsible for the operation. Lessons learned with focus on a stable operation it-self was not the main focus.

The most used classification system for automated driving that describes the role of the Human and the System in various levels of automation is the International Standard J3016. It covers the taxonomy and definition of terms related to Vehicle Automated Driving Systems ((SAE), 2016), and defines six steps from 0 (no driving automation) to 5 (full driving automation). Automated shuttles are generally on the SAE Level 4, which requires the presence of a physical legal responsible safety operator in charge of traffic safety like in normal vehicles, although the AVs mostly operate by themselves. In this paper, focus is on the SAE Level 4.

Setting up an automated shuttle operation is a major work that involves more than just identifying the relevant site. The set up also includes adhering to current regulations and obtaining approval, as well as a considerable amount of preparation and commissioning required at the site. The shuttle must pass relevant national vehicle regulations, and the pre-operation site must undergo a site assessment i.e., fulfil various criteria for the selection of a site. We have gained significant experience from setting up demonstration sites at three locations in Europe, and this paper summarises the lessons learned from preparing AV shuttle operation sites, to facilitate the implementation of other operation sites.

2. Aim

This paper aims to consolidate lessons learned during preparation and implementation of automated shuttle operations in near urban environments and to identify the path toward future implementation. The lessons learned were gained from setting up automated shuttle operations in three different areas in Europe: Brussel (Belgium), Linköping (Sweden) and Turin (Italy).

3. Background

The text below presents a description of the three demonstration sites. For the specific selection of driving site each environmental context undergoes a site assessment, carried out by the OEMs forming criteria and guidelines for a successful AV operation implementation. Thus, it is up to the client to either neglect or accept the necessary infrastructure requirements. An overview of the operational data of the different demonstration sites can be seen in Table 1.

3.1. Brussels

In 2018, Brussels Intercommunal Transport Company (French: Société des Transports Intercommunaux de Bruxelles (STIB)) decided to carry out a first test program of autonomous shuttles based on a one-year rental contract comprising two shuttles. These shuttles were deployed between 2019 and 2020 through a step-by-step approach based on 3 different consecutive demonstration sites in Brussels of increasing difficulty, each one for a period of 4 months: 1 month for the setup and tests phase, and 3 months of commercial service open to the public. During 2020, passenger operation has been limited due to the Covid-19 pandemic. In total a team of 18 trained safety operators secured the two shuttles on the three driving sites. The layout of the three areas differs as per the characteristics outlined below, see Fig. 1.

The setup phase on the first site started at the end of May 2019 in the Woluwe Public Park in Brussels. This first site consists of a park free of car traffic but with asphalted roads of 8 m width. The shuttles were used in operation during the summer season 2019 and the firsts objectives were to learn more about shuttle technology, train our staff in a relatively simple context, and invite the public to experience an innovative mobility service, in a friendly and relaxing context. There were 2 different routes with 5 fixed stops, for a total of approximately 1.7 km with a speed limited to 12 km/h. The shuttle service was free of charge and running from Friday to Sunday between June 2019 and September 2019 serving 5963 passengers and driving 1902 km in autonomous mode.

The second site, was in Solvay Campus in the north of Brussels. It is a private site with limited access, offering the advantage of allowing testing of shuttles on roads also used by cars and trucks. The site is more complex than the Woluwe Park in terms of routes that can be taken. The objectives of the test at Solvay were to refine the understanding of the technology of the two rented shuttles, train the staff in a context more like a real urban environment, launch and test an "on-demand" service and test the viability of the shuttles in a business environment. There were no fixed routes but 9 fixed stops. The shuttles selected the shortest way to go to the destination entered by the safety driver. The total distance being available for the 2 shuttles was approximately 1.7 km with a speed limited to 16 km/h. The shuttle service was free of charge, and running from Monday to Friday, from 9 am to 5 pm, between October 2019 and February 2020 serving 1143 passengers and driving 1200 km in autonomous mode.

The third chosen site was at the Brugmann Hospital in Brussels. It is a private site with public access, offering the advantage of roads shared with cars and trucks as well as bikes and pedestrians. The site is more complex than the two previous in terms of the routes that can be taken by the shuttles and of sharing the road space with many other users. The objectives of the test at Brugmann Hospital were to understand the flexibility of the shuttles in a complex city-like environment with unpredicted obstacles such as illegally parked cars, interaction with cyclists and heavy goods vehicles (HGVs), testing the shuttle service to ascertain if it would be suitable as a permanent use case and total cost involved, and test the viability of the shuttles in a hospital environment, with lots of people with reduced mobility capacities that may be in need of such a service. Here again, there were no fixed routes, but 10 fixed stops and the shuttles selected the shortest way to go to the destination entered by the safety driver. The total distance being set up and available for the 2 shuttles was approximately 1.2 km with a speed limited to 16 km/h. The shuttle service was supposed to be free of charge and running from March 2020 until June 2020. Unfortunately, the Covid situation made it impossible to operate inside the hospital. The test was cancelled when

Table 1
Demonstration site data information.

	Brussels **Woluwe**	**Solvay**	**Brugmann**	Linköping **Campus Valla**	Turin **Piedmont Capital**
Starting date	2019–06–20	2019–10–28	2020–03–13	2020–03–10	2020–02–01
Closing date	2019–09–20	2020–02–14	2020–03–20	Preliminary end 2023	2020–07–31
Numbers of AV	2			2	1
AV models	2 EasyMile EZ10 Gen2			1 EasyMile EZ10 Gen2 1 Navya DL4 Arma	1 Olli
Safety drivers	18			8	10
Lengths of the driving track	1700 m	1600 m	1200 m	2100 m	700 m
Max AV operational speed	12 km/h	16 km/h	16 km/h	16 km/h	33 km/h
Min AV operational speed	5 km/h	5 km/h	5 km/h	6 km/h	10 km/h
Number of AV bus stations	5	9	10	8	6
Shared connection to PT	1	1	1	3	0
On Demand	No	Yes	No	No	Yes
Free of charge	Yes	Yes	Yes	Yes	Yes
Numbers of passengers	5293	1143	0	2263	150
Driven milage	1902 km	1200 km	20 km	6776 km	500 km

Fig. 1. Operating maps of the Woluwe Park (1), the Solvay site (on demand) (2) and the Brugmann Hospital (3).

the setup and test phase were just finished, the day before starting the public service.

3.2. Linköping

In 2019, work began to establish a demonstration area with two automated shuttles in Linköping. The city is located ca. 200 km south of Stockholm and is one of Sweden's fastest growing cities. The population of 157,000 at the beginning of 2021 is continuously increasing. Linköping is currently the fifth largest city in Sweden and is part of the expansive East Sweden Business Region. The demonstration site in Linköping is located within the Campus Valla area at Linköping University, with more than 27,000 students, next to Linköping Science Park. The demonstration site is a collaboration between Swedish National Road and Transport Research Institute (VTI), Linköping University, Transdev, Östgötatrafiken, Rise, Linköping Municipality, Linköping Science Park and Akademiska Hus. Two multi-brand shuttles operate within the Campus Valla area, and a third AV is in the planning stage. At the VTI depot, a total of eight safety operators manages the daily operation. The route has eight fixed bus stops, it is approximately 2.1 km, and takes around 15 min to complete. The speed limit on the route ranges between 6 and 16 km/h. The shuttle service, which is free of charge, has been running between March 2020 and June 2021 serving 2263 passengers, a limited number of passengers due to Covid-19. The aim of establishing the demonstration site in Linköping is to contribute to a better travel experience for a wide range of users and to assess the cooperation between involved stakeholders, including multiple OEMs. Another objective is to provide a robust, safe, and reliable operation for so-called first/last mile service. The operation in Linköping have also been extended to cover a recently developed residential area nearby, called Vallastaden. The extended route will provide a means of transport for the first and last mile to PT trunk lines close to a school and a residential home for elderly. It will be supported by an adaptive Mobility as a Service (MaaS) solution with the end users in mind. The extension, which is part of the EU funded SHOW project (https://show-project.eu/), aims to evaluate the effect AV shuttles has for the independence of the elderly and school children.

3.3. Turin

Bringing an automated shuttle to the Piedmont capital, the first deployment of its kind in Italy, is part of the whole strategy of Turin Municipality. The city is highly committed to initiating the penetration of autonomous mobility, facilitating the process and fostering cooperation between private enterprises, local facilities, academia and civil society. The vehicle involved in the Turin demonstration is the Local Motors Olli shuttle, a self-driving (autonomy Level 4), electric, 3D-printed shuttle, developed for urban mobility and designed with particular attention to accessibility and sustainability. During the demonstration, the shuttle provided transport services within the International Training Centre of the International Labour Organization (ITC-ILO) campus. ITC-ILO is an advanced technical and vocational training institution located in the heart of a riverside park in Turin. The Centre is dedicated to the pursuit of learning and training to reach the UN Sustainable Development Goal 8: "Promote inclusive and sustainable economic growth, employment, and decent work for all". Entrance to the campus is open only to employees, students and booked visitors. Still, the campus is an area characterised by traffic mixed with pedestrians, bicycles and motorised vehicles, (i.e., employees are allowed to enter in their own car).

The demonstration period took place between February and July 2020. The shuttle ran along a 700 metre route at an operational speed between 10 and 33 km/h. The users of the transport service, which was free of charge, could access the shuttle by standing at one of the six stops along the route, without having to book the service. In total, about 150 users boarded the shuttle during the test programme: about 80 campus employees, in addition to about 70 guests and other participants.

This demonstration is a forerunner for the actual experimentation that will be carried out in Turin in 2021–2022 within the H2020 SHOW European project (https://show-project.eu/), where two autonomous Demand Responsive Transport (DRT) shuttles will provide flexible public transport services to special categories of users in a real traffic environment.

4. Method

Preparing and implementing operation with autonomous shuttles in cities is something new and a rather disruptive business that, if it works, has the potential for market changing the area of mobility and hopefully replacing the highly car dependant transport system to a more shared mobility solution. This paper aims to identify the path toward future implementation and to provide a good understanding of common limitations. The work is explorative, identifying pros and cons with such an innovative operation. The paper describes, in a structured way, similar experiences from sites setting up demonstrations, formulated as lessons learned. This can be used to identify important areas for improvements to support future AV operations and to avoid repeating the same mistakes at other coming sites.

The method is based on a collection of experience from 5 sites in 3 countries, here seen as Cases. Each site has identified their lessons learned and the experiences that are common at all sites are described below.

5. Lessons learned

In general, a substantial amount of planning and preparation is required before realisation of an AV shuttle operation at a new site. Tasks include setting up stakeholder groups, applying for grants or budgeting for running the operations/demonstrations, selection of route or area to operate in, identifying use cases, benchmarking and negotiating the type of AV shuttles to use, applying for approval for operating, information and communication with users, etc. It is important to have a good understanding of the lead time and requirements for approval when establishing a new site, a process that differs depending on national regulations and legislations. Based on lessons learned, mitigation areas have been identified covering: other road users and road infrastructure, weather dependant operation, season dependant operation, improvement of localisation, digital infrastructure, design and working conditions, and citizens' user experience, each serving as headings in the text below. The sites operate different brands and number of shuttles, different types of infrastructure and varying local conditions. The focus here is, however, rather on generic lessons learned with the aim of facilitating start up of similar operations elsewhere and to avoid spending unnecessary time and resources on previously recognised issues.

5.1. Shuttle interactions with road users and infrastructure

5.1.1. Interactions in relation to those outside the shuttles

During AV shuttle operations, it is important to consider passengers as well as other traffic participants and road users outside the shuttle. It is essential to ensure that the AV shuttles interact safely and smoothly with vulnerable road users, as well as drivers of other vehicles. Furthermore, avoiding misunderstandings of interactions and intentions is vital. Based on the experience from the three sites involved in this paper it can be concluded that, up to now, standards for how to handle interactions safely and clearly do not exist. Different shuttle OEMs use different types of sound, activation of sound, lights, etc., that do not support a clear understanding of the shuttle's intentions and safe interaction with other road users. This situation becomes very demanding for visually impaired users, since it is not possible to ascertain if the sound is addressing you or someone else, whether it is a warning or information, etc.

The shuttles used in our sites are equipped with light detection and ranging (lidar) sensors for navigation, or rather localization, and obstacle detection. The technology of the lidar sensors and its computational power reduces the reaction time and braking distance compared to a human driven vehicle. This can have consequences for those travelling inside the shuttles, where hard braking can cause abrupt movements of the occupants and the safety operator. In addition, the lidar sensors are not always compatible with existing safety road constructions such as speed bumps, elevated crossings, etc., with the most common issue being when the lidar sensors identify such safety measures as objects and initiate a (hard) braking event.

Driven by requirements to obtain permits, where risks of interaction with other road users play an important role, the shuttles typically prioritize external safety over safety considerations for those inside the shuttle (internal safety). Research is ongoing about how to better balance deceleration with maintained safety from all these perspectives.

Improvements in sensor technology used to detect obstacles (cameras, lidars, radars) make it possible to better identify and classify objects in different categories. Based on this classification, shuttle providers tend to reduce the number of hard braking occurrences. A better understanding of the nature of the obstacles in the vicinity of the shuttle brings different opportunities for improvements. For obstacles that appear to be stationary, it would be possible to overtake some of those obstacles standing in the way of the shuttle. Some shuttles stop and analyse different alternatives before passing by any obstacles and returning to its route; others overtake without ever stopping. In some cases, the shuttle may request permission of an operator (locally or at distance) to allow the overtaking procedure. Detection and classification of moving objects in the vicinity of the shuttle, such as pedestrians and other road users, are also in the process of enhancement, which facilitates prediction of the future position of a detected object based on its current position and speed. It is then easier to proactively reduce the speed of the shuttle in specific cases and thus reduce the hard braking.

Recommendations: In the wake of the realization of these improvements we recommend injury mitigation actions in terms of seat belt usage for the protection of shuttle riders. In one site the shuttles have been equipped with a rear sign asking trailing vehicles to keep a safe distance to the shuttle.

5.1.2. Overtaking situations

The risk in circumstances when other vehicles are travelling in the same direction behind a shuttle is that the shuttle initiates a hard braking event in overtaking situations that occur too close to the shuttle. The problem arises when the lateral and/or frontal distances are too close to other vehicles during the overtaking event, see Fig. 5. If the shuttle deems the distance clearance too short to be safe, the shuttle will slow down or brake to increase its safety distance, see Fig. 3. In certain circumstances, this type of situation may lead to secondary problems for the vehicle behind the shuttle, increasing the risk that the driver in the car behind does not understand the reason for the shuttle reducing its speed. Hence, the driver of the vehicle behind might be encouraged to overtake the shuttle, which may cause additional interference with the shuttle's safety clearance distance, and thus initiate an abrupt braking event in the shuttle. Figs. 2, 4

Recommendations: Overtaking the shuttle may lead to safety risks. Ideally, vehicles travelling in the same direction as a shuttle should not be encouraged to overtake it, although overtaking may occur if the lane or road is wide. On the other hand, if overtaking is indeed taking place the road should be wide enough to allow other vehicles to keep a sufficient lateral distance to the shuttle.

5.1.3. Oncoming traffic and other road users

Vehicles travelling in the opposite direction of the shuttle may cause problems. This can occur when the oncoming vehicle travels at high speed and the lateral crossing distance is not long enough according to the shuttle, see Fig. 5. The size of the "safety bubble" of the shuttle depends on its speed. If the shuttle moves faster, the size of the bubble will increase and objects on the roadside and/or obstacles inside the bubble will cause the shuttle to slow down or even stop. Those obstacles can be of different types such as moving obstacles, for example, pedestrians, bicycles or vehicles, or fixed obstacles such as an illegally parked car

Fig. 2. Overview of the Brussel areas; the Woluwe Park (2 km) (1), the Solvay (5 km) (2) and the Brugmann Hospital (2 km) (3).

Fig. 3. Description of the Linköping demonstration site.

Fig. 4. Location of the Turin demonstration site.

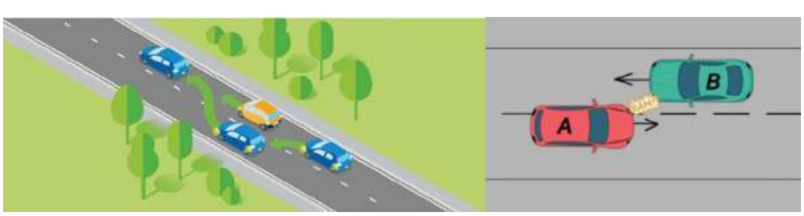

Fig. 5. Overtaking situation[1] and Oncoming situation.[2]

or a parked car with the tyres turned that would be detected as an unforeseen obstacle by the shuttle. Turning left is complicated in countries with right hand driving, as the shuttle cannot act intuitively if another vehicle is coming on its right. Hence, traffic lights, or safe stops, are required to secure any crossroad the shuttle would need to turn left or go straight forward at. Turning right is easier, but only if right priority is applicable at the crossroad. The opposite problems apply in left-driving countries.

Recommendations: Based on lessons learned, with regard to recommendations in relation to road infrastructure, it would generally be best to avoid adapting the road infrastructure for running the shuttle. Preferably, shuttles should be developed to handle existing road infrastructure. However, this is currently not the case, and it is thus recommended to adapt the road infrastructure, also taking speed into consideration, to avoid overtaking by other vehicles driving behind the shuttles as well as to allow a shorter distance between vehicles in the oppo-

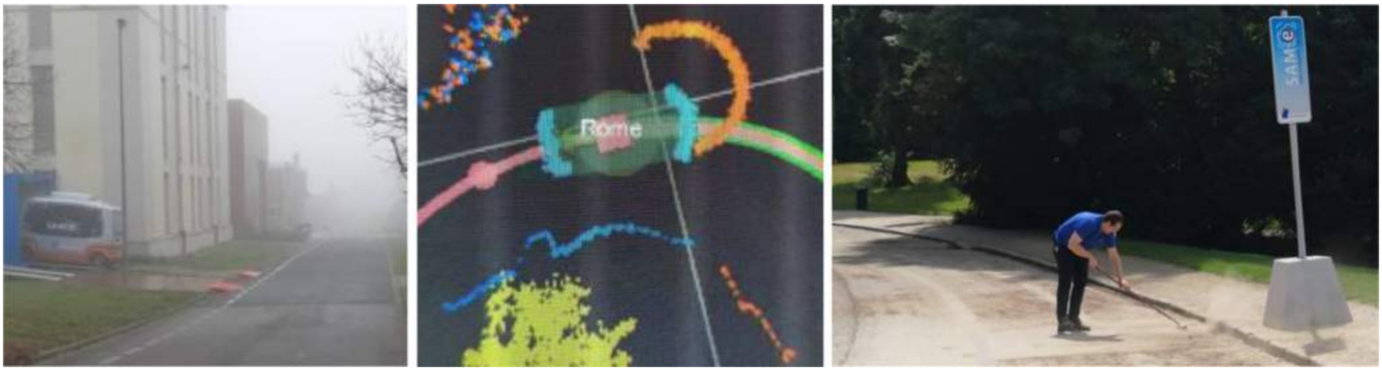

Fig. 6. Being stopped by fog detected as a wall by the LIDAR technology (left). The orange curve is the fog as detected by the front left lidar of the shuttle (middle). The blue curves are the fog as detected by the central front and rear lidars. Removal of dust from the road that triggers emergency stop events(right).

site direction. In addition, filtering functions to safeguard shuttles are not in opposition to the aim of the road design is required. Furthermore, feedback from safety operators, monitoring any unexcepted or hazardous situations, improvements on the spot, etc., must be taken into consideration.

5.2. Weather dependant operation

Obstacles identified by the lidar sensors, such as grass, tree branches or flowers moving in the wind, cause problems for the shuttles. The shuttles will recognise such obstructions as moving obstacles which makes the shuttles slow down, an issue that is overlooked during the mapping process.

The lidar technology fitted on some shuttles detect water, dust and leaves in the air, increasing the risk of detection of unforeseen obstacles appearing suddenly and instigating hard braking events. Below is an outline of some common issues encountered at the sites described in this paper:

Rain is not detected by the lidar until the drops reach a certain size, that will be identified as many small obstacles. The shuttle then starts to “lag” (random speed reduction) and finally stops. Fog is detected by lidar sensors as actual walls surrounding the shuttle and it will therefore come to a halt as it perceives fog as an object too close in its field of view, see Fig. 6.

Dust on dry and windy roads is problematic as dust might be perceived similar to fog and in certain circumstances even more critical than fog. As shuttles driven over a certain speed can whip dust up by themselves, the lidar technology fitted on the shuttles will suddenly see a wall of dust appearing and trigger an emergency stop (hard brake) event. If the shuttle is not “taught” to recognise this particular obstacle, each journey it will continue to stop on the same dusty area on the road, until the dust is removed.

Recommendations in relation to weather conditions, based on lessons learned:

Using radar (sound based, not light based) technology to complement the lidar might be a solution to mitigate weather dependant braking and stopping issues. The shuttle should then be able to recognise various weather conditions and decide to utilise the radar instead of the lidar in case of fog, for instance. Another solution might be to use Artificial Intelligence (AI) and developing smart filtering functions and algorithms that learn to discern what to act on and what to ignore. Solutions using AI training looks promising to avoid future emergency stopping events due to temporary obstacles.

5.3. Seasonal dependant operation

Autonomous shuttles use different systems for their precise positioning on the pre-programmed maps. Global Navigation Satellite Systems (GNSS) and lidars are two of these systems that are sensitive to their surroundings. Growing grass and trees have the potential to cause problems, hence mitigation strategies should be implemented in green areas on the verge of the roads. Should long grass moving in the wind appear in the safety bubble of the shuttle, the shuttle will slow down or even stop completely The distance between the lawn and a driving shuttle should be far enough or else the grass must be mowed on a regular basis to avoid being detected by the lidar. The same is true for all kinds of vegetation that can enter into the safety bubble of the shuttle or reduce the visibility of the lidar. Similarly, objects such as plastic bags, birds, etc., can also instigate an abrupt braking event. It has been difficult to find a suitable solution for birds and other animals, therefore it would be beneficial in future filtering to integrate functions based on gained experience. An abundance of trees covering the sky above the roads used by the shuttles would require trimming or else speed reduction must be accepted. Although it is easy to understand that GNSS signal coverage is reduced in tunnels and underground, it might not be obvious that roadside trees have a similar effect, reducing the capacity of location precision and consequently affecting the speed of a shuttle. Keeping the branches trimmed is not only a budget issue, it also affects the landscaping of cities dependant on trees as well as the risk of damaging the trees.

Snow is another barrier for smooth operation. Besides snowflakes being identified as obstacles, like dust and leaves, snowbanks are also detected by lidar technology as fixed objects, see Fig. 7. To avoid triggering hard braking events, this issue may require further maintenance to move the banks further off the lane.

Recommendations: Rather than continuously clearing the environment from moderate seasonal dependant issues it is recommended to further develop the shuttles. Furthermore, it would be preferrable to work towards a solution that can ‘teach’ shuttles not only to identify that an object is ahead, but also what the object is and whether it is necessary to act on it or carry on. To this end, AI might be a powerful tool to be incorporated into shuttles.

5.4. Improvement of localisation capacity

The shuttles must be certain of their precise position at any moment in real time. For that purpose, different technologies are simultaneously used to keep to a satisfactory level of precision:

- GNSS, depends on satellite coverage, and is improved using Real Time Kinematic (RTK)
- RTK positioning depends on the data connection availability (4 G or higher)
- Odometry to extrapolate the present position based on last known position
- Lidar sensors, that compare the position of fixed objects in sight with their recorded positions on the registered mapping of the site.

Fig. 7. Snowbanks causing stops.

Fig. 8. Signs to support the lidars for orientation.

Lidar sensors are used to geolocate the shuttles. To compare its location with the map as well as detect obstacles in real time, a lidar sensor must always be able to distinguish certain fixed points on the shuttle route. As it is stationary, a building is a suitable geographical reference point, while trees are less appropriate since they move in the wind and low vegetation grows with time. For example, a specific environment such as a desert or a forest can render the lidar location technical tool unusable, as there are no permanent reference points. To reinforce the location and to guarantee safe operation, some shuttle brands require detection of visual aids such as physical signs or flat panels by the lidar sensors for additional physical reference points. For the shuttles to detect the signs, the covering area is required to be large (1 × 1.5 m) and preferably made of a material that is not reflective or in an absorbent colour, see Fig. 8. As such signs are not always visibly attractive, some countries require a building permit for signs displaying information. Therefore, installation of physical signs should be avoided or only installed if necessary in future operations.

Recommendations: The most promising solution is to further develop the localisation functionality rather than adjusting the infrastructure to make it suitable for AV shuttles. Although common for obstacle detection, shuttle manufacturers are less likely to use lidars for localisation purposes. The issues caused by lidar based localisation systems should soon be eliminated by the progress in GNSS + RTK and odometry systems combined with the use of cameras. Our recommendation is to double check if physical signs are necessary before installation.

5.5. Digital infrastructure

If on the one hand mechanical components of an automated shuttle are quite simple, autonomous driving, on the other hand, requires continuous contact with remote systems and considerable processing power onboard the vehicle. All the elements of this type of ‘travelling ICT system’ and their smooth operation to govern a self-propelled vehicle is sometimes critical: the future of digitalisation is evolving and AV shuttles are a part of and depends on the development of these systems. The performance of the shuttle operation can be seen in real time on a heatmap running on a screen inside the shuttle. However, it is not possible to see the reason for malfunction of operation to identify why a shuttle has stopped, which would have been very useful for troubleshooting. In future, it would be of great importance to receive feedback from the system about what has happened and why a certain decision was made. The unwillingness of OEMs to share their application programming interface (API) is also producing some extra work, since most customers need to evaluate the shuttles’ performance and hence require data of a rather high resolution, to be able to measure and calculate basic Key Performance Indicators (KPIs) such as acceleration, deceleration, etc.

Recommendations: To support and encourage future development, open APIs is something to recommend, this is also in line with the trends of innovation development in general.

5.6. Safety operators’ working conditions

Hard braking is causing problems for safety operators, resulting in safety operators having been injured at two sites. The OEMs do not share information about the reason behind an external hard braking event, which is problematic for developing and applying mitigation strategies. Future development of maps displaying shuttle routes should also highlight any reasons for en route hard braking events and of course use learning algorithms to avoid similar stops in the future. In order to prepare safety operators for hard braking events, there is also the potential of informing the safety operators that a stop is imminent. It might also be useful to incorporate a solution to support safety operators so that they do not to fall during braking events, especially when the control unit is in the hands of the operator who therefore is unable to hold on to something in case of a braking event. For this purpose, one of the sites has equipped shuttles with an extendable safety arm that should make the working conditions more stable for the operators, see Fig. 9.

The safety operator on the shuttle is responsible for the operation as if they were driving a conventional city bus. Their tasks have very little to do with that of a traditional driver. Apart from a certain aptitude for manual driving using a joystick instead of a steering wheel, the vehicle is mechanically ‘simple’. The real skills, on the other hand, are of IT nature, linked to start-up procedures, continuous verification of the alignment of various processing and telecommunications systems, restart procedures in the event of unexpected events and data backup at the end of service. In terms of future work, this aspect is a concrete example of how autonomous technology can require greater professionalism of employee profiles without necessarily having a negative impact on employment. The driving task in a shuttle is more monotonous and the risk of driver fatigue is a fact. Another difference compared to driving a normal bus is inattention due to involvement with the passengers. A further lesson learned is that the behaviour of shuttle passengers is a bit different to travelling on a conventional bus, since the shuttle compartment is different, providing more space for other activities. The role of the operator is then also to make sure that all passengers, especially those with special needs, the elderly or children, are seated.

Some OEMs are now improving safety and comfort for onboard operators. Even if this issue would be eradicated once safety operators are not required in the future the experienced imbalance between internal and external safety also poses the question of how mature the shuttles are for passenger travelling without using seat belts. During operation, safety operators must pay attention not only to the external traffic situation but also internally to the graphic user interface (GUI). This is where vehicle specific interactions take place and where the driver confirms yields, checks vehicle status and communicates in general with the shuttle. Sometimes this can be demanding, especially if the operator is not a native English speaker, since the GUI is not configurable in any other language than English. There is a risk of failure in case the time available for action is limited. Also, the size of the control

Fig. 9. Safety arm to support safety operators during ride, developed by VTI, Sweden.

unit and the lack of somewhere to secure it when not in use, is not in line with good working conditions. Here the situation requires operators to keep track of the road, traffic safety and simultaneously care for passengers.

Recommendations*:* Working conditions for safety operators are taken very seriously and to date there is no clear timeline for when safety operators will be able to operate from a control tower, for example. Meanwhile, to guarantee a safe and fair working environment it is clear that the need for improving working conditions for safety operators is still a priority. This includes keeping the safety operator safe during braking events, a place to store the hand control, space to keep personal belongings (lunch, coat, etc.), a seat to rest on and measures to avoid slippery floors.

5.7. Passengers' experience, comfort, and safety

The interior design varies between shuttles. The design of the seats, especially when wooden seats are used, is not providing optimal friction conditions. One lesson learned is that the combination of no seat belt and wooden seats increases the risk of falling off the seat in hard braking events for users in clothes made of certain types of fabric. The recommendation is to provide seat belts on seats facing forward and if possible upholstered seats, until hard braking events can be avoided. It has also been noted that there are indications that citizens in urban environments, rarely travelling in cars, are not very familiar with seat belts. Hence it might be important to inform and educate passengers of the reason for wearing seat belts and how they should be worn.

Certain groups of citizens require different solutions to be able to use the shuttles safely and reliably, see Fig. 10. Blind persons, for instance, must be able to predict the shuttle's paths and actions, which is difficult at this point since the external and internal sounds and the activation of warning sounds are not generic. Different brands use different sounds, both with regard to the actual sound and when to use it (Pelikan, 2021). This is an area that needs further development. The role of the safety operator also looks different for groups with special needs. For example, the shuttles have not been fitted with exit buttons, and to date a generic way to inform where you are and where to get on or off has not been implemented. This needs further development to support safe and independent mobility, especially for on-demand solutions.

Due to Covid-19 it has been difficult to collect users' views on using the shuttles at the sites involved in this paper. A survey was undertaken at one of the sites, focusing on user acceptance of autonomous mobility (Caroleo et al., 2021). According to the survey results, the general experience of people who had travelled on the autonomous shuttle was positive (average score: 4.3 on 5) and they expressed a willingness to try such a service in real traffic conditions (87.5%). In general, the attitude towards autonomous driving is rather positive: people with no or few concerns prevail, however there is still a considerable share having at least some concerns. It seems that the travelers are open to the technology, as the majority (75%) believes that it will be a part of our daily lives in the future. The main concerns involve safety of vulnerable road

Fig. 10. Entering and exiting must be adapted to the users of special needs.

users and reliability of the technology. Due to these issues, the majority believes that a supervisor should always be available inside the vehicle, either in person or via immediate audio-video connection. Other frequently mentioned fears are the possibility of job losses due to automation and an increase in public transport cost. Amongst the possible applications, the most attractive situation when using the shuttles seems to be for mobility in congested city centers (41.7%). Several respondents (20.8%), also see the advantage of using autonomous shuttles in closed areas. The lessons learned is that an autonomous shuttle demonstration should consider the need to inform passengers about the context and the technology they are using,also to allow them to give their personal feedback.

In line with earlier research (Piatkowski, 2021), the experience to date indicates that novel users, or so-called early adopters, are very positive in comparison to other users who are not so positive. In the Brussels site, 70% of the users reported to enjoy travelling on the shuttles (Feys et al., 2020). In studies on users with special needs, it could be seen that there is a need for a more standardized way of handling communication during interactions with those outside the shuttle. This applies to pedestrians, cyclists as well as other car drivers.

Recommendation: The recommendation is to provide seat belts on seats facing forward and if possible upholstered seats, until hard braking events can be avoided. But also to engage user to use and to collect a more mature understanding of their experience, needs and whishes.

5.8. Charging and vehicle maintenance

This technology is in development, with continuous software updates. In several instances essential measures have been necessary by dedicated shuttle manufacturer staff at the site, which causes long lead times. The shuttles run on electricity and general standards are in place today for charging electric vehicles. One of the lessons learnt is the importance of checking that some of those standards are applicable for the shuttles at a particular site. If several shuttle brands are used at a site, then there is a risk that more than one solution is needed to cover both short and long-time charging, i.e., 1 phase or 3 phase electrical outlets configured with 10, 16 or 32 A. It is relevant to consider charging possibilities and their technical requirements already during the negotiation phase with the OEMs.

Closely related to the charging topic, to not damage the batteries, it was found that the bus depot must be heated during wintertime to avoid temperatures below 0 °C. This is an issue if you use cold depot solutions, especially for countries in with cold winter climate.

Cleaning and maintaining the AV shuttles is different from cleaning a conventional bus, especially the exterior as this requires specific competence and special procedures to ensure sustained performance of the sensors and the technical hardware. This is not always possible to guarantee, and staff training is necessary to avoid issues with lidar sensors, cameras, odometers, antennas, etc. On-site infrastructures are needed to protect, charge, and maintain the shuttles, see Fig. 11. Another option is to move the AVs to and from the existing facilities of a local mobility operator each operating day. However, the problem is that most shuttles are not designed to be driven manually outside of their operating site and certainly not long distances (2 km or more). Hence, special transport with a flatbed truck would then be needed. An alternative option, suggested by some OEMs, is the classical manual driving mode, which facilitates shuttle operator to drive the shuttle to and from local facilities before and after operations, or if in need of specific maintenance. Never-

Fig. 11. Flexible garage solution.

theless, a driver's seat and a steering wheel would be required, making the shuttle look more like a classical vehicle than an autonomous shuttle.

Recommendation: prepare for charging, cleaning, and maintaining taking into consideration the shuttle specific requirements and guidelines. Specific knowledge is needed.

6. Discussion

Already in 2017, Union internationale des transports publics (UITP) together with Transdev, stated that public transport offers the quickest development path to full autonomy because it can start operating in a limited area (UITP, 2017). Going back to the Vehicle Automated Driving Systems ((SAE), 2016) and Level 4 shuttle operation, it might be concluded that the policy brief from 2017 was very optimistic. The lessons learned from the demonstration sites in this paper clearly show that even though specific areas are used for operation, several issues remain.

As the shuttles are not yet able to operate freely on any road, a site assessment is the first required step for operation. From this assessment, usually realised by the shuttle provider, a lot will be learned about the operability of the chosen roads and the infrastructure adaptations that will be required to reach a suitable level of safety. Those conditions are generally also in line with the risk analysis that must be performed before receiving AV driving permission approval.

For wider use of shuttles it is however vital that shuttle development prioritises fitting into the existing traffic environment and eco system, rather than adapting the road infrastructure to enable the shuttles to run in the autonomous mode. Further development of the AV shuttles is vital to ensure that they operate smoothly in complex traffic situations considering lane and road width, shared spaces, snow, dust, rain, leaves, birds, etc.

The prospect of driving without an operator in public spaces has been postponed for the time being. The safety operator's task is to monitor what happens, interact if needed but mostly to support at shuttle stops, although formally they have the same obligations and responsibility as a driver of a regular city bus. Shuttles are programmed to run in special areas using virtual "tracks" and the driver is not provided with a steering wheel or a seat. Based on the lessons learned, it might be concluded that even if the safety operators were no longer needed, the need for dedicated resources responsible for the maintenance of the route, e.g. to cut the grass/trees, remove snow/sand, etc., or handle the shuttles remotely remains. Establishing a budget and a business plan is crucial, especially in relation to the practical problems that must be solved in order to have the shuttles up running. There is a risk that a support and maintenance solution for a shuttle with eight passenger seats will be far more expensive than having one driver on a regular bus with approximately 40 passengers.

A shuttle operation needs an ecosystem of stakeholders behind it, such as local and regional partners, landowners, safety operators, insurance companies and users. A shuttle is a new component and the demonstration sites included in this paper have required a lot of adaptations regarding road infrastructure before the realisation of the operation. It is recommended that the effort necessary to have AV shuttles up running should not be underestimated.

There is a wish to move from prototypes to vehicles that have passed a homologation process not only valid in a specific country but in all EU countries as soon as possible. The legal framework is still under development and is continuously revised and could even be subject to change during the tendering phase. As the shuttle OEMs focus on software automation solutions, they are often new players in the business of vehicles. Their level of maturity and standardisation (applying automotive industrial sector standards) is not yet mature enough for Public Transportation Operators (PTOs) that have experience of dealing with major industrial partners. Most shuttles available on the market or under development are still regarded as prototypes (Iclodean et al., 2020).

There are reasons to believe with regard to Safety Assurance of Self-driving Autonomous Vehicles that gaps of knowledge prevail (Tahir & Alexander, 2020). To the best of our knowledge, in mid-2021, there were no generic or standard approved AV vehicle types, and they are not adhering to normal standards as buses for PT do. This includes issues such as vehicle standards, but also issues related to turning light activation, braking light activation, etc. Simultaneously, a new trend has emerged of equipping existing models of classic vehicle manufacturers with autonomous technologies through industrial partnership. This could enhance the inherent technical quality of the vehicles and their integration with existing fleet management systems. However, the driving and driver perspective must still be addressed to achieve a solution ready for the market.

The importance of studying interaction and intentions with autonomous vehicles in real world traffic has been identified before (Pelikan, 2021). The authors underline that this is required throughout the entire rides, including aspects of driving that appear utterly mundane. To be part of a smooth traffic flow, autonomous vehicles must constantly coordinate with other road users and collaborate in joint manoeuvres with human driven vehicles

Hard braking events and stops represent one of the main challenges to solve. The balance between internal and external safety is important, as is a more "intelligent" handling of obstacles in the way of the shuttles. Even if hard braking events were experienced as an important topic for the future operation, it is worth mentioning that users at all three sites included here were very positive, just as in other studies (Bellone et al., 2021). Developing filtering functions and software algorithms to make sure that shuttles are not contradicting the aim of the road design, and to use AI to avoid hard braking event and stops when not required, is certainly promising (Martínez-Plumed et al., 2021). To safeguard pedestrians outside of the shuttle concurrently with making the shuttle operation smooth, new methods based on Short Range Communication might be of interest to develop further (Gelbal et al., 2020). Here also infrastructural investments with an integration of traffic lights at pedestrian crossings could be important to implement. At the same time all three sites recommend that to achieve an operation with high quality in a reasonable time there is no option to rebuild or adjust the infrastructure to support the shuttles. Future AV systems need to be able to operate in interaction with other vehicles, VRUs etc. using the existing infrastructure.

Another area of importance is the use of sound as a technology solution for information and warning, both to those onboard the shuttle and for those outside (Pelikan, 2021). The interaction with external road users is an important issue for achieving acceptance and trust amongst future passengers.

Despite the level of maturity of existing shuttles, the belief that there will be a demand for future last-mile automated services that can be integrated with MaaS concepts is strong (Bellone et al., 2021). However, the demand varies according to socio-economic and location-based conditions across different countries. The willingness to use shuttle services and pleasure in using them is seen as some of the main components for future shuttle success (Piatkowski, 2021). Similar results were seen in a study from Gothenburg, Sweden, in which the researchers highlight three different topics as the predominant reasons for not wanting to go on the shuttles: performance expectancy, route reasons and effort expectancy (Malmsten et al., 2020).

7. Recommendations

When starting a shuttle project for the first-time organisations most likely have limited knowledge about what to expect. Descriptions of shuttle projects and demonstrators typically share objectives and high-level details such as length and map of route, shuttle brand, expected or actual number of passengers etc. There are also processes for permissions and discussions about risks. There is however much less information about the difficulties you may run into when your shuttle travels on the road. This paper shares practical hands-on learnings from three sites – experiences that we ourselves would have found useful to know about when planning the sites described in this paper. The paper aims to contribute to avoiding known mistakes, to assessing use cases in a more efficient way, and thereby saving time and budget.

Based on the lessons learned, it is recommended not to underestimate the process and the time needed to bring an AV shuttle transport solution up and running, in contrast to purchasing a conventional bus. The PT operator/region or their partner, will be responsible for most of the preparation required for setting up the operation, even if the shuttle is purchased by another partner. As different shuttle brands have different strengths and weaknesses, it is important to have a clear view of what you aim to use the shuttle for before deciding what brand to select.

In addition, the results from this study show that further work is required to guarantee safe and smooth operation. The threshold between interior and exterior safety must be more balanced to safeguard both passengers onboard and that those outside are safe, a solution for this requires a good interaction/intention strategy provided by the shuttles.

Passengers, safety operators and those on the outside but in the vicinity of the shuttle, are exposed to the highest risks during hard braking events and sudden stops. While waiting for improvements to the actual shuttle vehicles, the following should be considered when setting up a demonstration site with AV shuttles:

- Consider road width, the risk of possible entrances into the shuttle's "safety bubble", and how to handle these situations.
- Implement an action plan for maintenance of the route surroundings, including trimming of greenery, handling of snow, etc.
- Ensure all passengers are seated, and those facing forward should be recommended to be buckled up.
- Secure the safety operator to avoid falls during braking events.
- Prepare the passengers and other road users before the introduction so the expectations are realistic.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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MaaS platform features: An exploration of their relationship and importance from supply and demand perspective

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A B S T R A C T

Mobility as a Service (MaaS) aims to offer travelers easy and convenient access to transportation modes via a joint digital channel, often in a mobile application. MaaS has the potential to fundamentally change the way we commute as it encourages a more sustainable travel behavior. MaaS, as a business model, is an innovative concept that integrates a variety of these solutions and can significantly change the mobility environment by encouraging sustainable travel behavior. Despite the existing initiatives and efforts toward MaaS solutions, there is still no consensus on the essential features of MaaS platforms for actors from the supply and demand sides. This study explores the critical features of MaaS platforms from the perspective of mobility service providers - MSP (i.e., supply-side) and travelers (i.e., demand-side). We collected data via interviews with mobility experts for the supply side and a survey for the users' side. Based on a Gaussian Graphical Model, our results show that optimizing the number and use of the vehicles and appropriate data handling are the essential features of a MaaS platform for the MSPs. For the travelers, although retrieval of personal information and enhancing services, such as suggestions on local events and concert tickets, are expected, they are considered less significant. Our study provides insights into the features of MaaS platforms through synthesized and prioritized features -including their relationships-which would be helpful both for research and practice.

1. Introduction

Incremental technology advantages have created a digital-based economy where services like e-commerce platforms, digital health services, online distance learning portals, and mobility-related services are changing transportation needs and preferences (Vij et al., 2020). Due to the emerging demands, city authorities face many interconnected demographic, public health, and environmental challenges, such as climate change, traffic congestion, air pollution, and growing population (Zhao et al., 2020). Innovative mobility solutions based on the shared mobility concept have shown that they can address some of the mobility challenges of cities toward a sustainable society (Sochor et al., 2018). The increase in collaborative provision and consumption of shared mobility services demonstrates the shift from an ownership-based to an access-based economy (Shaheen et al., 2017; Vij et al., 2020).

Mobility as a Service (MaaS) is an integrated model of transportation. It can be described as '*systems [that] offer consumers access to multiple transport modes and services, owned and operated by different mobility service providers, through an integrated digital platform for planning, booking, and payment'* (Vij et al., 2020). It is a technological and social phenomenon that includes technical artifacts, processes, services, and business models (Mladenović & Haavisto, 2021) MaaS is expected to be a major disruptor of the mobility ecosystem (Polydoropoulou, Pagoni, & Tsirimpa, 2020), as it integrates various solutions and can significantly change the mobility environment by encouraging sustainable travel behavior (Reck et al., 2020), reducing traffic, and decreasing CO_2 emissions (Zhao et al., 2021). Despite the abovementioned potential benefits, there are uncertainties related to the societal implications, technology applicability, and social embedding of MaaS systems (Mladenović and Haavisto, 2021).

Besides the MaaS operators, Mobility Service Providers (MSPs) and end-users (i.e., commuters) hold the most critical roles in the core business of the MaaS ecosystem (Esztergár-Kiss & Kerényi, 2020). The end-users represent the *demand side, expecting to use the commuting services*. Furthermore, MSPs offer mobility-related services and expect added value in profits or societal/public gains. Therefore, MSPs represent the *supply side,* implementing and supplying MaaS platforms with various mobility services (Polydoropoulou et al., 2020)[1]. The integration and unified service provisioning is the responsibility undertaken by the MaaS operators, which are between the *supply* (i.e., MSPs) and *demand* (i.e.,

[1] https://www.statista.com/statistics/575401/devices-used-with-mobile-internet-in-the-netherlands-by-age/#professional

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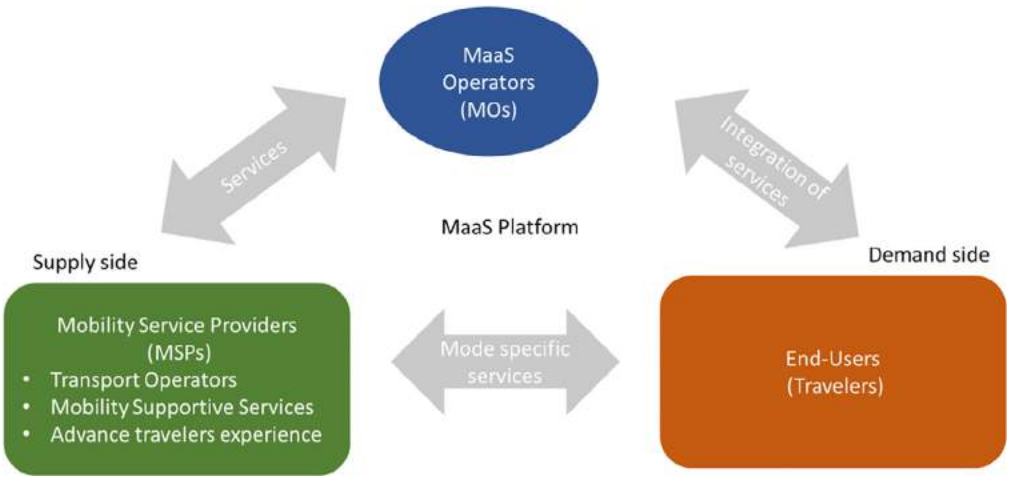


Fig 1. The three main MaaS stakeholders and their primary value exchange relationship.

travelers) (Kamargianni et al., 2018). MaaS operators combine the offering of various MSPs and offer the integrated service often through a single interface -aka the MaaS platform- allowing the users to plan, use, and pay for their commute (Polydoropoulou et al., 2020). Therefore, the growth of the MaaS market is highly dependent on MSPs' and the end-user's acceptance of the MaaS platforms (Esztergár-Kiss & Kerényi, 2020). Fig 1. presents the three main MaaS stakeholders and their primary value exchange relationship.

The potential of MaaS depends on various aspects, such as the integration of service-related information across different transport models through a single digital interface (Vij et al., 2020), the business models, scalability, data privacy, and security of the user acceptance (Jittrapirom et al., 2017). Given these considerations, the development and implementation of MaaS is a complex task (Karlsson et al., 2020). Therefore, it is unclear how and into what configuration these objectives can be translated into the requirements and addressed in a single MaaS platform. The requirements are the necessary functions and features for designing, implementing, and operating a MaaS platform based on the diverse expectations of travelers, MSPs, and other stakeholders.

As an emerging phenomenon, academics have investigated different aspects of MaaS features, such as how transport system models can be incorporated to support the design of MaaS services (Musolino et al., 2022), consumer requirements and motivations (e.g., willingness to pay) (e.g., (Polydoropoulou et al., 2020), or the expectations of mobility operators to join a MaaS platform (Vij & Dühr, 2022). Existing literature mainly focuses on identifying MaaS features by investigating end-user and (to a lesser extent) MSPs requirements *in isolation,* meaning without investigating their importance, relevance, and connection between and with other features. Adopting a network approach can give more valuable insights into the more central network features, have more connections, and bridge other features. Therefore, the objective of this exploratory study is (i) to identify relevant requirements for MSPs and end-users and cluster them under specific domains, and (ii) to identify the relationships and relevance of these domains for the design of a MaaS platform.

To address our research objective, first, we extracted features (i.e., requirements) from the literature. We grouped the requirements into *Features Domains*, fitting them on either the supply or demand side. Next, we elicited MSP-related MaaS requirements and performed an online survey to elicit travelers' preferences on certain functionalities. Survey participants were asked for their preferences on the MaaS platform's features for travelers. To capture the perspective of MSPs on requirements relevant to the supply side, we interviewed MaaS experts. We followed an exploratory analysis to understand how the requirements and variables are related. This explorative study can support MaaS operators and other stakeholders in identifying and implementing features based on their importance as travelers and MSPs perceive.

The rest of this paper is structured as follows. Section 2 provides a detailed description of our research design. Section 3 discusses the identified requirements clusters (under the label feature domains). Section 4 presents our analysis and findings regarding MSPs and end-users, and we discuss them in Section 5. Finally, we discuss the policy implications, limitations, and future research.

2. Research Design

We followed a four-step research approach. First, we performed desk research on literature (2017-2021) discussing MaaS features and requirements. Additionally, we reviewed the grey literature (i.e., practice-driven works, such as white papers and reports) and examined the features of the platforms implemented by existing MaaS initiatives. We formulated search queries using a set of selected keywords, namely, ("MaaS" and "MSPs") ("MaaS" and "mobility" operators"), ("MaaS" and ("travelers' or "end-users"), ("MaaS" and ("features" or "requirements" or "functionalities"). While reviewing the papers, the keywords string changed based on the relevant terms we found in the literature. In total, 40 research papers were found and analyzed. Additionally, we were interested in reviewing the features of existing MaaS initiatives. We focused on 12 initiatives, as discussed in Jittrapirom et al. (2017).

We clustered the requirements gathered from the literature based on two main MaaS stakeholder types: MSPs and travelers. Accordingly, we grouped the features into Feature Domains. Furthermore, for confirmation, we checked whether the identified feature domains are implemented in existing MaaS initiatives. Jittrapirom et al. (2017) reviewed twelve existing MaaS initiatives and indicated their functionalities. We compared our results and concluded that the features are implemented in existing MaaS initiatives and cover sufficient Feature Domains.

To better understand the features, we interviewed mobility experts in an online setting. We presented them, the Feature Domain, and features relevant to the MSPs. We asked them to indicate the services they consider as crucial for a MaaS platform. We provided the experts with a set of statements corresponding to each feature for each Feature Domain. The experts expressed their opinions regarding MaaS features that they find important (or less important). We target experts with 5-15 years of experience on relevant topics. Apart from their working experience, these experts were chosen as they were involved in a number of national and EU-funded projects focusing on designing, developing, and piloting MaaS platforms. During the interviews, we explicitly asked them to consider the preferences of a variety of possible suppliers on a MaaS (rather than reflecting solely their practical experience).

Table 1
Demographics of the Survey. Percentages are rounded to the nearest integer.

Age (%)		Residency Area (%)		Familiarity with MaaS (%)		Public transport usage (%)	
18-34	37	Urban	58	Not at all familiar	20	Daily	11
35-54	34	Suburban	18	Slightly familiar	13	Once to several times a week	25
55+	29	Rural (including villages)	24	Somewhat familiar	15	Once or several times a month	10
				Moderately familiar	41	Several times per year	32

Furthermore, we developed a questionnaire to obtain data from a broader range of travelers/commuters for the features targeted at the travelers (demand side). The survey was distributed to the respondents through online platforms. As MaaS is not a well-known concept, a figure and accompanying text introducing the concept of MaaS platforms were included on the cover page of the questionnaire (Appendix: Introductory text and figure regarding MaaS in the survey). The questionnaire had 11 sections. One of these sections included questions concerning demographics, and the remaining sections were based on the Feature Domains and included statements relevant to the features. The link to the survey (developed in Google Forms) was shared via social media (e.g., LinkedIn). The survey was conducted in February 2021. Before disseminating the survey, a pilot test was conducted to verify the completeness of the questionnaire. In retrieving our participants, we focused on the Netherlands for four reasons (1) the public transportation system is well advanced, (2) the mobility services and concepts such as shared mobility are of high interest, many services are already developed and offered, (3) MaaS initiatives are already under development, and (4) the majority of the Dutch population is extensively familiar with the use of mobile apps [1].

For the data analysis, we included ten variables reflecting the Feature Domains. For the data analysis, we calculated the composite scores for each respondent and investigated the priorities of the Feature Domains. Furthermore, we investigated the relationships between Feature Domains that are *Planning (my trip), Remember me, Payment, Booking (my trip), Ticketing, Share my trip, Help me (Assistance), Rate my trip, Enhanced service (I want more services), Non-Functional Requirement (Quality attributes)*.

To explore the relations (or the lack of) between the Feature Domains and their importance, we adopted a network perspective. We estimated a partial correlation network (a.k.a. Gaussian Graphical Model) using the qgraph statistical analysis package (Epskamp et al., 2012). The partial-correlation network shows correlations between pairs of nodes after controlling for the influence of all other variables in the network. A network comprises nodes representing variables (i.e., Feature Domains) connected by edges. Section 4 provides the details regarding the data analysis and our findings.

Participants Profile

Regarding the supply side, we interviewed five experts in an online focus group setting. The experts were practitioners from the industry (consultants from international private companies). Two experts were innovation consultants, one innovation manager, one R&D director, and one was innovation strategist. They have 5 to 15 years of experience on mobility-related projects. Four out of five participants argued that MaaS is a business opportunity, while one asserted that it is not clear to them whether MaaS is a business opportunity or not.

Table 1 presents the demographics of the survey. During the data collection, Dutch residents were discouraged from commuting by public or shared transportation during the data collection period due to the ongoing pandemic. The pool of active participants using MaaS platforms was significantly dropped. Eventually, data from 71 participants were analyzed. Most participants (37%) were between 18-and 34 years old. The majority of the participants lived in areas (58%). The majority of the participants argued that they are moderately familiar with MaaS as a concept, the transportation means of their choice, the most used transportation mode is the car, followed by bicycles, walking, and finally, public transportation.

3. Feature Domains

3.1. Demand side

Table 2 presents the features and related domains for the demand sides. Focusing on the travelers, specific Feature Domains, such as *planning* (Sakai, 2019) (Sakai, 2019; Yeboah et al., 2019), *ticketing* (Mukhtar-Landgren & Smith, 2019; Wong et al., 2020), *booking* (Pangbourne et al., 2020), and *payments* (Vij et al., 2020) are considered essential for any MaaS platform. Studies have emphasized the importance of customization in the design of MaaS offerings (Vij et al., 2020). *Personalized* packages based on city characteristics, environmental, usage, and financial features are also considered essential aspects of a MaaS design (Ashkrof et al., 2020; Esztergár-Kiss et al., 2020; Jittrapirom et al., 2017). While the mentioned above are well established, other attributes are of interest too. *Help me* refers to forecasts, travel history reports, accessibility support, etc. (Jittrapirom et al., 2017; Reck et al., 2020). *Ratings* (e.g., of the service quality) is another feature domain considered relevant (Ashkrof et al., 2020). The ability to share the trip with specific people and on *social media* platforms is another that is considered. Recently, the need for *enhancing services* offered via MaaS platforms has also been pointed out. Some of these services are related to booking accommodation close to the users' destination, information on touristic attractions, festivals, and other events (Turetken et al., 2021), as well as the ability to participate in the platform not only as a user but as a service provider too (Ashkrof et al., 2020). Finally, the *quality attributes* are critical when designing any digital artifact, as they describe *'how well the system shall perform or offer its functionalities'* (Eckhardt et al., 2016). *We defined ten feature domains that grouped the identified features.*

3.2. Supply side

Table 3 provides an overview of the identified features and related domains for the supply side. *Transportation* refers to the requirements related to the number and types of necessary vehicles per case. For instance, Jittrapirom et al. (2017) indicate that it is essential to identify the optimal vehicles for a given transportation model and the best location for the cars for optimal usage. Another feature related to transportation is the possibility of alternating the offered services (UNECE, 2020), features that support the improvement of utilization of the transportation assets (MaaS Scotland, 2018) and features that allow the determination of needed vehicles for a specific event.

The *analysis* refers to the features that enable the analysis of users' data for improved services, such as the user demand, the users' response to prices and quality (Jittrapirom et al., 2017), the key performance indicators (Hernández et al., 2020) and the analysis of complaints about improved services. The *management* feature domain refers to the features that support service providers in managing their value creation, capture, and delivery. These features can help service providers to improve the traffic flow and traffic management (UNECE, 2020), optimize the existing infrastructure, to manage the parking places (and whether different parking places are necessary), manage to charge locations, and esti-

Table 2
MaaS features related to the demand side – Travelers.

Features Domains	Features
Planning (my trip)	Departure times, Arrival times, Departure time change, Location selection, Directions to a location, Route favorites, Transfer time, Accessible transportation, Walking distance, Traffic changes.
Personalization (Remember me)	Cost, Time, User ratings, Transport mode, Environmental impact, Weather situation, Subscription allowance, Previous travels, Linked with calendar, Response's personalization.
Payment	Single tickets, Pay-as-you-go, Mobility subscriptions, Payment terminals, Debit/credit schemes.
Booking (my trip)	Ticket confirmation, Coupons, QR-/barcodes, Tip, Anonymous/person-bound tickets switch, Ticket change, Ticket cancelation, Ticket refund.
Ticketing	Ticket/time slots, Use-restricted filters, Joint journey discount, Offer comparison (providers), Offers comparison (mobility subscriptions), Travel class, Seating options, Age group, Discount offers, Singe ticket for all, Business to business payment.
Share my trip (in social media)	Trip sharing.
Assistance (Help me)	Journey changes notification, Departure time reminder, Step-by-step guidance, Text-to-speech directions, Offline navigation, Reporting an issue, Rating reminder, Audio function, Distinguishable pattern for color blind, Customer service via phone, Appropriate usable size, Customer service via live chat, Customer service via social media.
Rate my trip	Overall journey, Rating visible, Rate individual parts.
Enhanced service (I want more services)	Adapted travel options based on rating, Adapted travel options based on past travels, Entertainment booking, Accommodation booking, Event tickets purchase, Based on events tout recommendation, Tour plan recommendation, Recommunication on the return trip, Car insurance subscription via an app, Facilities exploration, Travel insurance, Mobility service provider sign up.
Non-Functional Requirement (Quality attributes)	Quick response, Predictable response, Easy to learn, Easy to use, Unauthorized access protection.

Table 3
MaaS attributes and entities related to the supply side – MSPs

Features Domains	Features
Transportation	Optimal number of vehicles, Vehicle relocation for optimal usage, Changes in available services, utilization of transport assets, Number adjustment based on events.
Analysis	Users' demands, Users' response to prices, Users' response on quality, Calculation of KPIs, Complaint analysis, Filtered results of the study based on the need.
Management	Traffic flow improvement, Traffic Management, Improvement of existing infrastructure, determination of the need for extra parking places, determination of the need for extra charging places, Insurance rates, management of existing parking places, management of existing parking places, management of existing charging places.
Interaction with the environment	Safety improvement, Communications with other providers, Data on air pollution, Data on carbon emission.
Quality attributes	Quick response, Predictable response, Unauthorized access protection, Easy to learn, Easy to use.

Table 4
Standard deviations and Means of the Features Domains.

Features Domains	Mean	Standard Dev.
Assistance (Help me)	3.67	0.62
Booking (my trip)	4.06	0.45
Enhancing Services (I want more services)	2.76	0.74
Non-Functional Requirement (Quality attributes)	4.51	0.38
Payment	3.87	0.62
Personalization (Remember me)	3.38	0.55
Planning	4.25	0.36
Rate my trip	2.90	0.99
Social Media (Share my trip)	1.59	0.62
Ticketing	3.81	0.52

mate insurance rates (MaaS Scotland, 2018). The *interaction with the environment* includes features such as the collection of insights to improve safety (MaaS Scotland, 2018), the communication between providers for decision-making processes (Turetken et al., 2021), air pollution level, and carbon emissions (Banister, 2008). The *quality attributes (i.e., non-functional requirements)* should also be considered for the supply-side perspective.

4. Analysis and Findings

4.1. Demand side (End-users)

Table 4 presents the means and standard deviations of the ten FDs based on composite scores. The highest scored Feature Domain was quality attributes (non-functional requirements), (μ=4.51, σ=0.38) with relatively low uncertainty. Quality attributes are essential to ensure the usability and effectiveness of the entire system and increase user satisfaction. This indicates that travelers value non-functional requirements equally or even more than functional requirements (Eckhardt et al., 2016). Planning booking and payments were ordered higher than the rest regarding the Feature Domains. This is in line with the arguments that these attributes are essential for successful user adoption (Sakai, 2019; Yeboah et al., 2019).

At the same time, the *rating* system had the highest standard deviation among all features but with a relatively lower mean. This shows that the agreement among the participants on whether it is an important feature was low. *Sharing* their trips on social media was ordered as the least essential feature, followed by *enhancing services*. Both might be related to privacy issues due to the involvement of third parties (Ghazinour & Ponchak, 2017). This highlights the importance of a user-friendly platform where users can provide their inputs to the system (e.g., rating system, sharing) with features planning, booking, and payments to improve user experience. The rest, well-established Feature Domains '*Help me!*,' *'remember me', and ticketing* did not rank as high as hypothesized.

Next, the survey data was analyzed to examine the network structure of the Feature Domains, their relationships and significance within the network. Fig 2. presents the partial correlation network of the feature domains. The size of the nodes corresponds to the nodes' strength. Wider and more saturated nodes indicate partial correlations further away from zero. The absence of a line implies no or very weak relationships between the relevant items or variables (Epskamp et al., 2018). If the partial correlation is zero, no connection is available between the two variables. The absence of a connection indicates that these variables are independent, and that one variable cannot cause the other. Considering our content sampling size, we need to control the *network's*

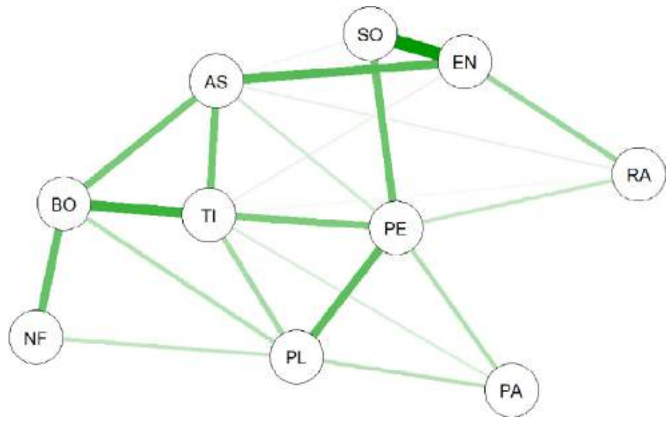


Fig 2. Partial Correlation Network displays the relationships between Features Domains. Feature Domains are illustrated as nodes. Wider and more saturated lines indicate stronger partial correlations: Planning (PL:), Remember me (PE), Payment (PA), Booking (BO), Ticketing (TI), Social Media (SO), Help me (AS), Ratings (RA), Enhancing Services (EN), Non-functional requirements (NF). R package qgraph was used.

sensitivity (true-positive rate) specificity (true-negative rate). Sensitivity increases with the sample size. However, a moderate sensitivity is acceptable as the strongest edges are discovered. In low specificity, edges that are not present might be detected (i.e., false positives). To address the issue of false positives and retain only meaningful associations, we applied a Lasso regularization (Epskamp & Fried, 2018) that shrinks small partial correlations, setting them to zero, so only the most robust partial correlations remain visible (McNally, 2016).

We can see that the strongest relationship is between enhancing services and social media. Furthermore, booking features and ticketing are closely linked. Planning and features related to previously stored data ('remember me') are well connected. On the contrary, the booking feature domain is not associated with the 'remember me' or payment domains.

To further investigate how vital the nodes are in the network, we used centrality indices, namely *strength, closeness*, and *betweenness* (Epskamp & Fried, 2018; Opsahl et al., 2010). Centrality indicates which nodes are more 'central' (Freeman, 1984). In *strength centrality,* we consider the edge weights (Newman, 2004). *Strength* centrality[2] is calculated by taking the sum of all absolute edge weights of a node that is directly connected. Strength centrality denotes the sum of the weights (e.g., correlation coefficients) of the edges connected to a node. Therefore, a node with high strength is likely to activate many other nodes and may be a good target for 'intervention' (Fried et al., 2017). However, strength centrality only estimates the direct ties and does not consider the network as a whole or an indirect connection. A way to address the whole network is to estimate the *betweenness and closeness* centrality. Closeness centrality takes the inverse of the sum of distances from one node to all other nodes in the network. The higher the *closeness* centrality[3] value is, the closer the node is to other nodes in the network. (Epskamp & Fried, 2018; Opsahl et al., 2010). *Betweenness* centrality indicates how often a node is in the shortest paths between other nodes. A node with high betweenness centrality may influence the information passing between other nodes; therefore, it is critical to the network (Epskamp & Fried, 2018). A node with high betweenness centrality[4] is of an essential role in the network, and the relationship with the other nodes have between them.

Fig 3. presents the centrality indices plots for the Features Domains' estimated network (nodes) regarding strength, betweenness, and closeness. Regarding centrality strength, we can see that the *remember me* feature domain has the highest strength indicating that it is directly connected with most other feature domains. Regarding betweenness, the χ-axis shows the number of shortest paths through a node. Regarding closeness, the χ-axis indicates the inverse of the sum of distances from one node to all other nodes in the network. R package qgraph was used. This indicates that it plays an important role in the network, and its activation has the strongest influence on the other nodes in the network. The *ticketing, booking*, and *enhancing service* follow. We can see the *payment, ratings*, and *quality attributes* on the lowest centrality strength.

Remember me has the highest betweenness value meaning that it acts as the main bridge connecting the feature domains. Enhancing services and 'help me' follow with equal betweenness. We see that payment, ratings, and non-functional requirements do not serve as a bridge in the communities within the network. Finally, closeness centrality indicates that 'remember me' Feature Domains have the highest value again, meaning it is the Feature Domains with the most direct and indirect connections. Ticketing follows close by. Once more, payment and ratings have the lowest.

4.2. Supply side (MSPs)

As previously mentioned, regarding the demand side, we conduct interviews with experts. We presented them, the FDs, and features relevant to the MSPs. We asked them to indicate the services they consider as crucial for a MaaS platform. We provided the experts with a set of statements corresponding to each feature for each FD. The experts expressed their opinions regarding MaaS features that they find important (or less important). We asked them to place each statement on a scale from 1 (not important) to 5 (important).

Regarding *transportation,* the experts indicated that determining the optimal number of vehicles for a given transportation mode and supporting the relocation of the vehicles to a location for optimal usage is of high importance. Additionally, four experts indicated that changing or altering the offered services is essential. All experts agreed that a successful MaaS platform should consider events at a specific location and adapt the number and the site of the provided vehicles. The above features can increase MSPs' attractiveness, decrease market fragmentation, and facilitate commuters' freedom of choice (Boijens et al., 2021). When the experts were presented with *user data analysis* statements*,* they all agreed that the users' demand data must be analyzed and presented via the platform.

The experts stated that it is critical for a MaaS platform to have features that allow the analysis of the users' response to the service quality and their complaints and to be able to calculate performance indicators. That indicates that the data-sharing agreements between the actors are critical (Kamargianni et al., 2018). The experts do not find features related to the *management* equally crucial to the features of the previous two categories. From the options we provided, the statement that they find more important is related to the *performance optimization* (possibly for the same reasons they find the *transportation* domain important).

Furthermore, the experts indicated support for the charging infrastructure and parking places within the area of interest. Regarding the *interaction of the platform with the environment* domain*,* the experts denoted that it is relevant for MaaS platforms to provide features that help improve safety by including insights from places where the accident happened. Additionally, the experts suggested that the platform support close communication between the service providers (MSPs).

[2] $S_{strength}(i) = C_D^w(i) = \sum_j^n W_{ij}$ where w is the weighted adjacency matrix, in which W_{ij} is greater than 0 if the node i is connected to node j, and the value represents the weight of the edge (Opsahl et al., 2010).

[3] $S_{closness}(i) = [\sum_j^n d(i,j)]^{-1}$ (idem).

[4] $S_{betweenness}(i) = \frac{g_{jk}(i)}{g_{jk}}$ where $g_{jk}$is the number of binary shortest paths between two nodes, and $g_{jk}(i)$ is the number of those paths that go through a node (idem).

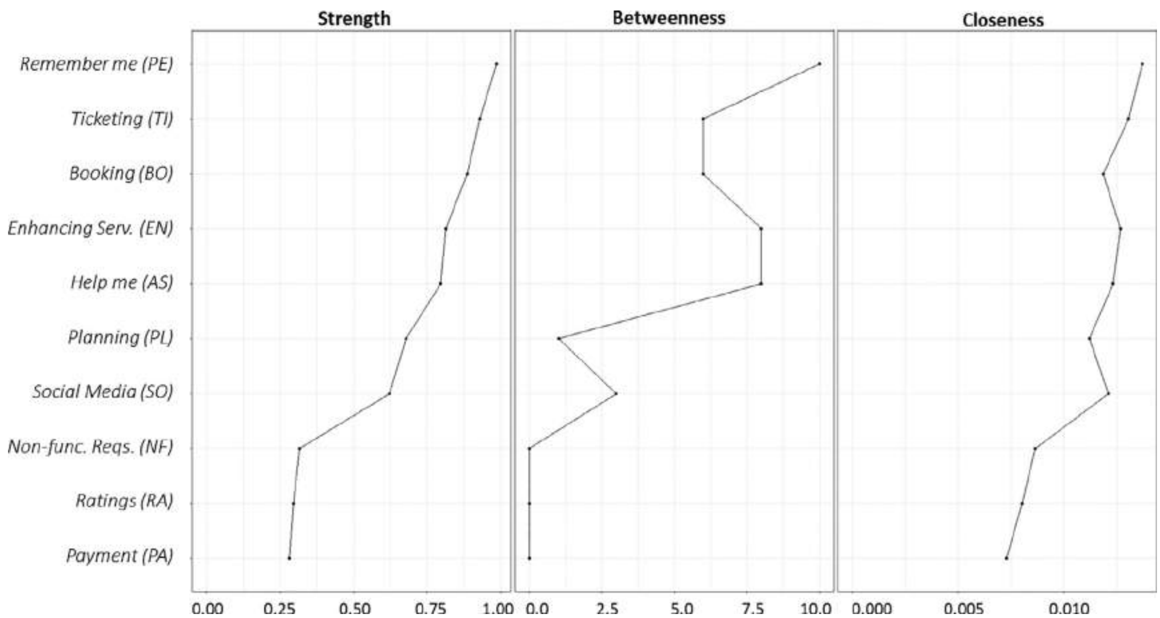


Fig 3. Plot of centrality indices for the estimated network of the Features Domains (nodes) regarding strength, betweenness, and closeness. Regarding strength, the χ-axis indicates the sum of all absolute edge weights a node is directly connected to.

However, two statements related to the *environmental impact*: 'air pollution and 'carbon emissions,' are not considered essential features of a MaaS platform by the service providers. A reason for this might be that the experts do not consider that the services related to renewable energies would enable business model innovation (Athanasopoulou et al., 2019) and therefore considered less essential for the MSPs.

Finally, the experts indicated their views on the *essential quality attributes*. There was a consensus on *ease of use*. Other critical quality attributes are the quick response to the inputs (*performance*) and ease of learning. The final quality attribute considered necessary was *security*: protecting against unauthorized access to the platform and its data. Again, as with end-user data, privacy policies and data protection for MaaS platforms and their MSPs are considered highly important (Kamargianni et al., 2018).

5. Discussion

5.1. Supply side (MSPs)

Based on the interviews with the experts, we created and proposed the final version of the MaaS features important for the MSPs 28 features grouped in five feature domains, as seen in Fig 4. We ordered the features based on the score given by the experts for each feature domain.

5.2. Demand-side (End-Users)

The network is characterized by a firm edge between social media and enhancing services. The second strongest edge is between *booking* and *ticketing,* while *planning* and *remembering me* are also strongly connected. *Help me* and *enhancing services* also have a strong connection. On the contrary, the network is characterized by weak connections between Help me, *social media* and *ratings, payments, ticketing*, and *enhancing services. Remember me* has the highest betweenness and strength centrality, indicating that, while it is ranked relatively low on importance, its absence could negatively affect the use of a MaaS platform for the whole network.

The results hint that the travelers do not highly value *remember me* (e.g., login account, previous session inputs saved, recommendations), but they do expect some form of personalization elements when using a MaaS platform (e.g., login page, store of language, and billing currency). The centralities of *booking* and *ticketing* were relatively high, confirming the existing literature (Pangbourne et al., 2020) on their importance. *Payment* has the lowest centrality, which might relate to the travelers' demographics, such as their cultural background or age. In a study conducted by the European Central Bank (European Central Bank, 2021), 24% of the Europeans indicated that they prefer to pay cash which in some countries, that percentage exceeds one-third of respondents (e.g., in Germany, Cyprus, Austria). Even in countries where the participants prefer cashless transactions, such as in the Netherlands, for older consumers, or low-cost transactions (as it can be considered a public transport ticket), cash is the preferred means of payment (van der Cruijsen et al., 2017). Our graphical model and the centralities indicate that the *help me* feature domain is medium to high centrality, with higher betweenness centrality than other feature domains. This might strongly affect perceived accessibility and transportation mode choice, even after including personal information (Scheepers et al., 2016).

5.3. Contributions and Policy Recommendations

This work contributes to the field of MaaS platform design and implementation by synthesizing, prioritizing, and uncovering the relationships and importance of MaaS platform requirements. The findings of this paper can be helpful for MaaS stakeholders, such as the mobility service providers, MaaS operators, or governmental authorities willing to participate in the MaaS ecosystem. More specifically, the results provide insights into the relationships and influence of well-established MaaS platform features on each other based on the preferences of the commuters and service providers. Our results can support stakeholders involved in the MaaS development projects by providing statistical-based insights via the centrality network (Reck et al., 2020). For instance, our results indicated that while environmental awareness and sustainability are essential (Storme et al., 2021), aspects of the environment and surroundings were considered less important for the MSPs. Furthermore, the findings deliver a better understanding of what MaaS platforms features commuters care about and thus how the involved stakeholders can create and deliver value to the stakeholders. Our results can support decision-makers regarding the design of MaaS platforms in addressing end-users' preferences. By revealing the consumer expectations, MaaS operators and other stakeholders can design MaaS

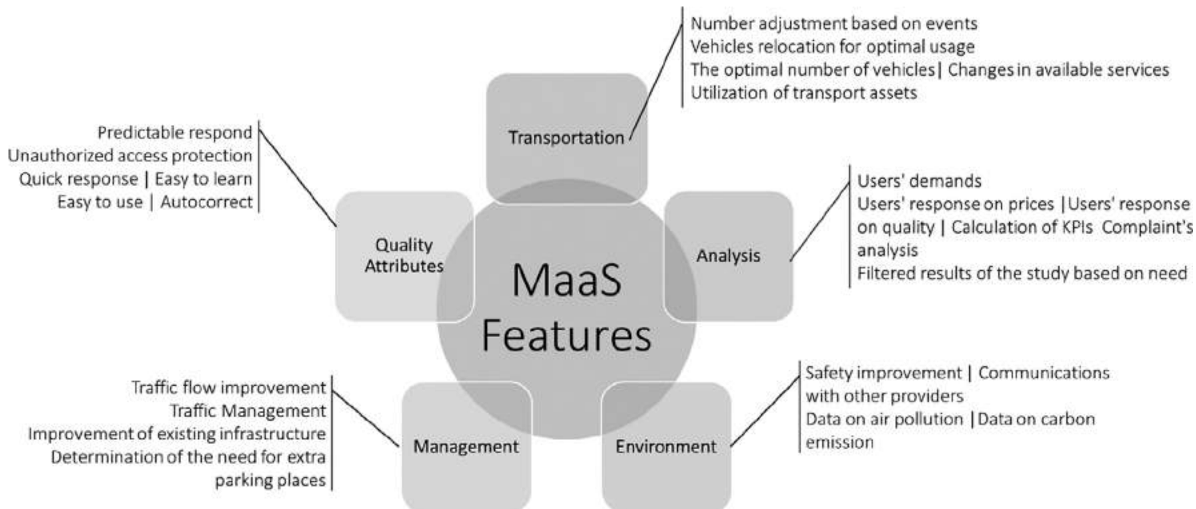


Fig 4. MaaS feature domains and features (supply-side). The features are placed (top to bottom) based on the experts' importance for each feature.

platforms that are more relevant and attractive to the commuters and potentially contribute to sustainable mobility efforts.

5.4. Limitations and Future Work

This research study has several limitations. First, the study included a limited number of participants from a certain geographical location. Further work should focus on validating the findings of this exploratory research with a larger and more representative sample size. It will be interesting to replicate the study in a more significant part of the population, located in different areas and with diverse characteristics, transportation habits, and cultures. While our study is the first to indicate relationships between the feature domains, a larger size will allow a stronger and better investigation of the relationships (or the absence of) within the features domains and between the features.

Additionally, more experts could help provide more conclusive results generalizable to a larger target stakeholder group. All involved in several MaaS initiatives, the experts we chose have already presented some patterns. However, a larger pool of experts would provide stronger evidence for the conclusions reached in this research study. Furthermore, the participants of the focus group meetings might have reflected the views and preferences of international private companies. In the future, data should be collected that reflect the preferences of local companies and other stakeholders, which might prioritize the features differently.

Another limitation regards the limited number of stakeholder types we investigated. For our study, we only focused on the MSPs and travelers and did not investigate the platform requirements from the perspective of MaaS operators or other involved stakeholders, such as cities and governmental bodies. Hence, a similar analysis should be repeated in the future to elicit the requirements and priorities of different users or stakeholders to provide a complete picture of the main features of a MaaS platform.

Furthermore, we assumed that there is one type of end-user. However, previous research identifies different types of travelers, such as car shedders (i.e., users trying to give up car ownership for economic reasons), car accessors (users that do not own, are planning to buy but are not sure if they need it), simplifiers (no car owners, various mobility options users), and economizers (not car owners, public transport users) (Sochor et al., 2018). Future research should investigate if the requirements differ per different types of end-users.

This study implicitly assumed that travelers *would* use a MaaS app. However, we did not consider the features that could convince travelers to use MaaS and onboard the MaaS platform (e.g., a new app, new account). Aligned with the study by Zijlstra et al. (2020), a future study focusing on these features could answer whether users would like to use a single app for their trips to different counties or install a new app when visiting new places. It would be interesting to investigate the features of the existing platforms that the users dislike (and make them uninstall the apps). Answers to these questions can be significant for both academics and practitioners. This would allow them to uncover specific aspects of MaaS platform design that are important or valuable.

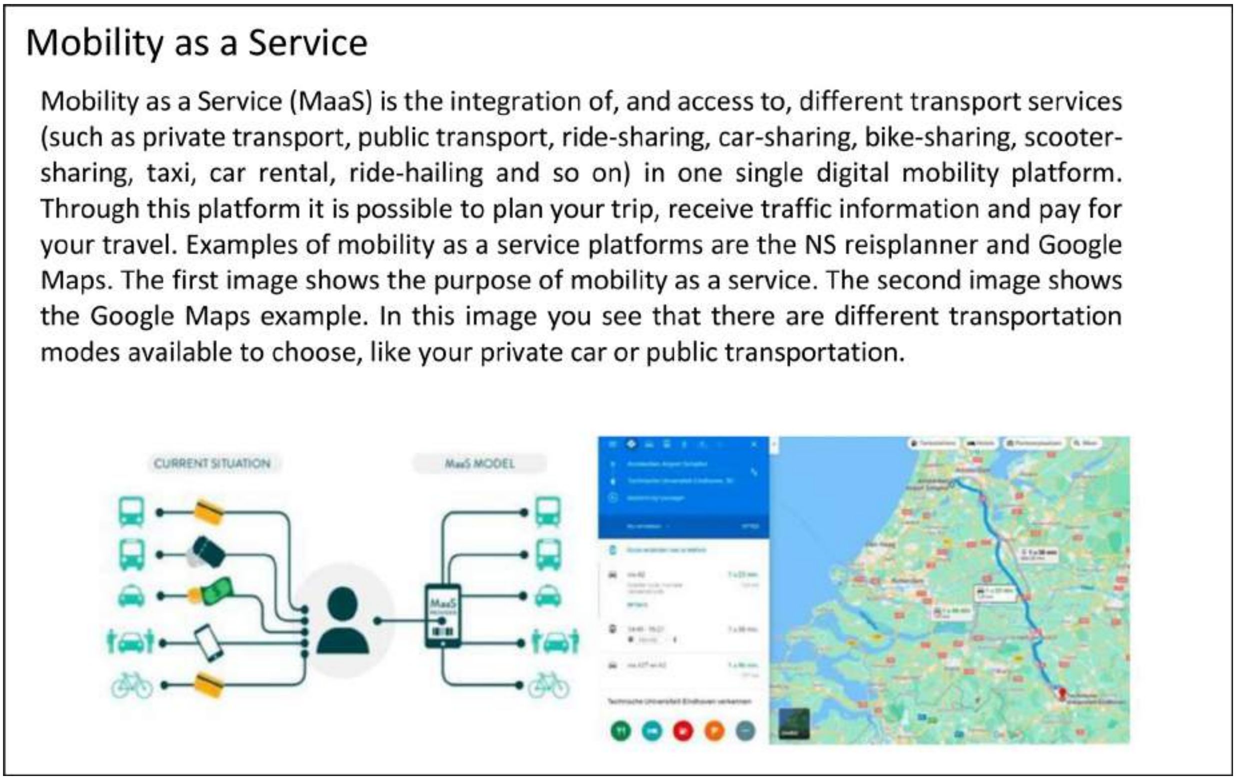
Future research can also focus on the MaaS-related business model innovation (Turetken et al., 2019). While we assume that stakeholders prefer features aligned with their business (and, therefore, their business models), it is not always clear what business model patterns and performance indicators should be used for added value from MaaS. This is especially evident when considering the motives behind a user's frequent use of the platform and choosing one service provider over the other. Future research considering the above views could lead to additional requirements for MaaS platform development and contribute to the emerging literature on the topic (e.g., Bocken et al., 2020; Boer, 2022; Polydoropoulou, et al., 2020).

6. Conclusion

This study explores the main features of MaaS platforms, including their relative importance and relationships. We focused both on the supply and demand side. While a 'solution that fits all' MaaS platform cannot be developed, our results provide strong indications of the main features essential for the main actors of the supply and demand side. Additionally, as end-users perceive, we further illustrate the associations between the main features

Mobility experts expressed their preferences regarding the features of MaaS platforms. Accordingly, the features concerning the transportation modes and data analysis are considered the most important for MSPs. By exploring the MaaS features with the mobility experts, we present a categorization that groups relevant features into features domains and places them based on the scores indicated by the experts from most to least important. Industry stakeholders, academics, and other actors can use our findings to initiate discussions regarding MaaS initiatives considering the preferences of MSPs. Different actors can also use our findings to collaborate on the re-design of MaaS platforms, apps, and services. Furthermore, our work can trigger discussions on the more advanced services and features that can be implemented in the future.

Our results confirmed that booking, ticketing, and planning are essential for any MaaS platform. Additionally, we identify that the travelers value the non-features requirements higher than the Feature Do-



mains because users prefer an easy-to-use app over a hard-to-learn platform with multiple features. From the results, we can understand that travelers do not find it essential that enhancing services (e.g., suggestions on events) be offered via a MaaS platform, but discounts and coupons for enhancing services should be offered during the booking and payment. Network analysis was used as it provides insight into the structural relations between the core MaaS features, and it has the potential to inform and trigger discussions among the involved stakeholders regarding the importance of specific MaaS features.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Introductory text and figure regarding MaaS in the survey

Mobility as a Service

Mobility as a Service (MaaS) is the integration of, and access to, different transport services (such as private transport, public transport, ride-sharing, car-sharing, bike-sharing, scooter-sharing, taxi, car rental, ride-hailing and so on) in one single digital mobility platform. Through this platform it is possible to plan your trip, receive traffic information and pay for your travel. Examples of mobility as a service platforms are the NS reisplanner and Google Maps. The first image shows the purpose of mobility as a service. The second image shows the Google Maps example. In this image you see that there are different transportation modes available to choose, like your private car or public transportation.

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Assessing the influence of connected and automated mobility on the liveability of cities

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ABSTRACT

In this work we are concerned with how the introduction of connected and automated mobility (CAM) will influence liveability in cities. We engaged with city and transport planners from both Europe and the U.S. and adopted a system dynamics approach to capturing the discussions and exploring potential outcomes. There are two aims in doing this: (1) to identify the concerns of city planners and how they differ from the traditional focus of transport researchers; but also (2) to develop a causal loop diagram (CLD) that can both explore the potential systemic effects of CAM and help to communicate those effects and the underlying mental models. Addressing these aims can inform policy design related to both CAM specifically and urban mobility more generally. In a change from previous related studies, we allowed the participants to establish their concept of liveability in cities and did not define a specific CAM scenario. This broad scope was critical in capturing the high-level view of what really matters to city stakeholders. We have established that a focus on a more holistic understanding of interactions related to sustainability is required rather than on specific transport modes or technology. A key insight that emerged was that quality of life (QoL) was the dominant concern of city planners, regardless of how it is achieved. The specifics of new services or technologies (such as CAM) are secondary concerns - which are important only insofar as they support the higher goal of improving QoL. As a result, we have produced a high level CLD that can be used as a starter for any future research in the area of CAM and liveability in cities and which may resonate better than previous CAM models have with city planners and policy makers—those who will ultimately play a key role in recommending and then implementing changes affecting QoL.

1. Introduction

Mobility is central to liveability (Anciaes and Jones, 2020). Particularly in an urban context, our understanding of both mobility and liveability is evolving as these concepts undergo a period of profound change. We are entering the era of the ‘smart city’, increasingly integrating and relying upon digitalisation and connectivity (Abu-Rayash and Dincer, 2021), set within a recent background of COVID-19 travel restrictions and social distancing. Looking forward, sustainable, healthy, and socially inclusive poly-centric cities are a commonly stated goal—to be achieved, for example, through development of “15-minute neighbourhoods” and “liveable streets”. Many cities hope to encourage the uptake of active forms of transport (cycling and walking) and shared micro-mobility while dependence on individual motorised vehicles (e.g., personally owned cars) is phased out. The introduction and integration of connected and automated mobility (CAM) within this paradigm could either help or hinder, depending on how individual citizens, businesses, and policymakers respond to the new technology (Milakis, 2019). On the one hand, a move towards CAM that uses certain models of vehicle and ride-sharing could open the way for an efficient, inclusive, and sustainable transport system (with several assumptions, including a zero emission, renewably powered fleet). At the other extreme, if the current model of individual vehicle-ownership and -use persists, we risk making our transportation system even less sustainable, while deepening societal inequalities with respect to accessibility, mobility, and liveability.

The central research question we are addressing is: *“How will the introduction of connected and automated mobility (CAM) influence liveability in cities?”* By answering the question we hope to be able to inform urban policy design. In order to do so, we carry out the following tasks:

- Explore the key concepts related to visions for ‘liveability’ in a city, identifying the elements required for attaining a good quality of life (QoL).

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Acronyms

ADS	Automated Driving Systems
CAM	Connected and Automated Mobility
(C)AV	(Connected and) Automated Vehicles
CLD	Causal Loop Diagram
PAV	Private Automated Vehicles
POV	Privately Owned (human-driven) Vehicles
PT	Public Transport
QoL	Quality of Life
SAV	Shared Automated Vehicles (fleet vehicles that are used either privately or as a ride-share)
SD	System Dynamics
VMT	Vehicle Miles Travelled

- Determine the potential system influences of CAM on urban liveability and how the vision of liveability held by city and regional planners may be affected.

We start with a conventional view of transport systems, then incorporate additional narratives that have recently come to light. Recognising that the systems involved are complex and dynamic, we use a system dynamics (SD) approach to examine them, with the goal of developing a high-level causal loop diagram (CLD), through group model building.

We engaged with metropolitan areas in the United States and Europe to gain a better understanding of what matters to them with respect to QoL and liveability in cities, and how these factors relate to CAM. Recognising that automation is being integrated into a complex transport ecosystem, this allowed us to collate perspectives from professionals who work within that existing system. Previous work (Rakoff et al., 2020) focused on the impacts of CAM scenarios that were developed in advance, mostly direct impacts on traffic from different developments in automated driving, with a strong emphasis on automotive technology. However, our goal here was to broaden the focus with respect to CAM to obtain perspectives we had not thought of before, thus getting the best value from having participants who work in different aspects of transportation than we do, especially including those who are closer to city planning and management and less focused on automation and research. To do so, we engaged in a group model building exercise during a workshop with city, metropolitan area and regional planners and modellers to discuss these complex systems in a meaningful way and capture new insights. The CLD we develop in this work is the first application of an SD approach to understanding the effect of CAM on liveability. It is generalised and high-level, so it can be readily adapted for use by others seeking to apply the framework to their particular circumstances and concerns.

The workshop also took advantage of new developments in virtual group model building to bring together city planners and modellers from regions that, in pre-COVID times, would not have found it feasible to send multiple staff to international in-person conferences. The session allowed fifteen technical-level professionals from five U.S. metropolitan areas and regions (in two states), and four European cities (in four countries), as well as a representative of the European network POLIS, to exchange and interact with each other's ideas and observations in real time.

In the next section of this paper, we provide a brief review of the concepts of CAM, liveability in cities, and the traditional transport system. We also explore the complex interactions among those concepts. Building on this context, in Section 3 we introduce our methodology, describing the system dynamics approach and the workshop activities as well as how the model was developed and refined after the workshop. We present the results (including the workshop output and resultant CLD) in Section 4 then in Section 5 we discuss key insights from the CLD in relation to CAM and liveability as well as reflecting on the methodological process. Finally, Section 5.7 is our conclusion summarising outcomes in relation to the research question.

2. Background

2.1. Connected and automated mobility (CAM)

Connected and automated mobility (CAM) has the potential to transform the world's road transportation system. Benefits could include (Milakis et al., 2017, Aittoniemi et al., 2020, Nahmias-Biran et al., 2021):

- Improved traffic safety (automobile collisions are a leading cause of accidental deaths)
- Higher transport network efficiency (most cities experience significant traffic congestion)
- Reduced energy use and emissions (oil consumption, air pollution and greenhouse gas emissions are of worldwide concern); and
- Improved personal mobility and accessibility (drivers and non-drivers alike may enjoy new mobility options).

For the purposes of this paper, we have chosen to use the term "connected and automated mobility" (or "CAM") to express the full range of potential mobility options enabled by connected vehicles and those with automated driving systems (ADS), including those with the ability to operate in a cooperative manner. This includes both private and shared vehicles, as well as public transport (PT) provision. We chose not to use other common terms, such as connected and/or automated vehicles (C/AVs) (except where a more restricted meaning is desired), as readers are likely to associate them with only private individual passenger vehicles, not the broader range of mobility services (such as public transport, fleet ownership and ride-sharing) where our interest lies.

CAM includes technologies enabling a vehicle to handle the dynamic driving tasks with increasingly limited human interaction and at the most extreme stage to operate completely without any human intervention whatsoever. There are six levels of driving automation recognised over this range, where Level 0 has no automation and Level 5 is fully automated in all situations (SAEI, 2021). At the time of writing, driver assistance technologies are already widely available in existing vehicles on our roads – such as (adaptive) cruise control, automatic parking and lane assistance, and there are a significant number of ADS being tested around the world. However, it is likely still many years before we would expect wide-spread market penetration of automation which completely frees the human from the driving task in a wide operational design domain, as even though technology may be maturing the socio-legal systems required to support any transition are still under discussion (Bellet et al., 2019, Pattinson et al., 2020, Milakis and Müller, 2021). The claimed benefits of CAM include safer, more efficient and inclusive travel. However, these benefits may not be fully realised under the model of individual ownership and car dependence that currently exists within our established transport systems (Chase, 2016).

While the benefits of CAM are potentially transformative, it is important to realise that it is being introduced into a complex transportation system, with highly uncertain outcomes. Second order impacts, such as the possibility of increased travel leading to more congestion and emissions, are of significant concern (Aittoniemi et al., 2020). Other farther-removed and longer-term effects, including potential feedback effects, could have significant impact on outcomes as well. Feedback effects occur when a system responds to initial changes in ways that either reinforce those changes (*reinforcing* feedback effects, which can drive "vicious" or "virtuous" cycles) or limit the effect of those initial changes (*balancing* feedback effects, often manifested as policy resistance) (Sterman, 2006). As a result, the impacts of CAM may be wide-ranging, and are very difficult to assess.

2.2. The trilateral working group on automation in road transportation (ART)

The Trilateral Working Group on Automation in Road Transportation (ART) is an initiative of the European Commission, the United States Department of Transportation and the Japanese Ministry of Land, Infrastructure, Transport and Tourism. Building on a long history of research collaboration and information exchange related to intelligent transportation systems (ITS), three bilateral agreements formalised ITS knowledge exchange activities between the parties in 2009-2010 (Dreher et al., 2019). These activities are coordinated by a Steering Group which established four working groups, one of which is ART, established in 2012. ART's mission goals are to "support shared learning, develop solutions to shared challenges, and harmoni[s]e approaches where appropriate. The working group seeks to achieve these goals by (Fischer et al., 2018):

- Allowing each region/country to learn from one another's programs
- Identifying areas of cooperation where each region will benefit from coordinated research activities; and
- Engaging in cooperative research and harmoni[s]ation activities.

When it comes to ADS, public authorities, industry, research institutions, and citizen groups struggle to comprehend the potential consequences of wide-scale implementation. It is challenging to have meaningful conversations about which impacts may be desirable, which ones should be avoided, and which ones might be mitigated by other measures. In order to structure discussions and further investigate these issues, ART established a sub-working group on Impact Assessment. The Impact Assessment sub-working group started to collaborate in 2015 in the development of a high-level framework for assessing the impacts of road traffic automation (Innamaa et al., 2018, Innamaa et al., 2017). The goal was to facilitate the impact assessment work in projects performing field tests with ADS in the three regions and beyond. With a harmonised approach, tests and studies can be designed to maximise the insight obtained and to arrange complementary evaluation across the world. Harmonisation also facilitates meta-analysis. The framework provides recommendations on how to describe impact assessment studies in such a way that the user of the results understands what was evaluated and under which conditions. In addition, a detailed series of key performance indicators was developed.

During the development of the trilateral framework mentioned above, several workshops were organised, both with experts in the field and with a wider public during international transport conferences, one of which had a public open day. One of the difficulties encountered was that the complexity of the impacts and their interrelationship made it difficult to engage in structured and meaningful discussions. For example, it is very difficult to discuss one impact area, such as mobility, without also considering what the effects would be on the environment. If CAM would make car use easier and more comfortable, would that mean that there would be more cars on the road? Although these workshops produced very useful ideas and insights, we began to realise that the participants in these discussions were usually coming from the transport sector, with a strong focus on the effects on transport. Some participants had a rather strong interest and belief in the beneficial impacts of road automation, and in any case, we framed the workshops to look largely at impacts of automation on travel demand and mode choice, rather than higher-order impacts on QoL. However, we realized that there are other important perspectives to consider. During one workshop, a representative from a large city remarked that they were very interested in CAM, but that one of their primary goals was to significantly reduce individual motorised transport in favour of public and active transport. They felt that if CAM could help to realise that objective, it was great; if not, then they were no longer interested. After the publication of the impact assessment framework, the trilateral group started to look for new, innovative ways of discussing impacts and helping decision makers address the wider issue of liveability. This paper describes how we used system dynamics modelling, in particular the use of group model building and CLDs, to establish a conceptual framework for assessing the potential impacts of CAM for cities.

2.3. Liveability and mobility

Urban sustainability is an increasingly global concern, indicated by "sustainable cities & communities" being one of the United Nations' sustainable development goals (UN, 2021). In the last half of the 20thcentury, urban areas in European Union member states grew by 80% while urban population grew 35% (Ferreira et al., 2021). By 2015, around half of the population of OECD (Organisation for Economic Co-operation and Development) countries lived in metropolitan areas, and it was projected that by the end of the 21st century, the global urban population will be around 9 billion, 85% of the total population (OECD, 2015). As we face this era of urbanisation we need to ensure that cities are "liveable", as an essential element of long-term urban sustainability.

There are many definitions and different ways to understand the concept of liveability. The annual Global Liveability Index ranks all cities in terms of five key factors: Stability, Healthcare, Culture & Environment, Education and Infrastructure (EIU, 2021). As suggested by Appleyard et al. (2014), liveability is "*best understood as an individual's ability to access opportunities to improve his or her quality of life"*, and those opportunities can be limited by conflicting desires and competition for resources across large populations. This raises the issue of ensuring equal access for all. Other researchers have attempted to define liveable communities in more detail, such as: "*safe, attractive, socially cohesive and inclusive, and environmentally sustainable; with affordable and diverse housing linked to employment, education, public open space, local shops, health and community services, and leisure and cultural opportunities; via convenient public transport, walking and cycling infrastructure"* (Lowe et al., 2013). At a local level, liveability may also be characterised by community identity. The sustainability and liveability of cities are also strongly affected by the form of urban development, which generally follows one of two approaches: dense with high-rises, or low-density and sprawling (Nieuwenhuijsen, 2020), each of which has transport and planning implications. In addition, there is a strong association of liveability with health (Khomenko et al., 2020, Lowe et al., 2015, Nieuwenhuijsen, 2020, Badland and Pearce, 2019).

There is no single recognised definition of liveability, as it is highly context-specific. Ultimately, liveability consists of multiple socio-physical and socio-cultural factors, with variations in assessment approach, but generally is used as a reference to the standard of living (or living standards) or overall wellbeing of those who live in a city (DoT, 2011, Barry, 2010, AARP, 2005, Paul and Sen, 2020). In this work we take a general definition of liveability, drawing from the literature outlined above:

> *Liveability in cities relates to the physical, social and cultural factors that can lead to equal access to opportunities, ensuring a sustainable and satisfying quality of life (QoL) for all inhabitants.*

Transport, or more specifically, the access it provides, is an integral part of QoL, whereas the externalities of transport negatively affect health and well-being. The liveability benefits provided by transport can be related to provision of (safe and sustainable) accessibility (DoT, 2011) or the facilitation of independence and choice (Barry, 2010, AARP, 2005). Anciaes and Jones (2020) suggest that there are nine dimensions of liveability related to transport, which fit under the three broad categories of "movement", "place", and "society".

Vitale Brovarone et al. (2021) recognise from the literature that CAM may have both positive impacts on urban liveability (reduced collisions, improved accessibility, increased capacity) and negative ones (increased VMT, congestion, and sprawl, with reduced active travel and public transport). However, using a back-casting visioning process, they believe that it is possible for CAM to positively contribute to liveability, but that requires regulation of circulation and parking, as well as integration into the existing transport system. Agreeing with Vitale Brovarone et al. to some extent, González-González et al. (2020) emphasise that a model of like-for-like replacement of current conventional private vehicles with connected and automated vehicles would not help to achieve goals of liveability and sustainability, but such vehicles could support those goals with a move towards shared use and restriction of motorised transport to certain areas.

3. Methodology

3.1. System dynamics

System dynamics (SD) is a methodology for understanding complex systems, and in particular identifying effective interventions to make them perform better. The purpose is to capture all relevant variables, relationships and feedbacks that characterise the behaviours of the systems (Sterman, 2000). SD has both qualitative and quantitative aspects. Qualitatively, we build causal loop diagrams (CLDs) that represent key aspects of the system, consisting of variables connected to each other by causal links. These causal links can be positive (or "same") or negative (or "opposite"). A positive link means a change in the cause variable will lead to a change in the *same* direction in the effect variable (i.e., an increase in the first leads to an increase in the), whereas a negative link means the change will be in the *opposite* direction (i.e., an increase in the first leads to a decrease in the second). A closed sequence of these links form feedback loops that can be either reinforcing (ultimately resulting in exponential growth or decline) or balancing (which inhibit growth or decline). These can be used to then develop quantitative dynamic simulation models that capture both linear and non-linear effects. Liveability has been recognised as an outcome of complex systems, for which we need to develop our understanding of interactions, feedbacks and non-linear responses (Badland and Pearce, 2019), thus, making SD an appropriate method for considering the subject.

SD has been widely applied to transport (Shepherd, 2014) and in particular to the uptake of alternative fuel vehicles (Gómez Vilchez and Jochem, 2019). There are a few efforts to date that have used SD to examine CAM, but there have been no studies where an SD approach has been applied directly to understanding the influence of CAM on liveability. Qualitatively, CLDs have been developed to examine impacts on total vehicle distance travelled (Stanford, 2015) and vehicle use and modal shift (Gruel and Stanford, 2015). These papers concluded that predictable, linear transitions are unlikely, and while positive outcomes are possible in some scenarios, a key insight was that CAVs alone (in the absence of other interventions) are unlikely to lead to a sustainable transport system, so early policy intervention to avoid the dominance of privately owned CAVs is likely to be necessary. Focusing on socio-economic impacts of CAM, a group of international experts developed a high-level consensus causal loop diagram through a group model building workshop and conceptualised a general qualitative framework for CAM stakeholder interactions (Rakoff et al., 2020).

Five quantitative SD-based models addressing CAM have been identified in the literature, all concluding that there are high levels of uncertainty and risk. All of these studies were carried out using traditional transport indicators, rather than considering the wider QoL approach that was adopted in our study. Technology development and car sharing across all levels of automation were explored by Nieuwenhuijsen et al. (2018), who identified that positive economic and social acceptance conditions were required for high market share of highly automated vehicles. Three studies incorporated Nieuwenhuijsen et al. (2018) work into their own. Puylaert et al. (2018) and May et al. (2019) utilised the outputs in their own SD models and both found that total vehicle distance travelled may increase following the introduction of automated driving, though shared and connected mobility may mitigate this to some extent, but not enough to remove all increased distance. Harrison et al. (2021) further developed Nieuwenhuijsen et al.'s model to focus on the role of services linked to connectivity, finding that they could contribute to a 20% increase in Level 5 market share by 2050. Finally, using the region of Copenhagen as a case study, Legêne et al. (2020) applied SD and exploratory modelling and analysis to establish twelve key uncertainties of CAV on urban development and lead to the conceptualisation of two distinct scenarios, indicating that shared CAV ownership will be critical in reducing congestion and urban sprawl.

3.2. Workshop

We organised a virtual workshop in early 2021, using the Zoom platform City representatives and transport planners from four European cities, one U.S. state, and four U.S. metropolitan areas participated[1], and the session was jointly facilitated by the authors (from the U.K., U.S., and Finland)[2]. The U.S. attendees were invited to participate due to their partnership in ongoing related projects. In Europe, we invited cities representing specific region/city sizes, supplemented by an open invitation distributed to members of the POLIS network.[3]

The workshop, which lasted 3 hours, was titled "Liveability of Cities: A System Dynamics Perspective", and participants were told that we would be exploring the dynamics of improving liveability in the urban system and that a key consideration would be the role of automated mobility in improving liveability. They were also told that they would learn how to use system dynamics concepts to identify the key relationships and points of leverage among the causal factors in city transportation.

Through the workshop we develop a CLD for understanding the impact of CAM on Liveability, involving a three stage process as described in Fig. 1 and Sections 3.2.1 and 3.2.2.

Prior to the workshop, participants were asked to contribute to two online collaborative engagement boards (using the platform "Padlet"[4]). This important step in the process allowed the workshop organisers to start collating key concepts and building a causal loop diagram as a starting point for discussion in the workshop.

The first Padlet focused on identifying key elements related to liveability in cities, and asked, *"What are the most important elements for attaining a good quality of life in your City?"*. Participants were requested to provide their top three elements, along with a short description, and to add any links to other elements already posted. Respondents also had the ability to up-vote or down-vote elements proposed by others. In the second Padlet, the question was "*How might the introduction of automated vehicles impact quality of life in your City?"* Participants could add up to three "hopes" and three "fears" regarding this question, and could again vote for existing posts. This "hopes and fears" exercise is a standard activity in group model building[5]. The project team took the results of the pre-workshop QoL exercise to create a simple CLD in advance (see section 4.1 and Fig. 3 later), using the online tool "Loopy"[6].

[1] From Europe: Vienna, Austria; Gothenburg, Sweden; Madrid, Spain; Oslo, Norway; a representative from POLIS. From the U.S.A.: Oregon Department of Transportation [ODOT, the state DOT] ; Mid-Willamette Valley Council of Governments [MWVCOG, the metropolitan planning organization for Salem, Oregon metropolitan area] ; Oregon Cascades West Council of Governments [OCWCOG, the metropolitan planning organization for Corvallis and Albany in the region of the Oregon coast and Willamette Valley mountainous region] ; Central Transportation Planning Staff [CTPS, the staff to the Boston Region Metropolitan Planning Organization] ; Metropolitan Area Planning Council [MAPC, the regional planning agency for the 101 cities and towns of metropolitan Boston]

[2] One author (Jospeh Stanford) was not involved in the workshop facilitation. One facilitator (Hitesh Boghani, University of Loughborough) was not involved in the writing of this paper.

[3] POLIS is a network of European cities and regions working together to develop innovative technologies and policies for local transport. https://www.polisnetwork.eu/.

[4] www.padlet.com.

[5] https://en.wikibooks.org/wiki/Scriptapedia/Hopes_and_Fears.

[6] https://ncase.me/loopy/.

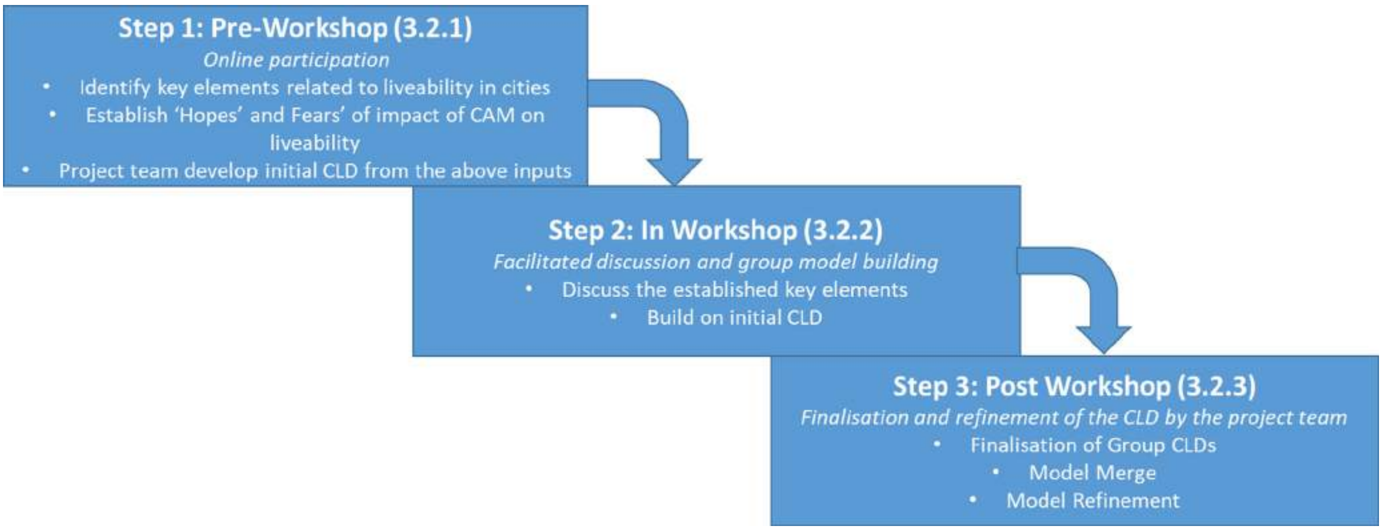

Fig. 1. Methodological process

What influences quality of life (starting from Loopy CLD, referring to QoL padlet)?

- Establish consensus of definition of the variables
- What metrics could be used to measure them?
- Do you agree with the variables currently included?
- Are there any key variables missing?
- What is the nature of the relationships between variables (+/-, strength, delays)?
- What are the key feedback loops that describe system behavior?
- Causal relationships among transportation, land use, and other factors
- Equity aspects: how different groups are affected

What role (if any) might automated driving play (Hopes and Fears padlet)?

- Establish consensus on definitions
- Which variables in the QoL CLD will be influenced, and how – establish the links in Loopy
- What is the relative strength of the influences?

Fig. 2. Prompt questions for the facilitators

3.2.1. *In-workshop CLD development*

During the workshop, the participants were first given a short introduction to the theory of system dynamics and causal loop diagrams. They were then divided into two breakout groups, each group comprising a balanced mix of European and U.S. participants. Each group built upon the initial simple QoL CLD in two tasks within the session. First, they discussed the existing CLD and QoL Padlet, and the facilitation team captured the consensus of the group regarding the key variables, relationships and feedback that characterize liveability of cities, with a focus on transport. Secondly, the groups identified what influences automated driving may have on these variables, including causal relationships and feedback. These sessions were facilitated by the project team, with three people working with each breakout group, taking the following roles: *Facilitator,* who guided the discussions (see Fig. 2); *Modeller*, who recorded the suggestions on the Loopy CLD; and *Note-taker*, who took written notes of the discussion. The notes taken at the workshop are available as supplementary information to this paper. A seventh member of the project (*Floater*) moved between the two groups to make further suggestions and to get an overview of both discussions.

During a short break in the workshop, the project team discussed the two respective CLDs that had been developed by the groups, and after the break presented the findings back to the whole group, followed by an overview of insights garnered by the Floater, and a round-table discussion that gathered feedback on the process from all participants. The topics raised in this discussion were also noted down for further work.

3.2.2. *Post-workshop CLD development*

Following the workshop, the project team continued to work on refining and merging the CLDs, building on the workshop notes and existing literature. The aim was to develop a high-level CLD that reflects conventional understanding of how transport systems work and incorporates potential impacts from CAM on the liveability of cities—and includes new insights regarding direct and indirect effects on liveability that were brought to light in the workshop discussion. This work consisted of three stages (see sections 3.2.2.1, 3.2.2.2 and 3.2.2.3).

3.2.2.1. Stage 1: finalization of group CLDs. The CLDs and notes for each group from the workshop were reviewed by the project team, in order to more adequately capture the discussions carried out, the knowledge of the project team and wider literature on CAM. In the first instance, the three members involved with each breakout group discussion worked together and agreed on a final version of the CLD for that group. In some cases, this involved editing variable names and relationships to make them more accurately reflect the concepts that had been discussed in the meeting.

3.2.2.2. Stage 2: model merge. Following finalisation of the Group CLDs in Stage 1, the project team set about merging the findings of the two

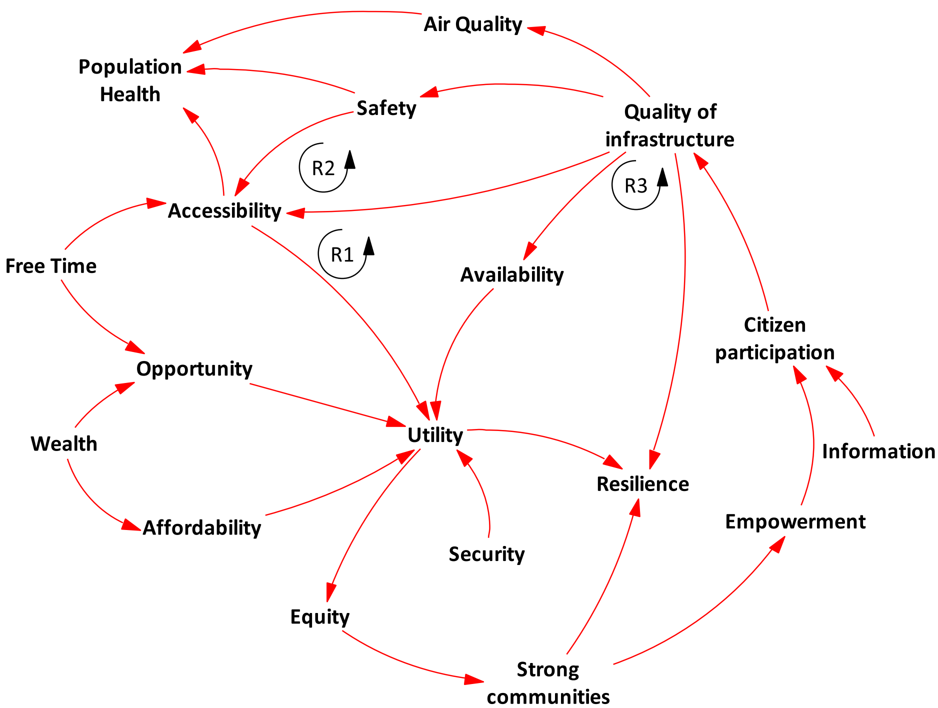

Fig. 3. Initial QoL CLD built from Padlet responses (Note: all links have been identified as positive (same) and there are three positive (reinforcing) feedback loops, all passing through Utility – see Table 1.

Table 1
Loops of the initial CLD.

Loop	Pathway
R1	Utility ->+ Equity ->+ Strong communities ->+ Empowerment ->+ Citizen participation ->+ Quality of infrastructure ->+ Safety ->+ Accessibility ->+ Utility
R2	Utility ->+ Equity ->+ Strong communities ->+ Empowerment ->+ Citizen participation ->+ Quality of infrastructure ->+ Accessibility ->+ Utility
R3	Utility ->+ Equity ->+ Strong communities ->+ Empowerment ->+ Citizen participation ->+ Quality of infrastructure ->+ Availability ->+ Utility

separate models into one final model that addresses the research question.

3.2.2.3. Stage 3: model refinement. At this point, another round of refinement was needed to fully integrate the two models. This consisted of four main tasks:

- Resolving inconsistencies and incompleteness in language and logical structure;
- Identifying and closing additional feedback loops;
- Improving visual arrangement and presentation; and,
- Creating a high-level summary.

4. Results

4.1. Pre-workshop

4.1.1. QoL padlet

We used workshop participants' perspectives on a vision for liveability from the QoL padlet, identifying the most important elements for relating to QoL, to construct a causal loop diagram, shown in Fig. 3[7] (with loops set out in Table 1). This served as a starting point for the group modelling during the workshop. The terms used in this CLD were drawn from the original QoL Padlet content from the participants (see Appendix 1). Some match exactly those used by participants (e.g. "safety", "accessibility"), whereas others were adjusted from suggested terms to terms felt to be more appropriate by the team (e.g. "utility' was chosen to be used in the CLD over "choice" as written in the Padlet, as utility is a more tangible/understood term which is well used within transport planning). Additional links were also added at the discretion of the project team with the objective of creating a coherent CLD which communicated the overall themes which emerged from the Padlet.

4.1.2. Hopes and fears padlet

Participants' hopes and fears relating to vehicle automation for liveability in cities that emerged from the Padlet exercise, are set out in Table 2. The original Padlet content is also available in Appendix 1. The hopes and fears broadly align with previous studies and conventional thinking as set out in Section 2.1, such as the focus on utility and accessibility, though do bring in some new concepts such as equity and community involvement.

4.2. Workshop outputs

Here we present a summary of the group discussions. The full workshop notes and resultant Loopy diagrams for each group are available as supplementary information.

4.2.1. Group 1 discussions

The CLD arising from the discussions of Group 1 is shown in Fig. 4. Group 1 recognised that liveable cities need to be sustainable (in a broad sense) and identified that most elements included in the presented CLD were linked to sustainability, The group added the variable *sustainability*, to explicitly recognise this. Furthermore, the *vision* of the city was raised as a crucial driver of key decisions. Although it could be argued that *vision* would influence all elements within city control, Group 1 specifically identified the links to *changing modes, competition for space/funds*

[7] Originally "Equality" was used rather than "Equity", but in post-workshop discussions it became apparent that "equity" was the correct term to use to describe the concepts discussed in the workshops eg. provision of resources for an equal outcome rather than providing equal resources to all.

Table 2
Hopes and Fears related to the impact of Automated Vehicles on liveability in cities.

HOPES	FEARS
• Improved travel comfort	• Reduced active travel and PT use
• Better compliance with traffic laws	• Increase in individual motorised vehicle kilometres travelled (VKT) as car travel comfort increases, cost decreases and due to empty miles,
• Decreased travel costs	• Increased congestion (especially at peak hours)
• Enjoying less noise	• Increased roadway maintenance, infrastructure and related costs
• Reduced parking needs	• Increase in energy consumption
• Improved safety	• Increased inequity
• New revenue opportunities	• Increased urban sprawl
• More accessibility for vulnerable individuals	• Decreased safety for other road users
• Increased energy efficiency	• Private companies putting profit above societal good
• Optimisation of road space and traffic flow	• Increased inequity – in road space use, accessibility, safety
• Increased road safety	
• Lower car ownership	
• More useful travel time	
• Advanced electrification	

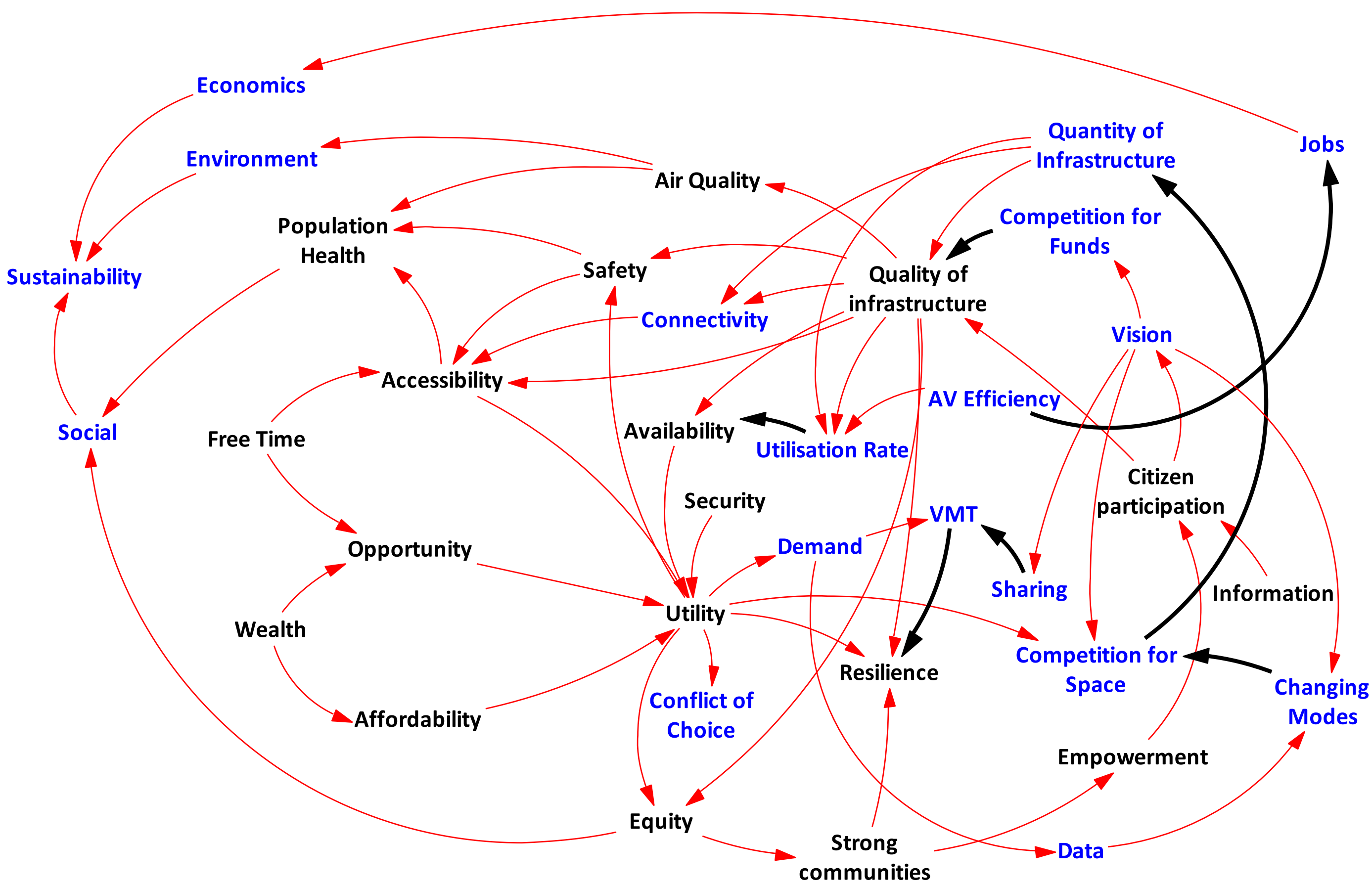

Fig. 4. Final Group 1 CLD: There are 36 variables and 39 feedback loops. Variables added to the initial CLD from the Group 1 discussion are in blue. For ease of viewing, negative links are thick black, positive links are thin red.

and *sharing* as being important in the context of this discussion. We did not actively pursue discussions regarding city visions related to intermediate variables, focusing instead on *vision* for outcomes that cities identified as key, such as sustainability; *population health;* and *strong communities*. Subsequent discussions were in three broad areas: public transport, personal choice and land use. Although public transport has been widely addressed in previous (transport-based) discussions around CAM, the latter elements, in particular personal choice, are relatively novel concepts within this domain.

4.2.1.1. Public transport. Public transport (PT) was discussed in terms of *quality of infrastructure*, which was already in the CLD, but also *quantity of infrastructure*. The *quality of infrastructure* is linked to the physical environment, (*accessibility* and *availability*) and installation and maintenance costs (*competition for funds)*,whereas the *quantity of infrastructure* is focused on the volume of PT available to users, such as the network coverage and frequency (*connectivity* – to desired destinations*)*. It is constrained by the *competition for space* and contributes to determining the *quality of infrastructure*. Both *quality* and *quantity of infrastructure* influence the *utilisation rate,* which is also important as demand for PT services is required, or else even a high-quality service is left unused.

There is a lot of uncertainty involved in the introduction of CAM into PT, especially in the transition phase. An increase in demand increases *VMT* but CAM may also increase *AV efficiency*. Lower *VMT* can provide many benefits, such as better safety, better air quality, and more space for other activities. An increase in simultaneous ride sharing (rather than consecutive vehicle-sharing) has positive impacts, by allowing more person-travel to be provided per unit of vehicle-travel. Although not explicitly captured in the CLD, pricing models can influence the system; digital connectivity (e.g. vehicle-to-infrastructure communication) creates *data* (such as who is driving where) that can be used to develop pricing models and better services. For example, combination of parking fees and dynamic road pricing can be ways to have CAVs compete less with PT. An authority could charge more for CAV trips that are parallel to a major PT corridor or have only a single occupant. Furthermore, when no driver is required, this may enable a lower PT price, which may open up the possibility of new pricing models by the public authority. This said, CAM will have an equity impact on employment. Professional driving (in PT) is a major employment option for people with lower levels of education. If these *jobs* are no longer present, the city needs to consider what other options are open to these citizens.

4.2.1.2. Personal choice. Personal choice played a strong role in initial discussions, with participants acknowledging that, while choice of where to live, work, play and shop is a goal for many cities, unlimited choice of destinations and travel modes (within given time/cost thresholds) is simply unworkable. Providing services and networks that deliver this would be highly costly, complicated and lead to use of land for transport assets overwhelming space available for the destinations themselves. Attempting to do so may result in creating a poorly-functioning transport system and too much choice could lead to sub-optimal quality of life (people find difficulty in dealing with too many choices). In any case, although aspirational, it may be unrealistic to assume everyone would be able to access everywhere and be completely satisfied. *Conflict of choices* arises from *competition for space (via quantity of infrastructure)* and *funds(via quality of infrastructure)*. However, funding is not an absolute constraint but is, rather, a policy decision. Some other constraints are also more political than absolute, such as *information, jobs* and *quality of infrastructure*. The freedom to make choices enables choices that may not lead to system-optimal outcomes. Regulation and rules are there to limit these effects. Unlimited choices link negatively to air quality, safety, etc. Competition will also produce negative effects (e.g., not enough space for all desired uses; all parts of a city cannot be made equally attractive), thus not all connections are positive, providing some nuance to the initial model built from the pre-work Padlets (Fig. 3). Limiting factors include space, climate impacts, costs and political ability to manage towards a consensus that everyone can agree with. Different sub-groups experience different impacts. Cities have an obligation to manage towards consensus, but also for equity (access, equal distribution of infrastructure for different activities, and equity of different regions).

4.2.1.3. Land use. CAM could reduce required parking capacity, releasing space for other activities, but could also reduce city revenues if parking fees are currently levied. New revenue sources could arise with new land use. Public authorities manage space; introduction of demand management and pricing are levers they often hold. Group 1 also acknowledged the reality that, while cities may aspire to move space to higher uses than parking, parking fees are a significant source of municipal revenue in many places. Discussion turned to policy levers which can both nudge travellers towards less energy- and space-intensive modes, and form replacement sources of city revenue. There was a recognition of the importance of understanding foremost the desired transport and land use system, rather than allowing unregulated development – in other words, what is the city *Vision*. That said, although there are policy instruments that can affect consumer demand, there are also elements over which cities have limited control, such as *wealth* or *free time* (outside of travelling).

4.2.2. Group 2 discussions

The discussion held by Group 2, whose final CLD is presented in Fig. 5, was much broader than that of Group 1, though with focuses on two similar areas: public space and personal choice. Other areas of discussion included mobility services, and safety and security. The group recognised that a multi-functional city is more attractive for *Active Travel*, with less dependence on long commutes.

4.2.2.1. Mobility services

The transition towards mobility services (e.g., *Ride-hailing, Micromobility*) could significantly influence liveability in cities both positively and negatively. Mobility services can contribute to a reduction in *private vehicle use* (and subsequent negative externalities) and promote *equity*. On the other hand, they may compete with *active travel*, which in itself may have a greater positive influence on liveability. The success of mobility services may depend on CAM being used for shared (rides and/or vehicles), rather than individual private use.

4.2.2.2. Public space. Similar to Group 1, Group 2 recognised the important relationship and competition between *urban transport* and *use of public space*. For example, *pedestrianisation* can aid with *active travel, safety* and *equity*. However, there are business models (particularly in relation to mobility services) of commercialising public space, such as placement of *micro-mobility Hubs*, which could have both positive consequences (improved access, increased income to the city) and negative ones (reduction of public space; increased nuisance).

4.2.2.3. Personal choice. The group identified that a liveable city offers choice, which they viewed as *utility*, which also flows from *affordability* and *accessibility*. Choices include good availability of transport and employment options. Diversity and access to information are important in (equity of) choice. CAM can make cities more accessible but may diminish the sense of community if private trips allow quicker access to essential needs. CAM could help non-motorists and those who cannot access PT by providing a lower-cost mobility option than a taxi. On the other hand, if rides are not shared, CAM can be used to avoid human interaction. If a door-to-door service is provided, active and PT trips may also be avoided, and the additional convenience could lead to increase in trips. It is important that authorities introduce appropriate policies to mitigate negative effects. This could include access regulations such as congestion charging, which could also increase city revenue (with questions on where these funds may be directed. Authorities could also introduce mobility hubsto supplant door-to-door service.

4.2.2.4. Safety and security. Many cities are auto-centric. To improve *equity* and *population health*, the city needs to be safer (and be perceived to be so) for both non-motorised modes and PT. Use of these modes also depends on a certain level of security, with differing effects across the population. Linking back to personal choice, increased *safety* and security increases utility. If travellers feel less safe and secure on non-motorised modes or PT, they will be more likely to drive personal cars, which has negative externalities. More broadly, a sense of *safety* and security helps to strengthen local communities, improving their *resilience*.

4.3. Post-workshop CLD development

4.3.1. Stage 1: finalization of group CLDs

The CLDs that resulted from this stage of work were presented in Fig. 4 and Fig. 5. Although both CLDs have a similar number of variables, many more links were made by Group 1, resulting in many more feedback loops.

4.3.2. Stage 2: model merge

Following finalisation of the Group CLDs, the ambition of the project team was to merge the two models. As both models were built from the same base model (Fig. 3), we initially thought that this could be a

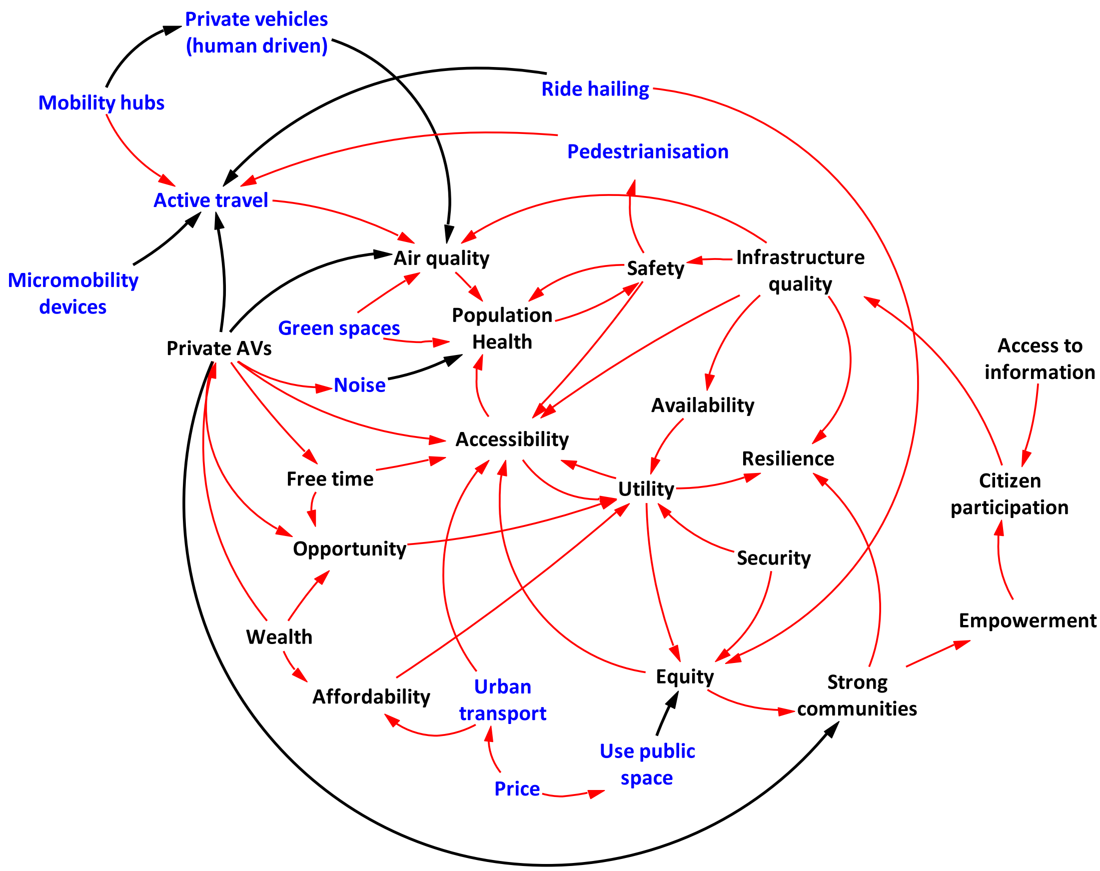

Fig. 5. Final Group 2 CLD: There are 30 variables and 9 loops. Variables added to the initial CLD from the Group 2 discussion are in blue. For ease of viewing, negative links are thick black, positive links are thin red.

straightforward exercise. However, interestingly, as the two groups had such different discussions, it quickly became apparent that the merging process would not be so simple if we were to adequately reflect the views of both groups. Therefore, the decision was taken to start with the Group 1 CLD and build the differences that were discussed by Group 2 into that CLD. We recognise that this may somewhat bias the final CLD towards the discussions of Group 1. With the two models merged, some of the larger causal pathways become clearer - showing connections from key input variables to key physical, social and cultural factors related to urban liveability.

4.3.3. Stage 3: model refinement

4.3.3.1. Resolving inconsistencies and incompleteness in language and logical structure. These resulting changes were mostly minor, and primarily made for clarity—for example, we changed *strong communities* to *community cohesion/strength*. In other cases, variables were re-worded to ensure they support the logical structure of the model—for example, *accessibility for everyone* became *attractiveness of city for disadvantaged populations*. Furthermore, some minor structural revisions were required, where causal links were removed when the logic was not fully supported, or where causal pathways could be better connected elsewhere.

4.3.3.2. Identifying and closing additional feedback loops. One of the benefits of the iterative revision process is that feedback loops may become apparent that were not initially identified. For example, the variable *support for public projects* was added to connect *community cohesion/strength* to *tax rate* (Fig. 6). This completes ("closes") a reinforcing feedback loop and supports a key insight—that a city only survives when there is public will to pay for it and the very vitality of any city is defined by community cohesion/strength, which both supports and is supported by public spending. Similarly, another potentially powerful feedback loop emerged with the addition of the variable *economic vitality*: as *accessibility* increases, *economic vitality* improves, which grows *tax collection* and *revenue,* which further support *quality of PT infrastructure*, which ultimately reinforces *accessibility*, and so on.

4.3.3.3. Improving visual arrangement and presentation. While this final step is not essential to the underlying logic (or ultimate operability) of the model, it can be essential for the value of the model as an external communications tool, by making it more accessible to unfamiliar audiences and by telling clear, compelling stories. Improving visual arrangement can also play an important role in sustaining the model as an internal systems-thinking tool. Improved visual clarity helps the project team identify feedback effects and draw new connections that establish new feedback effects. This step did not involve significant structural changes but was more a matter of arranging variables and links in a way that reveals the underlying structure of the model. The rearrangement helped establish a general flow of cause and effect from the left side to the right (see Fig. 7 and Appendix 5), to help illustrate the effect of different levels of quality and availability for different mobility options on ultimate liveability outcomes. In other words, this clear flow helps the model communicate its answer to the question:

> *How will the "Key Primary CAM Variables" affect "Key Liveability Outcomes"?*

When mapped onto our research question, this yields:

> *"How will the introduction of CAM (Private AV ownership, Shared AV service provision, and PT service provision) influence liveability in cities (Environmental Sustainability, Public health, Community cohesion/strength, and Economic vitality)?"*

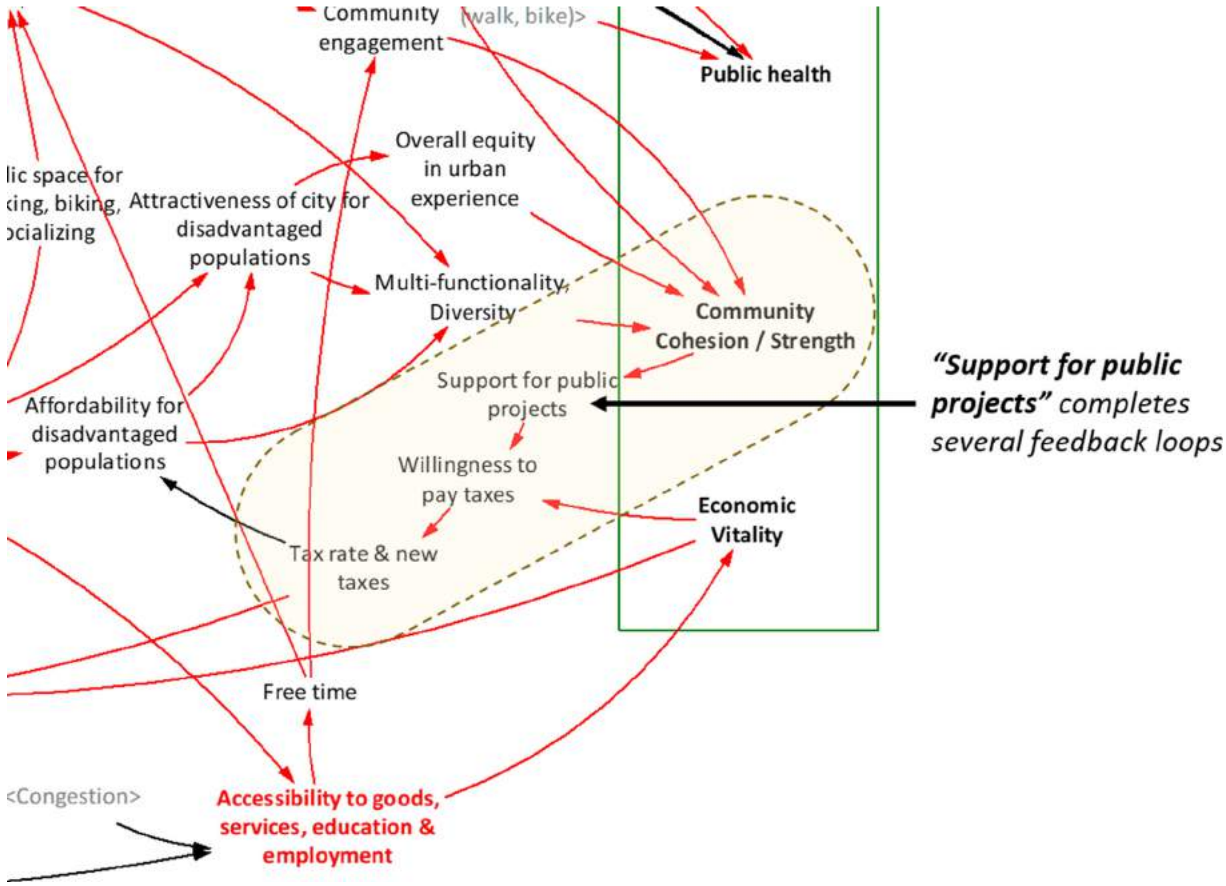

Fig. 6. Detailed view of key new variable, which connects several feedback loops.

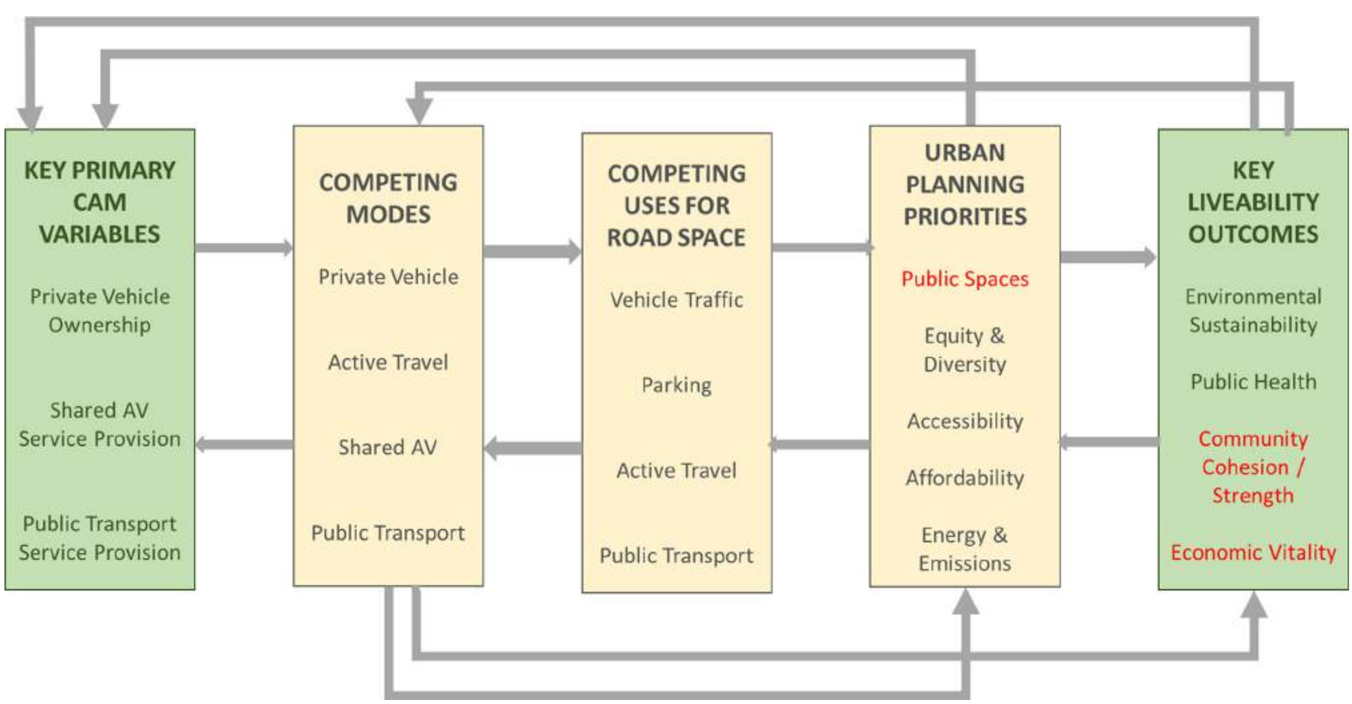

Fig. 7. High level summary of the fully integrated and refined CLD (full CLD in Appendix 5). Urban planning insights which differ from traditional transport perspectives are highlighted in red.

To further clarify the message of the model, the complex interactions among two clusters of variables were reduced and simplified, and we took liberty with certain conventions used in drawing CLDs. The clusters represent: (i) the competition among modes and (ii) competing uses for road space. Modelling the detailed mechanisms of these interactions would involve several more variables and links, making the model less readable, less accessible to external audiences, and less valuable as a systems-thinking tool. Therefore, instead of completing all the logical connections between the variables, they were labelled in yellow boxes. Finally, we drew a final clear box around the variables representing urban planning priorities that were revealed in the workshop and went beyond traditional transport perspectives.

4.3.3.4. Creating a high-level summary diagram. The resultant diagram is highly complex and may be difficult to interpret for a non-SD practitioner. Therefore, we further simplified the full final CLD in order to make it more understandable to planners and policymakers. We removed all intermediate variables other than the main clusters (competing modes, competing road space and urban planning priorities), as well as the causal link polarity. Thus, the high-level narrative of the CLD can be easily introduced before delving into the complexities of the full CLD.

4.4. Final CLD

Fig. 7 shows the high-level summary diagram, with the full final version of the CLD available in Appendix 5. It should be noted that the full CLD is a reflection of what was said during the workshop, and does not include every possible relationship. We capture our **key primary CAM variables** on the left, and the resultant **key liveability outcomes** on the right. Of these outcomes, two of the four are not traditionally considered in transport planning (community cohesion and economic vitality).

In both diagrams the main intermediate transport variables are the **competing modes** (which will all be strongly affected by the initial service provision variables) and the **competing uses for road space** (which will be largely determined by the outcome of competition among modes, although also by quantity and quality of infrastructure, as this competition is affected by the competition of road space overall with non-travel uses of the public space). These capture the 'traditional' transport perspectives we would perhaps expect, though also hinting towards a wider understanding of competition for public space . The elements of competition relate to the personal choice aspects which both workshop groups captured in their discussions. The focus on space, and on competition between transport and non-transport uses of space, was much more salient here than in traditional transport-focused workshops on CAM.

Exploring this wider perspective further, we remark that the "penultimate variables" (the proximate causes to the "key outcomes") are **urban planning priorities**, to which transport-focussed studies of CAM have paid little attention as a comprehensive group. Again, the interaction between city vision and urban transport planners' leverage in use of public space marks this work as distinct from most transport-focused work on CAM. For example, while there is an emerging literature on societal aspects of CAM (Milakis and Müller, 2021), and CAM studies attempt to determine the effects of CAM on energy and emissions (e.g. Brown and Dodder (2019), Stephens et al. (2016), Wadud et al. (2016)), model the effects of CAM on accessibility and equity in travel options (e.g. Nahmias-Biran et al. (2021), Cohn et al. (2019)) and even look at equity aspects of emissions from induced demand (Ezike et al., 2019), they tend not to link all of these aspects to use of the public space, instead focusing on policy decisions relating to use of vehicles (e.g. ride pooling) and technology (e.g. electrification). While pooling was a topic of discussion in the QoL workshop, a wider set of city-controlled levers was the greater focus.

5. Discussion & conclusions

The following sections discuss four key areas of insights regarding CAM and liveability from the full final CLD (Appendix 5), alongside illustrative extracts in which several variables and links have been moved and/or omitted for clarity. We focus on public benefits, reflecting the findings of Milakis and Müller (2021) that 'societal implications' are one of three key dynamics (alongside governance and acceptance) reflecting the societal dimension of ADS technology transition. In section 5.1 we focus on the key revealed 'urban planning priority', Public Space, then in the next two sections we focus on the two highlighted liveability outcomes of Community Cohesion and Economic Vitality. We then combine these insights for wider system perspectives in section 5.4. These are by no means the only areas of insight regarding CAM from this model, but seemed to us to be most relevant to understanding workshop participants' perspectives on liveability and how those go beyond the 'traditional' transport perspective. We then set out our thoughts on model quantification and our methodological reflections, before a final summary of our findings and conclusions.

5.1. Public space

Private automated vehicles (PAVs) share many of the same disadvantages as privately owned (human-driven) vehicles (POVs), in that they consume more shared resources than either the non-motorized or shared modes. If the service provided by shared automated vehicles (SAVs) can be good enough to lead to a reduction in private vehicle ownership, the reduction in private vehicle use may lead to additional benefit in terms of land use, energy and air pollution (Fagnant and Kockelman, 2014). There are four ways captured in the final CLD to decrease *private vehicle use* and thereby mitigate undesirable effects: through *road use pricing,* and by improving competing mobility options through policies and investments aimed at making *active travel, SAV use*, and *PT use* more attractive. This affects several key outcomes, as shown in Fig. 8, including some potentially powerful effects involving non-transportation uses of public space, beyond the land-use change relating to road and parking space focused on by previous authors (González-González et al., 2020, Soteropoulos et al., 2019).

For example, greater private vehicle use leads to more *air pollution, noise*, and the *traffic barrier effect* of having to cross a busy road to reach an attraction such as a park or waterfront. All of these reduce the *attractiveness of public spaces*, thus leading to less *social use of public spaces*, a diminished feeling of *security*, and potentially less *community engagement* (loss of informal meeting places). These weaken *public health*, and *community cohesion/strength* (Macmillan et al., 2020, Roe and McCay 2021). Other undesirable impacts include decreased *sustainability* (due to increased energy consumption and air pollution) and decreased *economic vitality* (due to traffic congestion reducing accessibility).

As shown in Fig. 9 below, the model also clearly identifies a feedback loop here, similarly identified by Macmillan et al. (2020) in relation to active travel, which would be driven as a vicious cycle with an increase in VMT: As *VMT* grows, *air pollution, noise*, and the *traffic barrier effect* all increase, which reduces the *attractiveness of public space*. As the *attractiveness of public space* decreases, the *social use of public space* decreases, reducing the *feeling of security in public space*, further decreasing the *attractiveness of public space,* and so on.

5.2. Community Cohesion/Strength

Both privately owned automated vehicles (PAVs) and (more importantly) SAVs, provided they are affordable, may lead to improved *mobility options for non-motorists*, leading to improved *community cohesion/strength*. Fig. 10 is an extract from the full CLD, which illustrates the relationships driving this outcome.

Firstly, as personal mobility is one of the key components of QoL identified by Aittoniemi et al. (2018), increased *mobility options for non-*

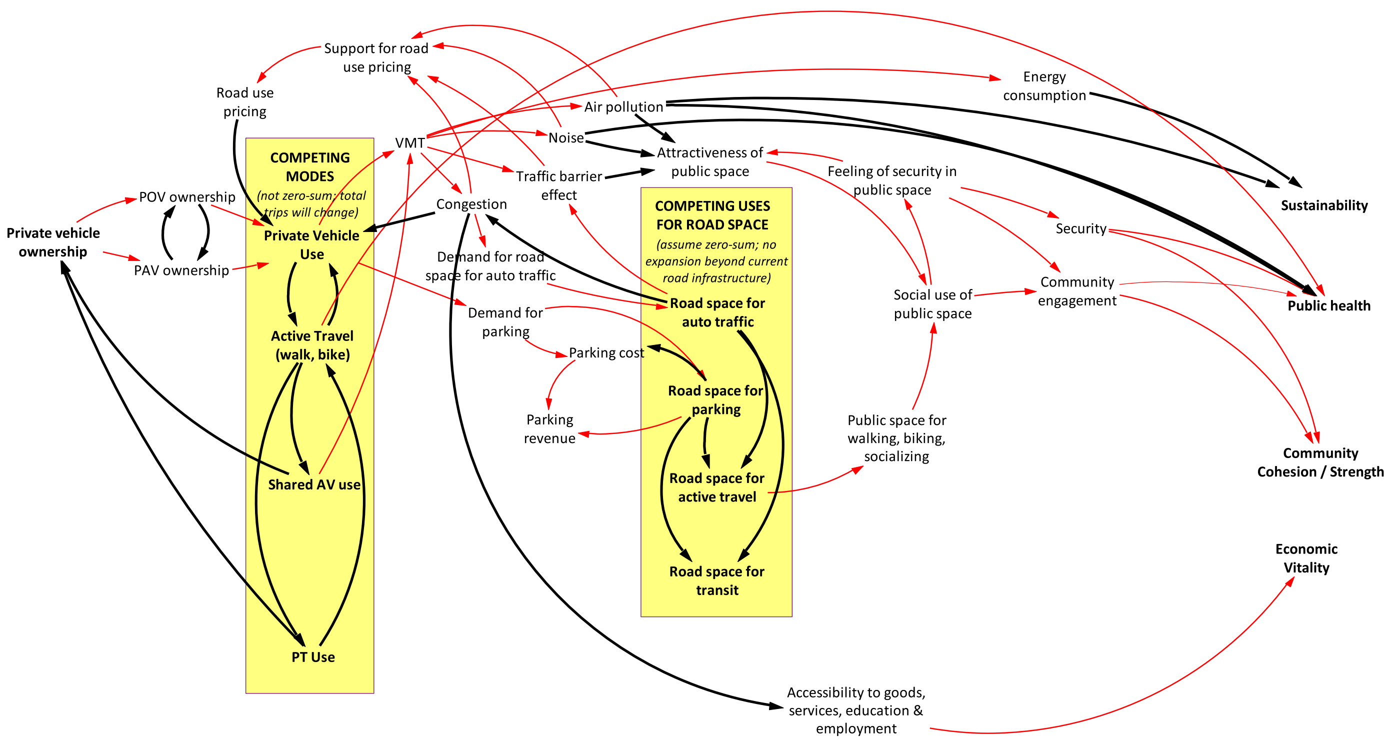

Fig. 8. Effects of private vehicles on public space(extract from full CLD—several variables and links have been moved and/or omitted for clarity)

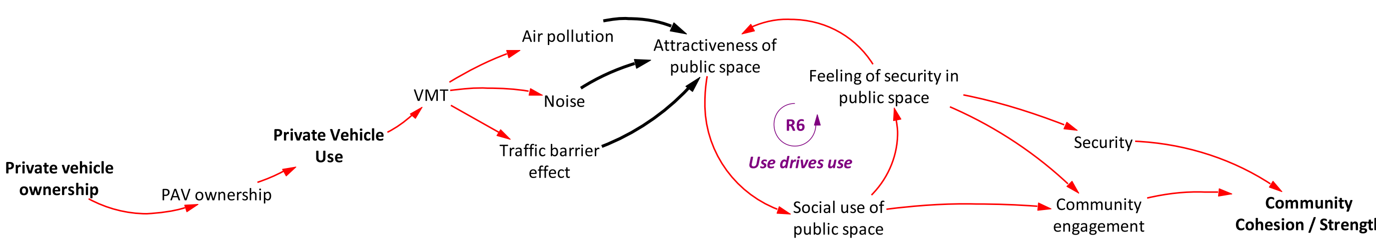

Fig. 9. Detailed view of feedback effect related to public space

motorists make the city more *affordable* and *attractive for transportation-disadvantaged population* (non-motorists – more likely to be lower income and/or elderly/disabled) (des Cognets and Rafert, 2019, Harper et al., 2016). This improves *overall equity in urban experience* as well as the city *multi-functionality/diversity*. Both of those factors improve the urban *community cohesion/strength*, as the population generally experiences the city on a more equal footing and fewer citizens feel "left out." Indeed, Macmillan et al. (2020) have already captured feedbacks between attractiveness of public space and community empowerment and Paddeu et al. (2020) have identified that equity and social inclusion were strong considerations regarding social acceptance of CAM.

Secondly, increased *mobility options for non-motorists* also has the potential to increase *accessibility to goods, services and employment*. We recognise though that this accessibility may not be evenly distributed (Milakis et al., 2018, Cohen and Cavoli, 2019). Improving *accessibility* can also increase the amount of *free time* which individuals have (Ezike et al., 2019). Though this may vary between socio-demographic groups (Pudāne et al., 2021), low income households have been found to take a substantial number of ride-hailing trips to avoid longer PT trips (Gehrke et al., 2018). The role of *free time,* often overlooked in more purely transport-focused workshops, is significant, and tells a compelling story that burdening a population with poor transportation options has harmful distal effects on *community cohesion/strength.* Put plainly, making everyone so busy just getting from place to place may mean that citizens can't connect with their neighbours, don't have time to go to community meetings, don't develop attachment to their city, and lack interest in investing in it, which may result in even poorer travel options, longer travel times, and so on: potentially driving vicious cycles of urban decline. Though we have captured the importance to urban planning of time outside the vehicle, often a focus of transport planners, another influence on *free time* not currently captured could be that of the in-vehicle value of time savings (Steck et al., 2018, Bjorvatn et al., 2021).

There are also a number of potentially significant feedback effects, which might drive *community cohesion/strength* much farther than the initial linear arrangement of causal links might suggest. For example, in Fig. 11, by adding three intervening variables (shown in purple in the diagram) we show how two reinforcing effects (R1 and R2) can emerge: *SAV service provision* may ultimately increase *community cohesion/strength*, which is likely to increase citizens' *comfort with ridesharing* (i.e., their willingness to take trips with people they don't know), which will increase the number of *SAV trips with ride-sharing*, as well as the number of *trips by PT*. Both of these factors will ultimately drive more service provision in both modes (PT and SAVs), completing two virtuous cycles which could compete with concerns that CAM may induce a mode shift from PT to AV (Lehtonen et al., 2021). This 'sharing breeds sharing' feedback loop mirrors previously understood 'safety/normality in numbers' feedbacks for walking and cycling (Jacobsen, 2003, Macmillan et al., 2014).

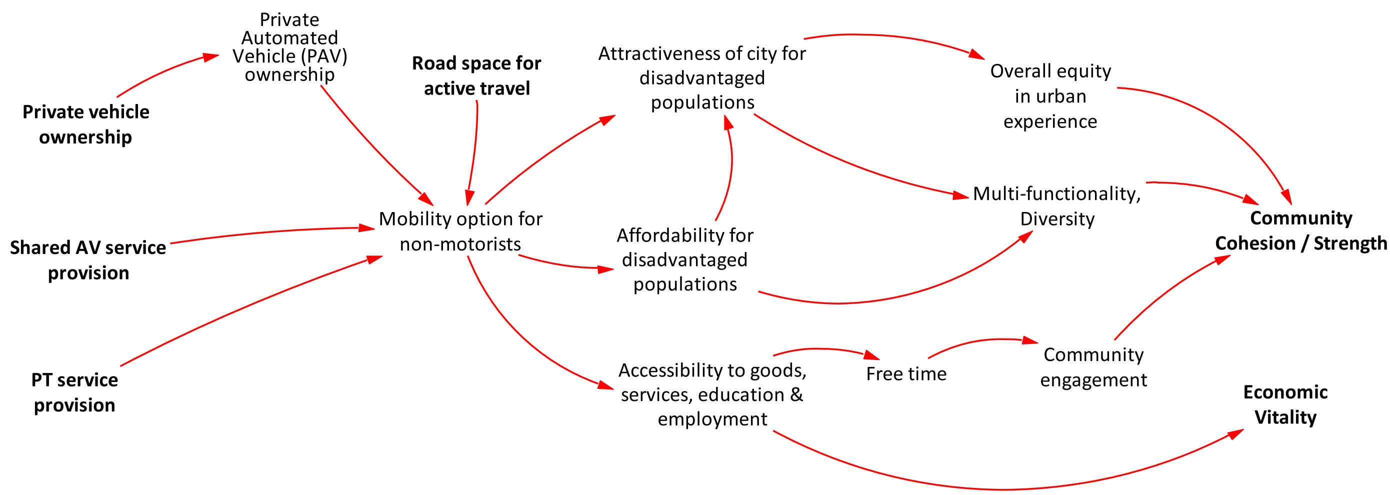

Fig. 10. Effect of improved mobility for non-motorists

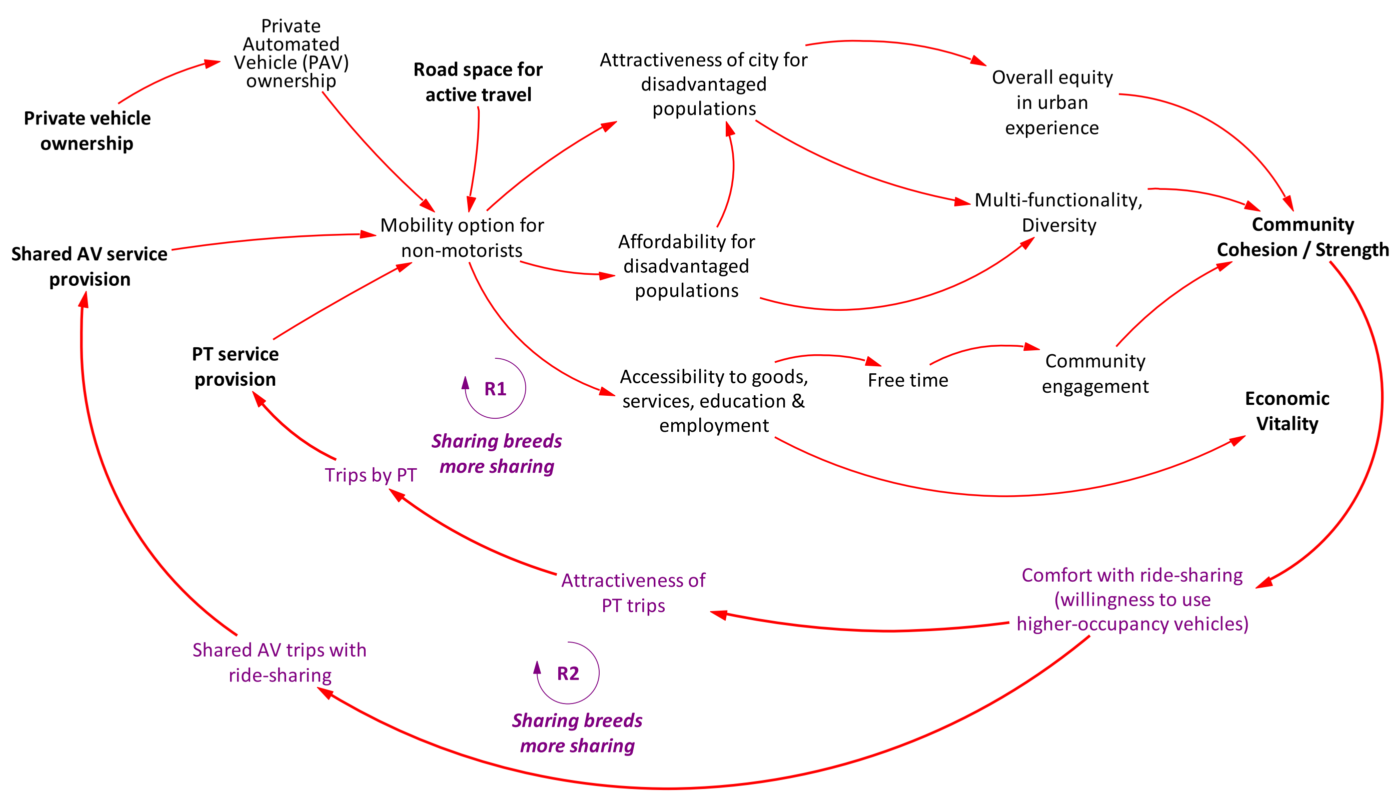

Fig. 11. Detailed view of potential feedback effects related to increased willingness to share rides (purple variables have been added to illustrate feedbacks not captured in the CLD).

Fig. 12 builds off the example in and includes one of the fundamental feedback effects that is key to PT service behaviour (R3). By adding the variable *attractiveness of PT trips*, we are able to connect *comfort with ride-sharing* to an increased number of *trips by PT,* which eventually (through links shown in the larger model) drives additional *PT service provision.* Although this may be in conflict with feedbacks suggested by other authors that AV could divert PT funds (Emory et al., 2022), it would increase higher-frequency service (with reduced headways and wait times), thereby further increasing the *attractiveness of PT trips*. These causal links complete the feedback effect R3, which in this example is shown as a virtuous cycle (note that this reinforcing effect, when it is driven in the opposite direction, is also commonly referred to as the "PT death spiral"). In addition, if SAVs are used as a first-mile/last-mile solution to supplement PT, we can capture this effect through the addition of the variable *mobility options for first-mile/last-mile.* Lau and Susilawati (2021) found that first/last mile SAVs could improve PT use, though this is dependent on the SAV waiting time. If successful, this will directly improve the *attractiveness of PT trips,* which, as noted above, could drive a virtuous cycle for PT (R3).

5.3. Economic vitality

Both groups discussed city finance, noting that in some locations, revenue from road use pricing and parking may be significant sources of city income. Previous authors have suggested that introducing road pricing and increasing parking fees may be required to constrain potential increases in VMT from the introduction of AVs (Shatanawi et al., 2021, Cohen and Cavoli, 2019). Higher *city revenue* may enable improved *PT*

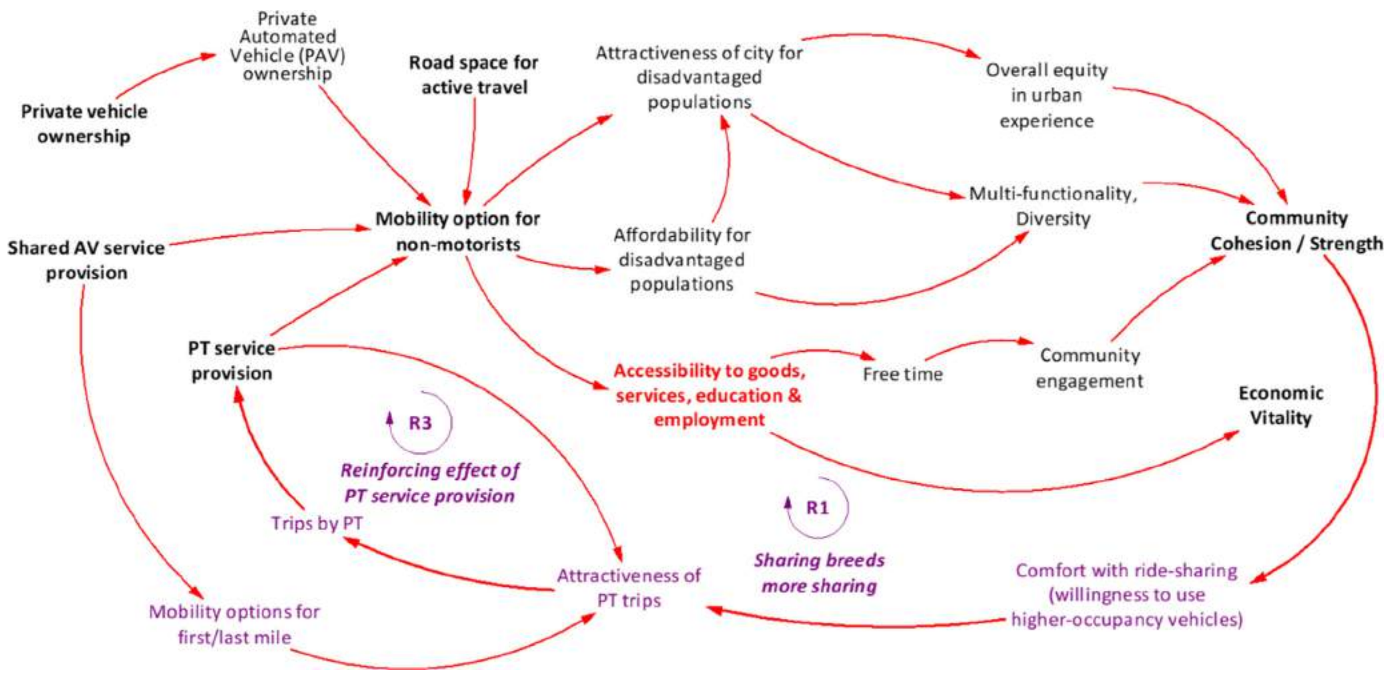

Fig. 12. Detailed view of additional feedback effects related to increasing the attractiveness of PT trips

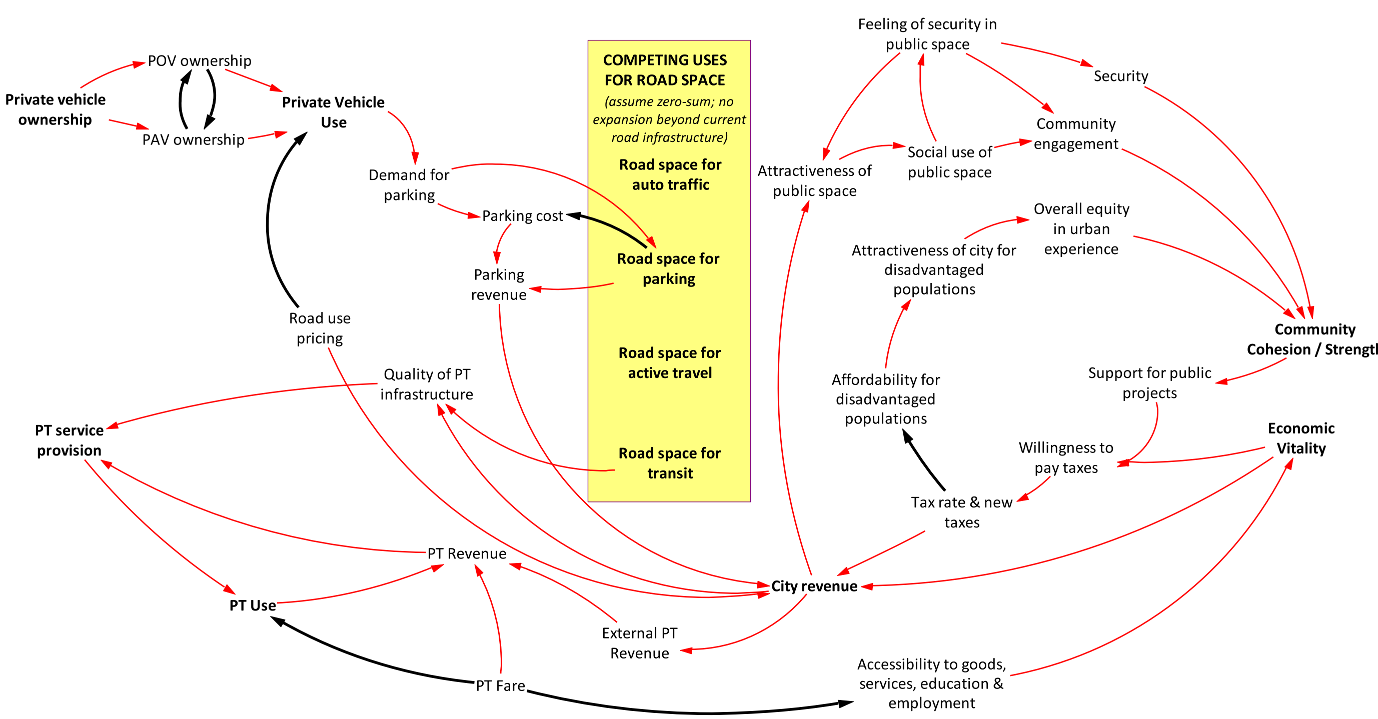

Fig. 13. Financial impacts

service provision and an investment in the *attractiveness of public spaces*. A stronger and more cohesive community is likely to have higher property values (Harnik and Welle, 2009) and is thus more likely to support investment in public projects (Putnam, 1995), so when initiatives arise that require raising revenue (through taxes or other means), they are more likely to be supported, which will allow the city to provide more funding for public space and PT services. That additional funding will lead to further improvements, thus completing a reinforcing cycle. Fig. 13 is an extract from the full CLD (Fig. 7) which illustrates these relationships. However, it should be noted that an increase in the tax rate may have a negative effect on the affordability for disadvantaged populations, and thus on equity objectives.

Fig. 14 highlights a few of the potentially relevant feedback effects related to city finances. The reinforcing loop R7 suggests that increases in city revenue driven by higher parking fees (*parking revenues*) and *road use pricing* could (at least partially) be committed to projects that improve the *attractiveness of public space.* Such investments (if done efficiently and effectively) could be self-reinforcing, as increasing *attractiveness of public space* will improve the *social use of public space,* which will drive *community engagement,* which should improve *community co-*

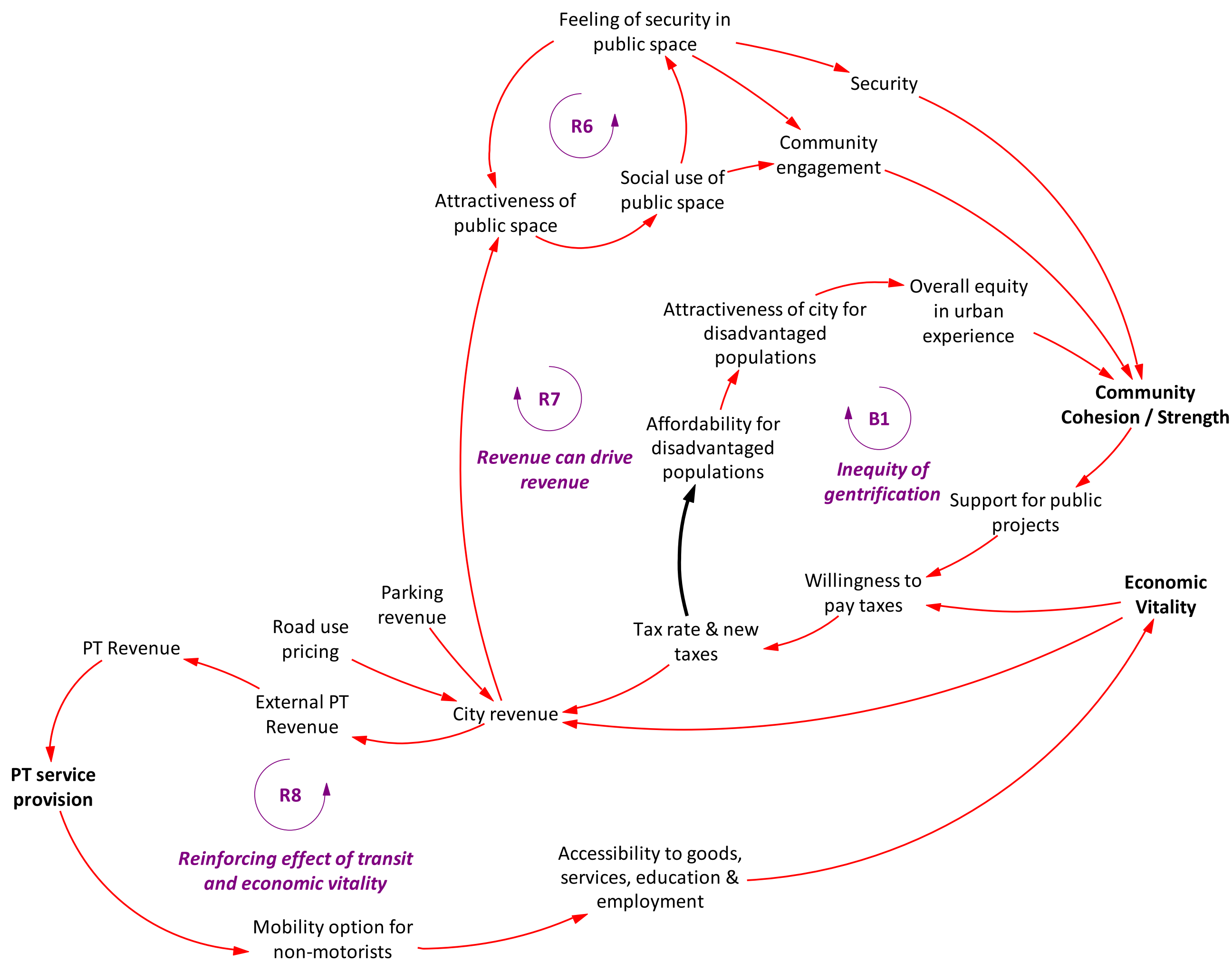

Fig. 14. Detailed view of a few key reinforcing effects related to city finances

hesion/strength. (Note that the reinforcing loop R6, discussed earlier, will further strengthen this larger reinforcing effect, R7). From there, we see that improvements in *community cohesion/strength are* likely to increase *support for public projects,* which will support citizens' *willingness to pay taxes*, which will allow for increases in *tax rates* and *new taxes,* further increasing *city revenue.* We recognise that these loops capture arguments for gentrification schemes, which may be criticised for their potentially negative impacts on social equity as poorer communities may be forced from the area, reducing social connection (Macmillan et al., 2020) (loop B1). Future development of these parts of the CLD may wish to also consider the wider costs of urban living such as housing and food. Furthermore, the loop identified in R8 suggests that increases in city revenues could trigger an additional virtuous cycle: if some of the extra *city revenue* is used to support PT (thereby increasing *PT revenue*), we'll see an increase in *PT service provision,* which will improve *mobility options for non-motorists,* which ultimately improves the city's *economic vitality*, further driving growth in *city revenue.* This loop illustrates the potentially powerful (and often-observed) relationship between effective public transportation and a city's economic vitality, although this also can feed into gentrification.

5.4. Combined effects (involving multiple areas of the larger model)

Each of the prior discussion sections examined key feedback effects associated with certain features of the overall model. However, there are also a number of significant feedback effects that can be identified when we consider the model in its entirety. For example, Fig. 15 identifies three such effects that might be triggered by the introduction of privately owned automated vehicles. As shown below, these appear to behave as "vicious cycles" if we assume an initial increase in *PAV ownership.*

5.4.1. R9 ("Vicious cycle of VMT, public space, and PT")

The (assumed) increase in *PAV ownership* increases *Private vehicle use*, which causes growth in *VMT.* As noted in section 5.1, increased VMT will harm public spaces, and ultimately reduce *community engagement*; this drives a series of causal relationships (as discussed above) that can reduce *city revenue*. If such a reduction in revenue persists and results in reduced *PT service provision, PT use* is likely to fall, as many travellers will respond to poorer service by switching to *Private vehicle use*, even further driving increases in *VMT*, and so on. This loop suggests that use of PAVs could drive a potentially powerful feedback effect involving VMT, the quality of public spaces, and the quality of a city's public transport system, adding a distinct space aspect to arguments for increased investment in PT in work such as Ezike et al. (2019)

5.4.2. R10 ("Vicious cycle of congestion and community cohesion")

As noted above, an increase in PAV ownership is likely to increase *VMT*. In addition to harming public spaces, this will also increase *congestion*, which will reduce *accessibility*, reducing the amount of free time citizens have to engage with their communities, which will erode *community cohesion/strength,* which—as noted previously—can drive causal

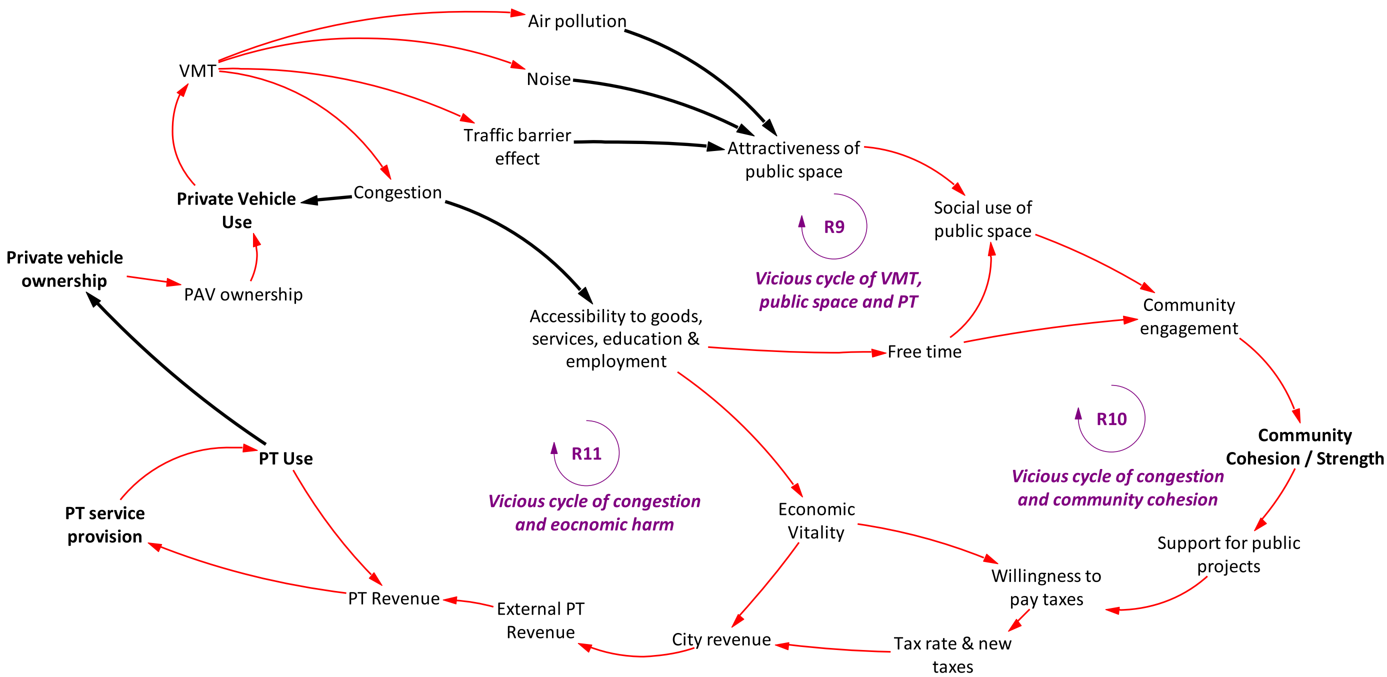

Fig. 15. Detailed view of feedback effects related to increased VMT and congestion (extract from full CLD—several variables and links have been omitted for clarity)

relationships that are essential to sustaining city revenues and providing essential services, such as public transportation. As identified in the discussion of R9, a sustained reduction in *PT service provision* can further drive increases in *VMT* and *congestion*, and so on.

5.4.3. R11 (“Vicious cycle of congestion and economic harm”)

.As noted for loop R10, the introduction of PAVs is likely to increase *VMT* and *congestion* and reduce *accessibility*. The reduction in *accessibility* will also harm a city’s *economic vitality*. As noted above, this drives a chain of causality that results in reduced *PT use* in favour of more *private vehicle use*, more *VMT*, and so on.

5.5. Model quantification

This particular stage of research was focused on the development of a qualitative CLD, without intention to develop a quantitative stock-flow model. It would be a large task to do so, considering all the linkages we found. However, this CLD, or parts of it, can be used in future research as the basis of development of a quantitative model. The variables and relationships identified can be further developed in order to construct simulation models by establishing the dynamic relationships either through further engagement with stakeholders or through existing literature. Although there is limited (if any) data currently available regarding CAM, and indeed not in a fully deployed capacity, many of the relationships which have been identified do already exist and so can be operationalised. Indeed, in addition to the CAM SD models already discussed in Section 3.1, there are already existing SD models that capture relationships inherent in active travel and health (Macmillan et al., 2014), transport and land-use (Pfaffenbichler et al., 2008), and urban resilience (Li et al., 2020). Our work here exposes the non-transport linkages (such as those around public space or sharing) and it is these which could be investigated further and added to existing models with some new relationships being imported from the literature or via primary data collection. There is an increasing volume of data available regarding urban mobility, as cities become ‘smarter’ and connected, proving potentially rich sources for model input and calibration. Development of such models and simulation of policy scenarios could be used to inform policy makers of the potential impacts of the introduction of CAM on liveability in cities.

5.6. Methodological reflections

In addition to our CLD insights, it is also important to reflect on the methodology we have developed and how it could be used in the future. Our methodological findings are in two parts: logistical and strategic.

From a logistical viewpoint, the online format provided a unique opportunity for cross-continental group model building, avoiding significant time, cost and environmental impact of international travel. This may be more commonplace as individuals across the world become acquainted with the online format, and has been the subject of previous papers (Zimmermann et al., 2021, Wilkerson et al., 2020, Jittrapirom et al., 2021). Furthermore, in our experience, online working has the potential to allow more perspectives to take part equally. A virtual workshop allowed cities, regions and PT agencies to send technical professionals, rather than only senior executives as would have been more likely to represent such organizations at international conferences, and also democratised participation for planning and modelling groups with lower budgets for research and external technical collaboration. On the whole, our participants were of a similar position within their respective institutions, making for a relatively comparable set of individuals – though we recognise that more diversity may require ‘more sophisticated facilitation techniques’ (Wilkerson et al., 2020). Managing dominant and shy participants can be challenging either in-person or online, but online these dynamics can shift as physical clues cannot be read and additional communication tools (raise hand/text chat functions) are available (Zimmermann et al., 2021). That said, we cannot overlook the value of additional informal communications – and even ice-breaking activities - that can be facilitated when meetings are in-person (Morrison-Smith and Ruiz, 2020), in particular in a collaborative process such as group model building, and the fact that power dynamics and biases may still remain in a virtual setting (Dhawan et al., 2021) and speaking time may not be equally distributed. Empirical research shows that required camera use during virtual meetings is more fatiguing for women than for men, and more harmful to women’s level of engagement (Shockley et al., 2021); we did not require camera use, but participants may have felt the expectation was there. It is also likely that many participants had previously met, or at least heard of, the other participants from their continent, but were unfamiliar with the participants from the other side of the Atlantic. Common ground from having worked together before, shared experiences, mental models, and even vocabulary have been identified as factors that can make distance collaboration more difficult (Morrison-Smith and Ruiz, 2020). Regarding mental models, a key aspect of group model building, we observed that views about the role of city planners, the levers available to them, and challenges such as displacement of public transport operator roles, may have differed across the Atlantic, but perhaps not as much as is commonly thought. Regarding vocabulary, indeed, a potentially overlooked issue is that of dialect and language between the participants—although EU participants may have been comfortable with using English as a second language in a work environment, the differences between terminology and concepts in European and American planning may have been more significant than we anticipated.

Regarding methodological strategy, we stand by the advantages of avoiding a scenario-based approach. Not leading off with scenarios led, we believe, to a much broader discussion that captured 'big' impacts and allowed greater understanding of complex feedbacks, without masking the complexities that exist in reality. Based on feedback from the participants, we recognise that though we deliberately kept the content broad, so that we would not obfuscate some significant concept, the lack of specific focus or scenario was challenging, with many ideas coming to the fore within a relatively short discussion period. As our background is transportation, and there are reasonably standard SD models regarding transport, we accept that we could have provided a starter model that incorporated these features and into which we built the QoL indicators. This not only could have saved time but also aided understanding and perhaps linked to mental models with which participants were more uniformly familiar. An alternative could be to provide longer workshops, but this itself is hindered by the practicalities of disparate time-zones and limiting screen-time to prevent fatigue. Reflecting on the need to add additional feedbacks to close loops in our CLD refinements, we accept that it is already established that individuals tend to think in short term causal chains but struggle with the concepts of feedback (Sterman, 2006). Without providing dedicated support to the participants in this form of system thinking, in some form of group model building script, closing loops can be challenging. In the case of this workshop, which was limited to three hours, this step was perhaps omitted though has been highlighted as being important in future work. The final reflection we have is regarding how much participants require briefing in SD concepts and methodology in advance of the meeting—and to what level this would aid rather than hinder the freedom of discussion and understanding of the complexities that are being addressed. We chose to provide a short overview at the start of the session of key CLD concepts rather than expect attendees to engage in complex pre-work (though the U.S. participants had some prior knowledge gain from related projects. This may have proved to be insufficient for their complete understanding and engagement, evidenced by the lack of closed loops and uncertain polarities, though that equally may have been due to time constraints.

5.7. Final summary

The objective of this work was to explore the question, *"How will the introduction of connected and automated mobility influence liveability in cities?"* In doing so, we have created a high level CLD that can be used as starting point for stakeholders to understand the key interactions and policy implications that yield insights to this question. Interestingly, the critical elements of our CLD map onto the three broad categories of liveability and mobility identified by Anciaes and Jones (2020): Movement (competing modes), Place (competing uses for road space) and Society (key outcomes).

The workshop revealed some city priorities that are different from what is often discussed in automation circles and in government transport roadmaps. Both groups converged on personal choice and equity, not on scenarios or business models, which is what transport operators tend to focus on. There was no mention by cities of being afraid of being left behind if they do not make it easy for technology developers to deploy in their territory, which is something that was a common discussion topic a few years ago. It was not clear if this was because the overall discourse has moved on, or that cities have a different perspective from those who come at things from the perspective of industrial policy, or frequent transport-focused conferences. Thus, we discovered, as transport researchers engaging with city planners, that the scope of transport policies is much wider than is often credited for in the literature. Although city stakeholders have an awareness that CAM will have an impact on liveability within their regions, they are actually to an extent agnostic about the general concept of CAM—rather, their concerns are directly related to the accessibility and opportunities that it would provide. However, the hopes and fears that arise from CAM are many.

Through the CLD we have gathered a number of reflections on the potential impacts of CAM, which could ultimately be relevant to the design of policies for both CAM and liveability, including the following examples:

- **Public Space:** CAM risks a continued lock-in of negative effects from privately owned vehicles, as there is likely to be an increase in VMT, leading to more air pollution, noise, and a stronger traffic barrier effect. In addition to the direct harm to sustainability, all of these factors will reduce the attractiveness of public spaces, ultimately harming public health and community cohesion. Both of these outcomes would drive several potential feedback effects, potentially greatly magnifying the initial impact of the introduction of PAVs and resulting in uncontrollable negative outcomes: increasing congestion, diminishing accessibility and free time (an effect consistent with the modelling performed in Ezike et al. (2019). The model also clearly highlights interventions that could mitigate these effects, especially if used early on: road use pricing and policies to support active travel, SAV use, and PT use.
- **Community Cohesion and Strength:** By increasing mobility options for non-motorists, CAM has the potential to improve a city's overall community strength and cohesion, through a variety of causal mechanisms, including: improving equity in the urban experience; enabling a more multi-functional and diverse city; and improving community engagement by reducing the time burden of less-effective transportation options. The improvement in mobility options will also improve overall accessibility to goods, services, education, and employment, with consequent benefits for the city's economic vitality. Such improvements in community engagement and economic vitality can drive a number of powerful feedback effects, which—given the right policy interventions—could be harnessed to produce desirable outcomes potentially beyond the scale of the initial investment.
- **Economic Vitality:** Key financial levers, such as road use pricing and parking revenues can drive a virtuous cycle (reinforcing effect with positive outcomes), by enabling investment in improved PT and more attractive public spaces, both of which can improve community cohesion and strength, leading to increased city revenues, driving economic vitality.

It is important to note that the feedback effects discussed here are a few key examples among many such effects that may be identified and articulated by the overall model. The effects discussed here are not intended to represent a comprehensive list—rather, they are intended as examples of the types of insights that such a model can bring to light, and in particular draw out new insights related to urban planning which may be overlooked when approaching this from a traditional transport perspective. While we examined feedback effects involving two of the key outcomes of the model, *community cohesion/strength* and *economic vitality*, we can expect several other feedback effects to exist that involve the other two key outcomes: *sustainability* and *public health*. For example, we would expect that improving *public health* outcomes would improve *economic vitality*, as it would improve worker attendance and reduce the burden of healthcare expenses on individuals and businesses. Similarly, by reducing the need for public spending on healthcare, additional public funds would be available to spend in ways that would further improve *public health* (e.g., investing in infrastructure for non-motorized modes), thereby completing a reinforcing loop. Developing a large, highly conceptual CLD is often a highly iterative process of ongoing refinement and discovery. This is especially true when separate models are merged, drawing on diverse perspectives and fields of expertise, as it may take multiple revisions to fully understand and harmonise the ideas and observations that went into building the initial models. Ultimately, the model is intended as a "living" tool that can be adapted and used by others to continue to explore and generate additional insights.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.urbmob.2022.100034.

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Assessment of the usefulness of the accessibility instrument GOAT for the planning practice

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ABSTRACT

Accessibility instruments could serve as powerful support in assisting planning practitioners. Though, accessibility instruments are usually not yet applied in practice. Past research has identified that besides institutional barriers in adopting accessibility, there is still a lack of useful instruments. It is suggested that tool developers engage closer with planning practice to better meet requirements from practice. The authors developed an interactive and web-based accessibility instrument called GOAT, focusing on active mobility in a co-creative environment with urban and transport planning practitioners. This manuscript aims to answer two research questions. Which planning questions exist for GOAT in the field of transport and urban planning? Is the accessibility instrument GOAT of useful support in the planning practice?

First, suitable planning questions were identified. The tools' utility and usability for the planning questions were self-assessed based on the experience in five applications workshops with 37 planning professionals in four German cities. The assessment was realized by analyzing workshop minutes and worksheets for the different planning questions. As a result, the usefulness was assessed for the planning questions and was summarized into four groups: Infrastructure Planning Walking, Infrastructure Planning Cycling, Location Planning, and Housing Development.

The assessment revealed that the tool helps answer common planning questions. In terms of usability, the tool could also be used by individuals unfamiliar with existing planning software after a half-day introduction. Meanwhile, practitioners requested further indicators and improvements in usability. Furthermore, stronger technical integration with existing systems should be envisaged. It is concluded that the involvement of planning practice was highly beneficial when developing and assessing the tool. Therefore, ongoing exchange and a long-term assessment of the tools' usefulness are suggested in the future.

1. Introduction

Active mobility is gaining escalating attention, while concepts such as the 15-min city have been presented as a vision for sustainable cities Cities (2020); Moreno, Allam, Chabaud, Gall, & Pratlong (2021); Pozoukidou & Chatziyiannaki (2021). Promoting active mobility is consistent, as no other mobility option combines benefits ranging from space efficiency, carbon neutrality, livability, and positive health impacts FGSV (2014); Kahlmeier et al. (2021); Koszowski et al. (2019).

There is consensus that active mobility, among others, requires an urban pattern characterized by relatively high density and diversity of opportunities, alongside appropriate transport infrastructure Buehler, Pucher, Gerike, & Götschi (2017); Kang (2015); Koszowski et al. (2019); Stead & Marshall (2001). In other terms, active mobility relies on high local accessibility Silva & Larsson (2019). The concept of accessibility, first defined by Hansen (1959), has been present in research for decades. However, little adoption in practice can be observed so far. Among other reasons, it is underlined that accessibility instruments are not yet meeting planning practice expectations (see Section 2.2).

Accessibility instruments are nowadays usually GIS-based tools to operationalize the concept of accessibility and therefore support planning processes. Accordingly, accessibility instruments are a subset of planning support systems (PSS) Papa, Silva, te Brömmelstroet, & Hull (2015). PSS promise to be appropriate tools for evidence-based and effective planning Geertman (2006); Geertman, Stillwell, & Top-

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pen (2013); Klosterman (1997). However, there has been an imbalance between the supply and actual use of PSS since the beginning. This phenomenon, usually labeled as the *implementation gap* is discussed intensively in literature te Brömmelstroet (2010); Geertman (2006); Russo, Lanzilotti, Costabile, & Pettit (2017); Vonk, Geertman, & Schot (2006). It is argued that PSS lacks usefulness te Brömmelstroet, Curtis, Larsson, & Milakis (2016) or relevance for the planning practice.

To develop more useful instruments it is suggested to actively involve planning practitioners when developing PSS te Brömmelstroet (2010); Russo et al. (2017); Silva, Bertolini, te Brömmelstroet, Milakis, & Papa (2017). In this context, the authors developed Geo Open Accessibility Tool (GOAT) Pajares, Büttner, Jehle, Nichols, & Wulfhorst (2021a), an accessibility instrument focusing on modeling walking and cycling. It was developed in an applied research project in a co-creative and open environment with planning practitioners. The authors aim to help bridge the gap between research and practice in accessibility planning with the presented instrument. Early testing and application in practice heavily influenced the ongoing development process despite the development's initial direction. Previous publications on GOAT mainly focused on its technical background and the development process Pajares et al. (2021a); Pajares, Muñoz Nieto, Meng, & Wulfhorst (2021b). Therefore, this presented manuscript focuses on identifying its relevance for practice.

In particular, it should be studied if there are existing planning questions in the field of urban and transport planning in which the instrument is of useful support in practice. This study defines usefulness by the tool's utility and usability (see Section 4.3).The following research questions should be answered:

- RQ1: *Which planning questions exist for GOAT in the field of transport and urban planning?*
- RQ2: *Is the accessibility instrument GOAT of useful support in the planning practice?*

While there is a clear focus on the instrument GOAT, some results can also be generalized. In particular, the presented results should help other tool developers to identify further development needs. Furthermore, the experience during the co-creative development process can help other tool developers. For the planning practice, this contribution can reveal the potential for accessibility-based planning and the use of accessibility instruments.

First, the literature review in Section 2 should provide a better understanding of the current state-of-the-art in the field of PSS and accessibility instruments. Afterwards in Section 3 the GOAT project is presented to provide the technical background for the study. Subsequently, in Section 4, the methodology consisting of literature review and the co-creative application workshops will be introduced. After that, the results will be presented in Section 5. A discussion and conclusion will follow in Section6.

2. Literature review

2.1. Planning support systems in practice

Harris first proposed the definition of PSS as a "systematic process of sketch-planning" Harris (1989). Geertman (2006) defines PSS as:

> *"the PSS, can be understood as geoinformation-technology-based instruments that incorporate a suite of components (theories, data, information, knowledge, methods, tools) which collectively support all or some part of a unique professional planning task"*

The basic structure of PSS involves a database, model, and decision-making, which gives planners the ability to understand the inputs and outputs of the program Zhang, Hua, & Zhang (2016). In essence, a PSS is a tool for assisting urban planners with planning strategies, models, and visualizations Geertman, Allan, Pettit, & Stillwell (2017).

With the advancement of interfaces and algorithmic planning, many examples of PSS applications are now available. Early programs such as *Online What If? (OWI)* and *UrbanSim* have been used in practice for the last 20 years for their ability to model interrelationships between transportation and population, for instance Geertman et al. (2017); Pettit, Biermann, Pelizaroc, & Bakelmun (2020). Some different uses for PSS include, but are not limited to, disaster management Oki & Osaragi (2017); Osaragi & Noriaki (2017), transport management Meng, Allan, & Somenahalli (2017), and urban planning Leao, Huynh, Taylor, Pettit, & Perez (2017)). However, there is a distinction between systems that can present and visualize static data and ones where that can simulate scenarios and situations. Programs like *OWI, ENVISION*, and *CommunityViz* can be used for scenario planning by using static data and given specific parameters. On the other hand, programs like *UrbanSim* and *UrbanCanvas* are used as simulators and modeling tools for scenario planning Pettit et al. (2020). Depending on different situations, different uses and programs can be designed to assist with respective solutions.

Essential to the functionality and widespread use of PSS are its usefulness, usability, and the understanding of such programs Pettit et al. (2020), Russo et al. (2017). te Brömmelstroet & Bertolini (2010) argue that with the growing importance of integrated sustainable land-use and transport planning, the most significant barriers for application in practice are different tools, priorities, and functional tasks between urban and transport planning offices. Some PSS tools can bridge this gap. However, they can and have also stood as an "implementation bottleneck" to the process when tool development and practice are not well-linked te Brömmelstroet & Bertolini (2010). These bottlenecks are broken down into three groups by Jiang, Geertman, & Witte (2020). The first group comprises the number of unusable PSS tools published that lack usable attributes, transparency, or evidence of their efficacy when used. The second group comprises a lack of acceptance by planning offices due to misunderstanding of the tools or perceived risk of use to make major decisions. Finally, the third group includes learning ability and time to use PSS properly. te Brömmelstroet (2017) challenges PSS applications one step further and criticizes the research field for its focus on the user-friendliness of the instruments rather than their usefulness.

There are many proposed solutions to these issues, with some already implemented in the PSS field. In general, there are many proposals for including different stakeholders in the development of PSS that can streamline communication and create a useful feedback cycle Jiang et al. (2020); Vonk et al. (2006). Cooperation between PSS developers, particularly universities and planning offices, can also lead to better results in the application of PSS Geertman & Stillwell (2020); Luque-Martın & Pfeffer (2020). Another suggestion by Geertman & Stillwell (2020) is better education within the planning field on PSS and its benefits on evidence-based planning decisions at early stages in planners' careers. The primary differentiation in land-use and transport planning challenges PSS integration into the fields.

The review of existing PSS literature shows that instruments have been developed for at least three decades. Meanwhile, there is a high awareness of the lack of successful practice applications. Lacking usefulness is of particular importance for this manuscript. The useful support in concrete planning questions is seen as a minimum requirement for applying the developed tool GOAT in practice. Further factors such as institutional barriers are seen as equally important but will not be addressed in this manuscript.

2.2. Accessibility instruments and their potential

The earliest known definition of accessibility to the field was by Walter Hansen as "the potential of opportunities for interaction" Hansen (1959). Since then, there have been attempts at further studying, understanding, and measuring accessibility. The broad spectrum of accessibility was categorized by Geurs & van Wee (2004) into four components: transport, land-use, temporal and individual. These different dimensions of accessibility can be operationalized using suitable indicators commonly known as accessibility measures. Geurs & van Wee (2004) define four groups of accessibility measures: infrastructure-based, location-based, person-based and utility-based. Ideally, an accessibility measure should take all four accessibility components into account Geurs & van Wee (2004). Accessibility instruments can be seen as a subset of PSS. Papa et al. (2015) defined accessibility instruments as:

> *"Accessibility instruments (AIs) are a type of planning support system (PSS) designed to support integrated land-use transport analysis and planning through providing explicit knowledge on the accessibility of land uses by different modes of transport at various geographical scales."*

It is considered that they bear a large potential to provide planners with planning support when analyzing the complex relationship between transport and land-use te Brömmelstroet et al. (2016); te Brömmelstroet, Silva, & Bertolini (2014); Hull, Bertolini, & Silva (2012). More specifically, it is stated that accessibility instruments have the potential to be utilized as a shared language between disciplines, namely urban and transport planning Büttner, Kinigadner, Ji, Wright, & Wulfhorst (2018); te Brömmelstroet et al. (2016). A further advantage of accessibility instruments is that they can produce analyses on various spatial resolutions and all transport modes, including walking and cycling.

Besides the described benefits, accessibility instruments are not yet widely used in practice Bertolini & Silva (2019); Boisjoly & El-Geneidy (2017); te Brömmelstroet et al. (2016, 2014); Hull et al. (2012); Papa et al. (2015). Accordingly, accessibility instruments face an implementation gap between research and practice like other PSS. Following the literature, there are several reasons for this. Levine (2019) is stating that strict mobility metrics persist because transport engineering and urban/regional planning are explicitly instructed to use them. Furthermore, it is mentioned that accessibility is often conceptually misunderstood Levine (2019). There is evidence of a 'disconnect' between the tool developers and the users te Brömmelstroet et al. (2016). In addition, the availability of data is mentioned as a barrier to the broader application of accessibility instruments by tool developers Papa et al. (2015) and practitioners Boisjoly & El-Geneidy (2017); te Brömmelstroet et al. (2014). Also, practitioners report a lack of knowledge Boisjoly & El-Geneidy (2017) and resources in their institutions for the application of accessibility te Brömmelstroet et al. (2014). Past research has also shown that a powerful way to increase the usability and usefulness of tools being developed is the close involvement of potential users in the development process Bertolini & Silva (2019); te Brömmelstroet et al. (2016, 2014); Silva et al. (2017).

The research project (COST Action TU1002) showed that the feature that practitioners most desired was the real-time calculation of scenarios te Brömmelstroet (2017); te Brömmelstroet et al. (2014); Silva et al. (2017). Also, the potential of web technology to foster easier use and the involvement of more stakeholders are described to bear high potential Büttner et al. (2018); Venter (2016). An updated review of 26 accessibility instruments showed that instruments were developed significantly further, and many new tools were released. Following the fast development of WebGIS technology, a large share of web tools was observed among the studied instruments Pajares et al. (2021a). However, from the review Pajares et al. (2021a), no tool was found that combines the attributes: interactive scenario building for street network and land-use, open source development, focus on active mobility, and web-based. The development of GOAT was theoretically addressing the described gap and aimed to involve practitioners in the development process. Meanwhile, the concrete usefulness of the tool for practice remained unclear and, therefore, will be studied in this manuscript.

3. Accessibility instruments GOAT

In the following, a brief overview of the software GOAT is provided. Besides describing the core characteristics of the accessibility instrument, the technical architecture, data sets used, and core indicators are presented.

3.1. Overview GOAT project

The development of GOAT intends to help bridge the described gap between research and practice in accessibility. Currently, the instrument focuses on modeling accessibility for walking and cycling and local accessibility. In addition, it includes barrier-free and electric bike analyses. The GOAT project started with a Master's thesis Pajares (2017) and is currently taken forward as part of a dissertation project Pajares (2019); Pajares et al. (2021a). The software is developed open source GOAT-Community (2021a). GOAT has been used in applied research projects and was transferred to at least 27 municipalities. Out of them, there were five international applications: Bogotá (Colombia), San Pedro Garza García (Mexico), Matosinhos (Portugal), Boca Raton (Florida), and Atlanta (USA). The rest of the applications were in the German context.

GOAT tries to position between a simple web tool and a fully-featured desktop GIS in terms of functionality. By positioning in this niche, GOAT shares some similarities with existing accessibility instruments like CoAXs Stewart & Zegras (2016), TRACC Basemap Ltd (2022) or Conveyal Conveyal (2022). One core aim is that the application is usable by planning professionals not being familiar with GIS. Unlike most accessibility web tools, GOAT allows users to perform scenarios on the street network, points of interest, and buildings Pajares et al. (2021a). Based on the scenarios, changes in accessibility can be computed and visualized. Accessibility is interpreted using contour and gravity-based accessibility measures (see Section 3.3). A planning scenario can be drawn directly using the web interface or imported using the GeoJSON-format. Therefore, scenarios can be created outside of the application and re-import at a later moment. The development is characterized by an open and co-creative environment involving practitioners from the field of urban and transport planning.

In the following, the focus is particularly on three case studies in the Munich Region (Munich, Fürstenfeldbruck, Freising) and, to a smaller extent, on the case study in the city of Freiburg. The online version of the tool was launched in different years for the cities: Munich (2019), Fürstenfeldbruck (2020), Freising (2020), and Freiburg (2021). Meanwhile, the applied version of the tool and the used data sources varied between the different deployments. To the date of writing this manuscript, the tool was openly available online for the four mentioned cities. GOAT is provided open access on the project websites GOAT-Community (2021b); Plan4Better GmbH (2021). Besides the tool itself, the websites host step-by-step tutorials and documentation on the indicators, data, and software libraries being used.

3.2. Technical architecture

GOAT uses the classical server-client architecture of the web and is built solely using open source software (see Fig. 1). The backend is built around a PostgreSQL database, which is spatially enabled by the extension PostGIS. The backend analyses are realized using SQL, PLpgSQL, and Python. The database contains non-spatial and spatial data, as well analytical functions for the computation of the implemented accessibility measures and spatial operations (e.g. spatial intersection). Traveltime calculations are done using a custom implementation GOAT-Community (2020) of the pgRouting extension pgRouting Community (2022). The interaction with the database is handled by an API written in Python. The results of the analyses are communicated to the client using different non-spatial (JSON) and spatial formats (GeoJSON, Gebuf, Vector tiles). The client of the application is written in Javascript using the Vue.js framework and Openlayers as a map library.

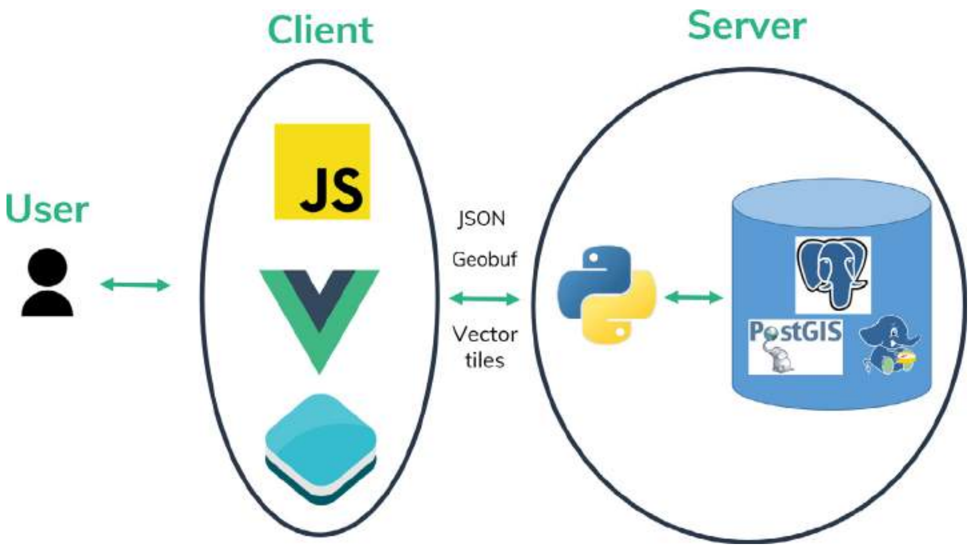

Fig. 1. Technical architecture GOAT.

Table 1
Data sets used.

Dataset	Purpose	Source
Points of Interest	Opportunities data set	OSM, own collection in OSM, Provided by Municipalities
Land-use	Population disaggregation, Visualization	OSM, Landesamt für Digitalisierung, Breitband und Vermessung Bayern, Urban Atlas - European Environment Agency (EEA)
Buildings	Population disaggregation	OSM, Landesamt für Digitalisierung, Breitband und Vermessung Bayern, Provided by Municipalities
Population grid	Population	ZENSUS 2011
Administrative areas with population	Population	Provided by Municipalities, Bundesamt für Kartographie und Geodäsie, Landesverkehrsmodell Bayern
Street imagery	Visualization and Mapping Mode	Mapillary, own collection in Mapillary
Street network	Routing	OSM, own collection in OSM
Elevation	Routing	European Environment Agency (EEA)
Accidents pedestrians and cyclists	Visualization	Statistische Ämter des Bundes und der Länder
Data on environmental quality	Visualization	Bayerisches Landesamt für Umwelt, FreiGIS
Bike counting data	Visualization	Geodatenservice München
Modal split	Visualization	Mobilität in Deutschland (MiD)
Basemaps	Visualization	OpenStreetMap, Mapbox, Bing

The tool was equipped with diverse (spatial) data for the different case studies and installed on a cloud server using Kubernetes. Data is seeded into the application using different data preparation, disaggregation, and fusion steps. Depending on the region deployed, there are used different data sets. Meanwhile, GOAT can theoretically work solely with OSM and population data sets. However, other (open) data sources are used to yield a higher data quality and completeness. The most important data sets used are summarized in Table 1.

3.3. Implemented indicators

The instrument is modeling and visualizing accessibility through an interactive web map. It interprets accessibility using contour and gravity-based accessibility measures from the group of location-based measures Geurs & van Wee (2004). Furthermore, different spatial data such as data on traffic accidents, street imagery, land-use, and modal split can be visualized and styled on the map. Fig. 2 visualizes the core indicators of the application.

As contour measures, two forms of isochrones are implemented. Single-isochrones are catchment areas from one starting location. The isochrone polygon shape intersects with the opportunity data set and population data to calculate cumulative opportunities. Results are visualized on the web map and a table. The second isochrone type are multi-isochrones. For multi-isochrones, the user either defines an area of interest by drawing a study area polygon or picking one or more city districts. Based on the user selection points of interest categories are considered. The coordinates of points of interest are taken as starting points. The individual isochrones are unioned and intersected with the population data. As a result the multi-isochrones are shown on the map and the share of the served population located within the study area of choice is listed in a table in relative and absolute numbers. Both isochrone types can be calculated with all supported routing modes and reflect all forms of scenario building (network, points of interest, and buildings). The user can adjust travel speeds for the different routing modes.

A third indicator is described as a connectivity heatmap. In the authors ’ opinion, the indicator can be positioned between infrastructure-based and contour-based accessibility measures. The heatmap is computed using a hexagonal grid with an approximate edge length of 150 m per cell for walking mode (5 km/h). Three isochrones (5, 10, and 15 min) are pre-computed using the centroid as a starting point for each grid cell. The size of all three isochrones is summarized per cell and compared with all other cells using statistical quintiles. The grids are colored from high (green) to low connectivity (red). Changes in the street network are reflected by recomputing parts of the heatmap and updating the statistical classification. As a gravity-based accessibility measure, an additional heatmap is implemented. The heatmap is created based on pre-computed traveltimes. Traveltimes are computed for

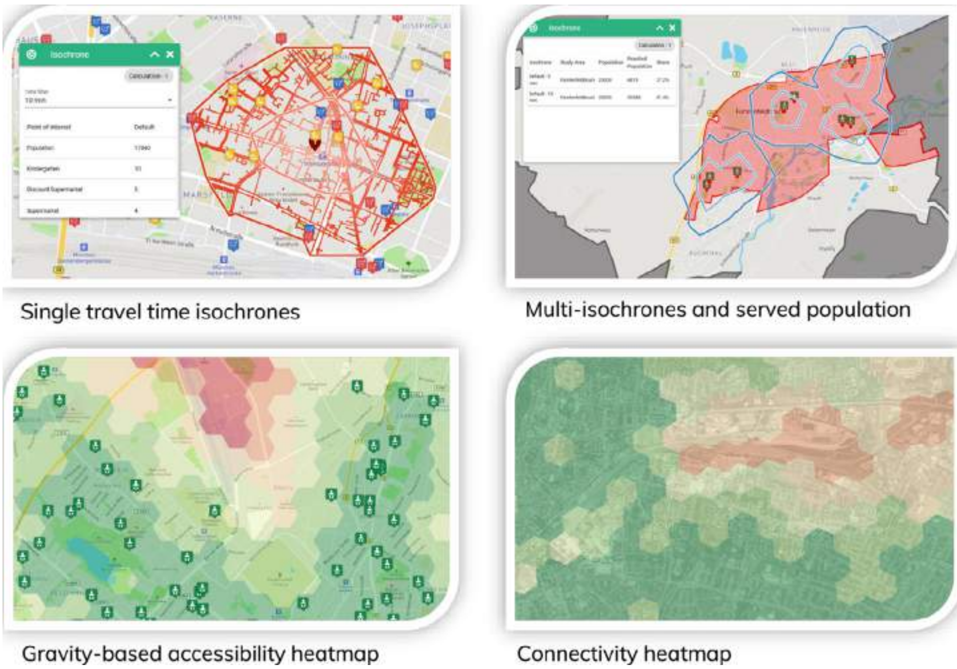

Fig. 2. Core indicators GOAT.

walking (5 km/h) for each grid to all points of interest within a 20-min cutoff. Accessibility values are computed per grid using the widely applied formula:

$A_i = \sum_j O_j * f(t_{ij})$

As impedance function a modified gaussian function is implemented:

$f(t_{ij}) = e^{t_{ij}^2/\beta}$

The heatmap is dynamically created for the selected point of interest categories based on the pre-computed traveltimes. Furthermore, the user can customize the heatmap by giving each point of interest category a weight and choosing an appropriate sensitivity value. Therefore, individualized composite indicators can be built by the user. Currently, the gravity-based heatmap only reflects scenarios on points of interest.

4. Methodology

The following chapters provide an overview of the methods used for the study. It focuses on providing an overview of the user involvement during the development, the workshop protocol, and the method for assessing the instruments' usefulness.

4.1. Overview user involvement

The input from practitioners influenced the development and application of the instrument. The open development and provision of the tool facilitated the involvement of diverse groups. In particular, three groups were involved: planning practice, research and developer community and students (see Fig. 3). The process brought up ideas on new features proposed new use cases and helped understand user needs. A particular focus was given to exchange with the planning practice. Past research has shown (see Sections 2.1 and 2.2) that the involvement of planning practice can help in developing more useful PSS. Involvement was realized through early testing workshops and later in application workshops (see Section 4.2). Besides practitioners' direct use of the tool, results or the tool itself were shown in presentations to planners and decision-makers. Alongside this, more informal exchange was carried out in personal meetings.

With ongoing development, the exchange with the research and developer community intensified. Besides early testing with German researchers, two workshops with international researchers were carried out. Next to scientific publication, the current development progress was continuously communicated in a blog and social media. Furthermore, feedback on users' experience was obtained via Social Media, E-Mail, and a chat group.

The involvement of students in different teaching formats was the third pillar of the co-creative development of GOAT. Direct contributions were realized in several students' theses, in which new features were developed, or the application was transferred to a new study context. The development was usually accompanied by internal or external testing of the tool. Furthermore, students used the demo version of GOAT in Munich in seminars and lectures to perform accessibility analysis or visualize spatial data. Due to the importance of (spatial) data for the development, students were also involved in four Mapathons, which aimed to collect data on street networks, buildings, and points of interest in OpenStreetMap (OSM). As part of this activity, a prototypical feature was developed in GOAT, which showed gaps in the OSM data set and provided a more structured crowdsourced mapping process. Despite the richness of the different involvement formats, the exchange happened largely unstructured and, in many cases, spontaneous. Therefore, in the following, a particular focus is given on the experience obtained in the application workshops.

4.2. Application workshops

For the early development phase, practitioners from the field of transport and land-use planning from the municipality of Fürstenfeldbruck were involved Pajares et al. (2021a). This first series of workshops primarily aimed to receive feedback on principle requirements of users and test different pre-release versions of the tool. Meanwhile, the main aim of the application workshops was to work on real-world planning questions using the tool. It was aimed to achieve an experience when using the accessibility instrument, which is close to the work reality of the practitioners. However, due to the unfamiliarity of the majority of the practitioners with accessibility measures and with using GOAT, the workshops also had characteristics of method and software training.

The workshops were organized in the citys' administrations of Fürstenfeldbruck, Freising, and Munich. An additional application workshop was organized with researchers from transport and land-use planning in Munich. The workshops took place in 2020. Due to the COVID-

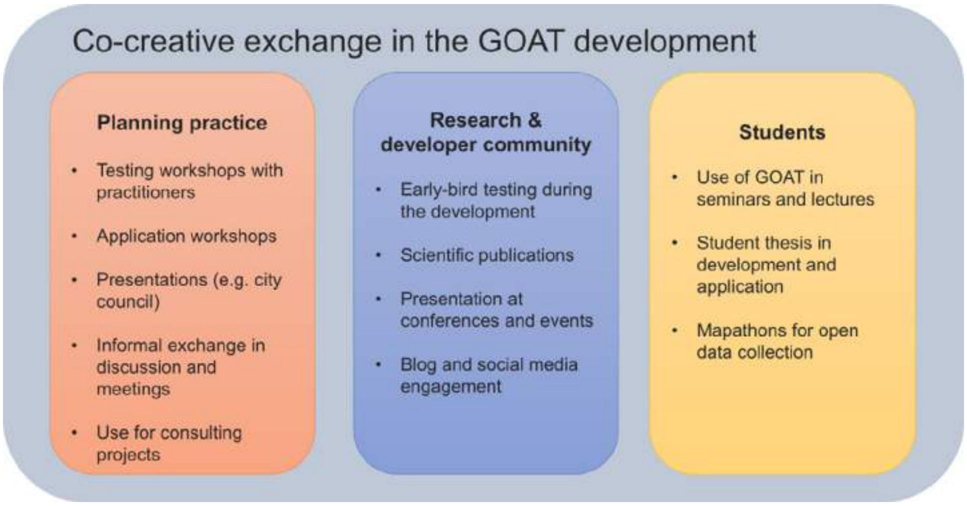

Fig. 3. Main user groups involved in the development of GOAT.

Fig. 4. Application workshop in Freising and Fürstenfeldbruck.

19 restrictions, two application workshops were organized remotely via teleconferencing. Overall, 37 persons attended the five application workshops, and each took approximately three hours. The practitioners were almost entirely coming from urban and transport planning (see Fig. 4). Approximately half of the practitioners focuses on urban and the other half on transport planning. From the authors' observations, the majority of practitioners though had a good understanding of the interrelation of both disciplines. One of the workshops was also joined by a politician from the city council.

The workshop design was inspired by the workshops conducted in the course of the COST Action TU1002 te Brömmelstroet (2017); te Brömmelstroet et al. (2014); Silva et al. (2017). However, the detailed workshop procedure was designed independently from existing protocols. The core difference between the workshops conducted in the COST Action TU1002 was that the practitioners were operating the accessibility instruments themselves, and the tool developers only intervened for support. Before the workshops, the participants were asked to share relevant planning questions in their respective municipalities. Also, it was communicated which functionalities the tool has by sending videos, links, and learning material about the software via E-Mail. However, most practitioners were not familiar with the software before the workshop to the authors' knowledge. An exception were planners from the city of Fürstenfeldbruck, who have used GOAT in the test cycles. The workshops used the worksheet presented in Fig. 5 and followed the protocol described in Table 2.

The research team documented observations, feedback, and discussion for each workshop. Although the focus during the workshops was on assessing the tool's usefulness, requests for new features or adaptions and bugs were documented. After the workshops, the participants had the chance to provide further feedback via E-Mail or telephone. An additional application workshop was realized in the city of Freiburg in summer 2021 as a videoconference with five participants. The workshop took two hours and was not supported by the working sheets. It was characterized by a short testing round and a discussion of the tool's functionality.

4.3. Usefulness assessment

Self-assessing the usefulness of an instrument under development is a complex challenge. The diversity of possible planning questions and the limited time the practitioners used the tool shows that there can be no definite answer. Therefore, the assessment should be seen as preliminary. The authors followed the assessment framework visualized in Fig. 6. The assessment started with identifying suitable planning questions for GOAT. In the following, the practitioners worked on the planning questions as described in Section 4.2. Because of the high number of possible planning questions, the authors grouped them into thematic fields (see Section 5).

In the following, the usefulness was assessed for each thematic cluster by showing the used tool features and qualitatively discussing the usefulness based on the users' feedback. Following the literature review (see Section 2), past research has identified that it should be differentiated between the usability and usefulness of a PSS. In the context of this study, usability is seen as part of usefulness. Grudin (1992) and Nielsen (1994) suggest splitting the usefulness of software into utility and usability. Both aspects together define whether the software is useful or not. More specifically, utility is defined by Nielsen (1994) as:

> *"utility is the question whether the functionality of the systems in principle can do what is needed"*

For the assessment of GOAT, the authors particularly examine if the instrument provides the planners with information relevant to them

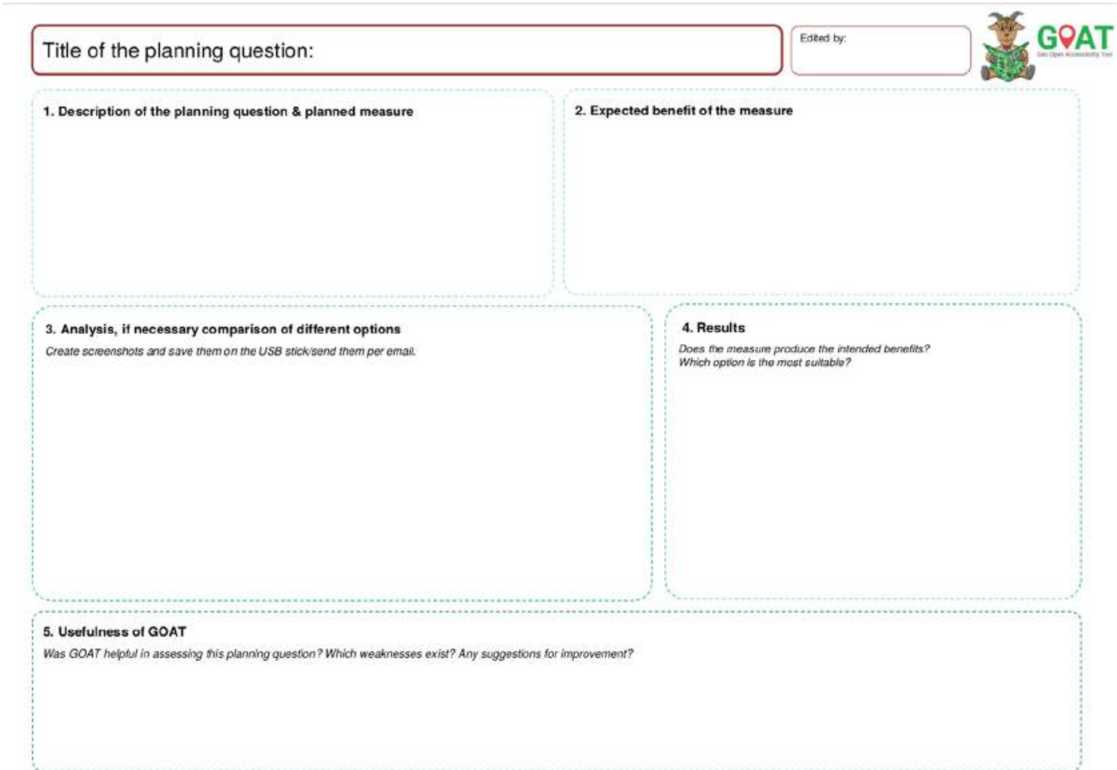

Fig. 5. Worksheet planning workshops.

Table 2
Agenda planning workshops.

Agenda item	Explanation
Welcome and a round of introduction (15 min)	Each person presented himself and described his core work-related responsibilities and interests. The aim was to build a relationship and understand the participants' motivation and interests.
Presentation of GOAT (30 min)	Two persons of the research team presented GOAT. The main aim was to show the core functionalities of the tool. Meanwhile, the practitioners could ask questions or describe planning questions they face in their daily work. The previously collected planning questions (via E-Mail) were expanded or complemented at the end. The introduction should provide enough information to get started on working with the tool.
Group work planning on planning questions (45 min)	A group of two to three practitioners for each planning question was formed. Each group should work on at least one concrete planning question using the tool on the territory of their municipality. They received a step-by-step guide showing the use of the tool. Meanwhile, they were supported by the research team in case of questions. The results of the analyses were documented on the worksheets and with screenshots. Furthermore, the results were within each group. The goal was that the practitioners obtain hands-on experience using the tool and assess its suitability for the respective planning question.
Coffee break (15 min)	During the scheduled break, the practitioners could take a rest. Furthermore, the research team had the chance to openly discuss their first experiences using the tool and possible ideas with the practitioners. Furthermore, the break should help to strengthen the relationship with the practitioners through the open exchange.
Group work planning on planning questions (45 min)	The participants continued working in the same group as before the break.
Presentation of the results per group/planning questions (15 min)	For each group, one practitioner presented the results of the analyses by explaining the content of the filled worksheet and by showing the analyses directly via the tool or with screenshots. The goal was to present all other attendees with the studied planning question and share their experience in using GOAT. Both the research team and the other practitioners could ask questions and discuss.
Open feedback and discussion (15 min)	Finally, the practitioners could openly express their feedback on the tool and propose possible enhancements. The goal was to give the practitioners the chance to provide unstructured feedback on the tool's usefulness and collect feature requests for upcoming versions of GOAT.

when answering a particular planning question. This also includes the appropriateness of specific indicators and the power to communicate the results to other stakeholders (e.g., politicians). Past research (see Section 2.2) identified that the tool interactivity, particularly the ability for real-time scenario building, is important. Therefore, the assessment of utility will set this as one important criterion.

However, high utility alone would not necessarily result in a useful tool. Instead, high usability is very relevant for the assessment of PSS. More specifically, GOAT is assessed whether it is usable for individuals with no or limited knowledge of GIS. In general, usability can be defined as:

> *"the extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use"* ISO (2018).

Of particular importance was to assess if the tool was easy and intuitive to use for the different planning questions. Furthermore, there was attention to users' emotional experience when operating GOAT. Despite

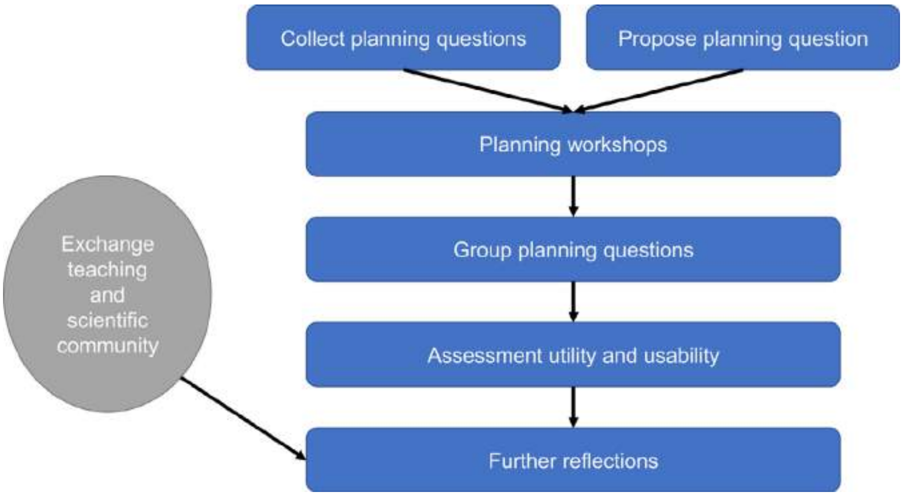

Fig. 6. Framework assessment usefulness.

Table 3
Overview planning questions.

Use case group	Planning questions
Infrastructure Planning Walking	Where is a barrier for pedestrians concerning the street network connectivity?
	How does a new pedestrian bridge influence connectivity?
	What effect brings the temporary closure of a path on accessibility?
	How does accessibility for a person in a wheelchair change by the barrier-free upgrade of an underpass or bridge?
Infrastructure Planning Cycling	How does a new cycle bridge influence local accessibility?
	What effect has a new cycleway on accessibility?
	How do different cycleway attributes influence accessibility?
	What are suitable locations for bicycle parking infrastructure?
	How comfortable is it to cycle on a certain cycleway?
Location Planning	How fair is the distribution of different amenities in a municipality?
	Which share of the population has access to a specific amenity? Moreover, which areas are underserved?
	Where is a suitable location for placing a new amenity (e.g., supermarket, kindergarten)?
	What effect brings the closure of a specific amenity (e.g., pharmacy) to local accessibility?
	Is the population served sufficiently with public transport stops?
	Where is the potential for a new public transport stop or a mobility hub?
Housing Development	Where is the potential for urban densification?
	What are the effects of densification on local accessibility?
	Is the layout of the path network appropriate in a new development area to provide high local accessibility?
	How good is the population supplied in a new development area with different amenities?
	How are population density and local accessibility balanced for a specific amenity?

the broader involvement of stakeholders, it is worth mentioning that the assessment focused on the feedback from planners during the workshops. A challenge for this study is to extract and classify distinct conclusions from the recorded results. Overall the participation process yielded only minimal quantitative results. Therefore the assessment is mainly based on the qualitative description of the user feedback and user statements. Furthermore, the authors' complemented the assessment with their own observations. In the following result section, if statements are based on authors' observations, they are particularly labeled to provide transparency.

5. Results

The co-creative process resulted in identifying a wide range of possible planning questions. It was decided to generalize the planning question and group them into four categories: Infrastructure Planning Walking, Infrastructure Planning Cycling, Location Planning, and Housing Development. The most widely discussed planning questions in the context of the workshops are presented in Table 3.

For each group, exemplary analyses from GOAT, done during the planning workshops, are presented. They can be regarded as the most frequently performed analyses in the respective group. Section 5.1 bundles results for planning Walking Infrastructure, Section 5.2 for Cycling Infrastructure, Section 5.3 for Location Planning, and Section 5.4 for Housing Development. It has to be mentioned that the analyses for the different use cases can overlap due to the high interrelation of the studied questions.

5.1. Infrastructure planning walking

5.1.1. Provided features and analyses

Different indicators serve as benchmarks for street connectivity and accessibility of local amenities for planning walking infrastructure. The connectivity heatmap in GOAT allows the user to understand the degree of street network connectivity in the study area. Using the heatmaps (see Fig. 7), the practitioners understood the street network connectivity. In the studied municipalities, especially rivers and rail tracks were identified as significant barriers. Users performed scenarios on the street network by adding, modifying, and deleting network elements. Accordingly, common infrastructural measures such as constructing a new footbridge, a temporary network closure, or a sidewalk extension were modeled. As shown in Fig. 7, connectivity is significantly improved with the proposed bridge over the river. The areas that benefited the most are in the direct surroundings of the bridge.

Also, by using single and multi-isochrones, changes in accessibility were computed and visualized. As shown in Fig. 8, a new pedestrian bridge over a river increases the catchment area. As a result, significantly more population and amenities can be reached from the respec-

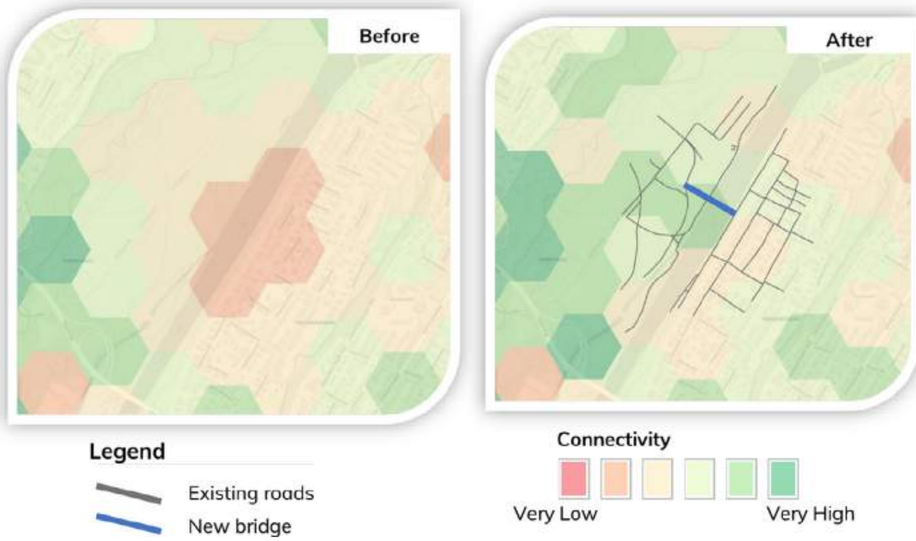

Fig. 7. Bridge scenario and changes in connectivity.

Fig. 8. Scenario new pedestrian bridge over a river.

tive location. The same calculations were done for the barrier-free mode. The effects of providing additional barrier-free crossings over a river are visualized in Fig. 9. Depending on the data available in the city, users visualized street illumination, noise levels, street crossings, surface, and more.

5.1.2. Assessment of usability and utility

In general, the practitioners reported that analysis using isochrones was straightforward. The local knowledge of the planners confirmed barriers in the street network identified by GOAT. They were surprised by the ease of changing the network and the performance of the scenario building. Users valued that the computed isochrones can easily intersect with diverse spatial data such as population numbers and points of interest. The isochrones were also commonly understood by participants unaware of the accessibility concept. Several planners mentioned that the produced maps using isochrones could be powerful when presenting results to politicians. While the connectivity heatmap offers an area-wide benchmark, the users had more difficulties understanding the indicator. Also, computing scenarios using the connectivity heatmap take significantly longer than single isochrones. The provided documentation of the indicator helped to improve understanding and required more time. In some cases, the network modification produced unexpected results. Reasons for this were problems with data accuracy and sporadic bugs in the relatively complex feature. In the workshops, it was observed that new users had difficulties performing network scenarios for the first time. In the workshops, not all users managed to design a scenario themselves but required assistance from one of their colleagues or the research team. While most users were interested in the travel time-based isochrones, others also used additional layers such as noise levels. Some users mentioned the need to consider walkability-related factors (e.g., sidewalk width, noise levels) to provide a complete picture. As sometimes new paths or bridges showed only marginal changes in accessibility, one planner mentioned that: *”Accessibility analyses cannot really show the effects of this measure”*. Users also requested to provide classical origin-destination-routing to supplement the isochrone calculation.

5.2. Infrastructure planning cycling

5.2.1. Provided features and analyses

Due to the fast-rising attention to cycling in the studied municipalities, several practitioners were particularly interested in using GOAT for analyzing the cycling infrastructure. There is no heatmap yet implemented for cycling infrastructure planning. Therefore only isochrones and multi-isochrones were used for cycling. However, similar to the network changes for walking, the cycling network can be changed. In addition, the road surface can be changed in a scenario. A common scenario

Fig. 9. Scenario new barrier-free crossing.

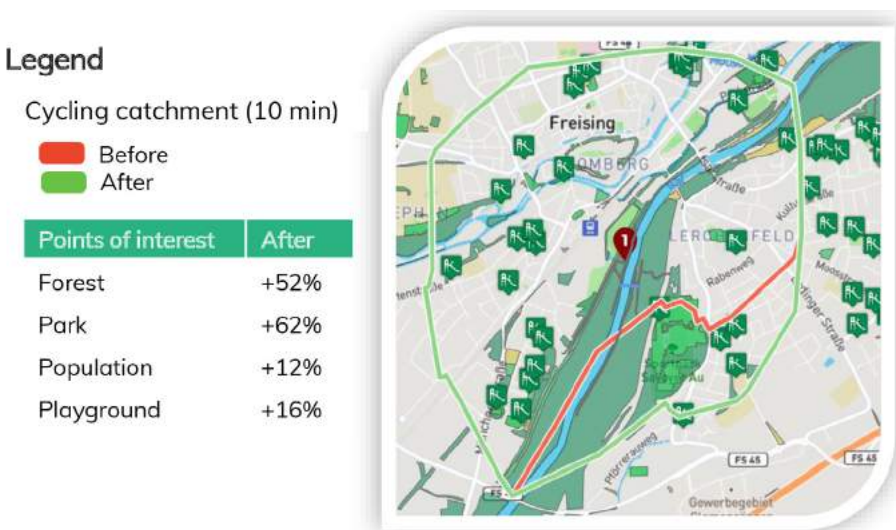

Fig. 10. Analyses and data visualization for planning cycling infrastructure.

in all three municipalities was to analyze the accessibility effects of a new cycling bridge over the local river as shown in Fig. 10.

Other layers were also used for analysis. For instance, street imagery from Mapillary was used to inspect the cycleway quality and get a better understanding of the study area (see Fig. 11). In the case of Munich, the data on cycleway quality from the local NGO Munichways Munichways (2021) was frequently viewed. Furthermore, data on cycling accidents were utilized to identify hotspots and particular needs for action.

5.2.2. Assessment of usability and utility

The user feedback revealed that, in general, computed travel times were perceived as realistic. It was highly valued that the travel time analyses included slope and surface type factors. Also, the ability to adjust cycling speeds and choose between different cycling profiles (standard or electric) was appreciated. However, it was also requested that the impedances (e.g., slopes, surfaces type) on the road network should be made more transparent. One user mentioned: *"I would like to have more transparency on the impedances applied for the cycling network"*. Others users mentioned that this would increase trust in the calculations.

Users also wished to model travel time differences between different cycleway types, for instance, between a narrow cycleway and a cycling highway. As this is not yet implemented, modeling the effect of high-quality cycling infrastructure could not be done so far. Due to the unavailability of appropriate data, travel time losses are only considered at major intersections with traffic lights. An average time loss of 30 s is applied for crossing the intersection in every direction. This was perceived as a limitation by some users. It was wished to model the effects of changes in the design of intersections or the traffic signal plan. Generally, it was claimed that the presented accessibility analyses could not model the effects of all discussed measures (e.g., traffic signal prioritization). The same was valid for walking analyses, but more planning questions related to cycling were not answered in the workshops. Meanwhile, as for walking analyses, the importance of additional comfort criteria (e.g., number of other cyclists) was raised.

As the catchment areas for cycling are much larger than for walking, the performance of the isochrone calculation is significantly slower. Especially for the computation of multi-isochrones uncomfortable long computing times of several minutes can affect the user experience. Furthermore, users missed a comparison of traveltimes between bicycles and cars. Users appreciated the additional data, particularly the street view imagery from Mapillary as GoogleStreetView imagery in Germany is usually either unavailable or out of date.

Fig. 11. Analyses and data visualization for planning cycling infrastructure.

Fig. 12. Location planning social facilities - nurseries in Fürstenfeldbruck.

5.3. Location planning

5.3.1. Provided features and analyses

GOAT was used for location planning, such as finding a suitable place for a new service or evaluating the served population with a particular amenity. With the gravity-based accessibility heatmap, the users evaluated the accessibility to a specific amenity for the city's territory. Therefore, underserved or not served areas were identified. By drawing scenarios, like adding a new bike-sharing station, the change in accessibility was modeled by the users. It was tested to add, modify or delete points of interest. Therefore, the accessibility effects of new and closed points of interest were evaluated. Fig. 12 shows the accessibility effects of two new nurseries in the City of Fürstenfeldbruck.

The population heatmap was also used to assess the balance of accessibility levels and population density (see Fig. 13). With the population density and local accessibility heatmap, accessibility was compared with the population density at the respective grid cell. Areas with a high population but poor accessibility were highlighted. As shown in Fig. 14, the areas with the proposed new nurseries indicate a modest density surplus. With the proposed two new nurseries, the affected areas are balanced or have a modest accessibility surplus in the scenario.

5.3.2. Assessment of usability and utility

For location planning, mainly the described heatmaps and multi-isochrones were utilized by the practitioners. Generally, they classified the local accessibility heatmap as a powerful indicator to highlight the distribution of a certain point of interest. However, one user also mentioned that more quantitative output would be desired: *“Difficult, to only work with visuals, more quantitative results would be helpful”*.

Although the sensitivity parameters of the gravity-based accessibility measure could be adjusted, the users did not do this. Instead, the default parameters were utilized. From the authors' observation, the users were already overwhelmed by many functionalities and therefore showed little interest in increasing complexity by calibrating the sensitivities. The multi-isochrones were seen as a powerful indicator to show which population share is served by a particular amenity. The scenario development for the points of interest was more straightforward than for the ways or buildings. Also, users liked how fast the heatmap reflected the scenarios. The combination of population densities and accessibility levels was seen as a good approach to balancing supply and demand. However, concerns were raised if it is sufficient to include population numbers solely. More specifically, data on the number of jobs or students at education facilities was considered essential to quantify the demand

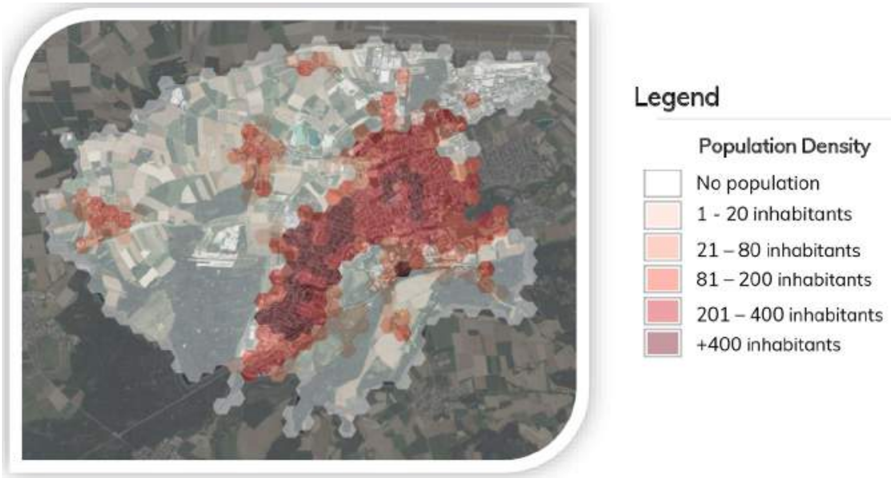

Fig. 13. Population density heatmap, Fürstenfeldbruck.

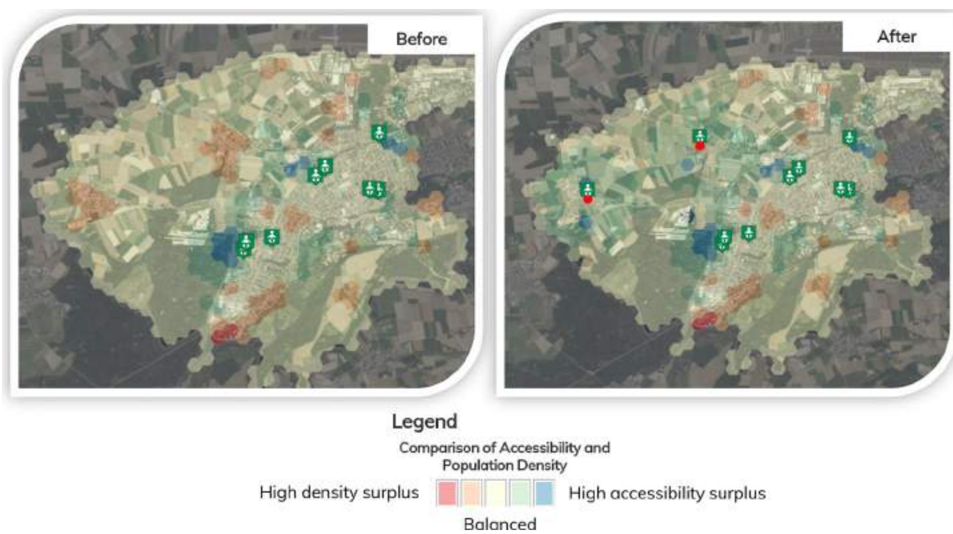

Fig. 14. Comparison of accessibility and population density heatmap, Fürstenfeldbruck.

for some points of interest (e.g., supermarkets, public transport stops). Generally, population numbers are static and reflect people's location at night or early morning. Spatio-temporal changes in people during the day are not available. Also, due to the unavailability of data on opening hours for all points of interest, temporal changes in accessibility could not be modeled. The authors perceived modeling the temporal changes of accessibility due to varying opening hours at the beginning of the study as particularly important. However, this was barely requested by the involved practitioners.

Users generally confirmed that the accessibility levels for the different amenities match their personal experience. However, they also requested more tailor-fitted indicators to assess the demand for a particular service and the quality of an amenity. Especially for public transport stops, it was requested to incorporate factors such as service frequencies to quantify the attractiveness of the service better. Additional sociodemographic data on age, family status, and income were requested to understand better the needs and demands for a particular point of interest. At the same time, users mentioned that this raises the complexity of the analyses.

5.4. Housing development

5.4.1. Provided features and analyses

The distribution of the urban population is constantly changing. Common interventions in the urban environment are the construction and demolition of buildings. To model changes in the population distribution in GOAT, houses were drawn and imported via the interactive web map. With an adjustable average gross floor area per resident, the population is estimated per building. Furthermore, it is possible to delete existing buildings. With the scenarios, the users aimed to model changing needs of accessibility by using isochrones, multi-isochrones, and heatmaps. As shown in Fig. 15, buildings were uploaded as GeoJSON from a building development plan in Munich. In addition, the planned street network was added to the scenario.

Fig. 16 shows the accessibility to kindergartens in the new development area. There are three existing kindergartens accessible in 8 min walking time. For better accessibility of the new residents in the scenario, a new kindergarten is proposed at the east of the new development area. Accordingly, around 20.9% of the population has access in 4 min, and 100% of the people in 8 min walking. The example shows that GOAT can be used for planning urban development.

5.4.2. Assessment of usability and utility

The practitioners liked that an entire neighborhood could be modeled as a scenario. This was considered useful as new development areas could be evaluated concerning their local accessibility to diverse destinations. Furthermore, the feature was regarded as suitable for identifying places with high accessibility and, therefore, potential for urban densification. The implemented accessibility measures, especially the

Fig. 15. Scenario with buildings uploaded from a building development plan and new road infrastructure.

multi-isochrones, were used to quantify the share of residents having access.

In terms of usability, drawing new buildings were generally perceived as intuitive. Nevertheless, some users mentioned that drawing individual buildings and building entrances is too time-consuming. It was mentioned that a coarser resolution of the population would also be sufficient for many use cases. It was welcomed that buildings can be uploaded in the GeoJSON format. At the same time, the format was not frequently used by all participants. One user mentioned that it would be necessary to allow uploading data in the shapefile format. Despite the option to export and later import drawn scenarios, it was raised that it would be beneficial to save developed scenarios in the tool. While being true also for ways and points of interest scenario, users mentioned this would be particularly important for buildings as drawing them takes more time. Working with the practitioners also revealed that additional, more granular accessibility indicators on the building level could provide valuable insights. One example could be providing information on travel times to selected points of interest when clicking on a building.

Table 4
User feedback - general .

Positive feedback	Negative feedback
"GOAT has developed very positively, many good new features."	"Sceptic about making the tool accessible to the public, due to sensitive data and data accuracy."
"Very impressive tool."	"Walking and cycling are great, but multimodal analyzes are needed for mobility concepts."
"Very exciting project."	
"Great what you can do with Open Data."	
"Scientific background is a big plus."	

Table 5
User feedback - usability.

Positive feedback	Negative feedback
"Very easy to use (good user interface)."	"User interface is not user-friendly and intuitive enough."
"Easy to understand after a short training period."	"Familiarization with the software takes too long."
"Simple user interface."	"Too complex to involve citizens."
"Quick and easy comparison of different scenarios."	"Overwhelmed by too many functions."
"The results are easy to understand and striking."	"Functions are not always self-explanatory."
"Intuitive to use."	"Terminology not comprehensive."
"Analyses are easily possible without extensive GIS knowledge."	"Too complicated, I prefer to hire a GIS professional."
"Time- and cost-efficient tool."	
"Interactivity of the tool is good."	

5.5. Overall assessment

During the workshops and beyond, the practitioners expressed direct feedback. This feedback was summarized and clustered into three categories: General (Table 4), Usability (Table 5), and Utility (Table 6). For reasons of comprehension, the comments have been translated from German. There was a focus on the overall evaluation of the instrument. Detailed feedback on bugs, data issues, and feature requests are not included in the collection. Instead, they were continuously documented and, if possible, directly considered in the development process. In Pajares et al. (2021a), a collection of the features requested can be

Fig. 16. New buildings and kindergartens.

Table 6
User feedback - utility.

Positive feedback	Negative feedback
"Useful tool, e.g., to evaluate potential locations for additional bridges over the [local river]".	"Accessibility analyses cannot show the effect of all measures. Sometimes it is more about safety and comfort."
"Good, logical tool that would be beneficial in the early planning stages."	"Application of GOAT rather not possible in rural areas due to poor data availability."
"Well suited for visualization of current planning and as an argumentation aid."	"It would be great if GOAT could be integrated into our existing municipal GIS."
"Well suited for bringing analyses closer to politicians."	"At some places, no calculation was possible."
"Politicians are super grateful for the preparation and visualization of data as it helps to make decisions."	
"With the help of such tools, municipalities could do more planning tasks in-house."	
"This could be a well-respected tool in transport planning, and there would be many use cases for the use of GOAT."	
"High potential of the tool, expansion to whole Germany would be a great added value."	
"Bundling functions (accessibility, visualization, etc.) and various data is an added value for planners."	
"Scenarios are very useful."	
"Very helpful for analyzing the cycling network."	
"Heatmaps are appealing."	
"For location planning and for calculating isochrones to assess accessibility, we could make good use of the tool."	
"We would like to continue to use GOAT for our planning tasks."	

found. Following the feedback, GOAT was assessed as a tool with high potential to be used in practice, but also the need for improvements was raised. The planners saw many use cases to apply the tool and stated that it adds value to the tasks they have to accomplish. As shown in Table 4, they generally liked using GOAT.

The large majority mentioned the instrument is usable (see Table 5), but also some perceived the interface as not intuitive and not self-explaining enough. A clear pattern can be found when tracking the statements back to the users. Participants who spent more time familiarizing themselves with the instrument perceived the tool as easier to use.

Planners from municipalities particularly valued that they could carry out the analyses themselves. They claimed that this helps to present results much faster to politicians compared to outsourcing the analyzes. To carry out studies beyond their municipal boundaries, they would like the tool to be available for neighboring municipalities. Planners from consultancies requested that GOAT should be available for the whole of Germany. They mentioned that it would be necessary to immediately access the tool without spending much time setting it up for their respective study area.

Some practitioners asked for better integration with existing software, such as desktop GIS and data platforms. The need to integrate with existing systems was described to avoid creating a technological silo in terms of software and data. Regarding the access to GOAT, there were different opinions. While some municipalities want to make the tool accessible to citizens, others have concerns about the disclosure and correctness of the data basis. Some representatives of the municipalities mentioned it could be helpful to integrate selected analyses into other existing web maps targeting citizens as users.

6. Discussion and conclusions

This research tried to answer two questions. Suitable use cases for the developed software GOAT should be identified. This was carried out by the involvement of planning practitioners, who proposed relevant planning questions, which were clustered into four groups. The collected list of planning questions cannot be completed by research design. Nevertheless, the different planning questions already cover a wide area. The second research question tries to find answers to whether the developed accessibility instrument is of useful support in practice. This research faces the challenge of having no clear answer to this very complex question.

From the utility perspective, the involved practitioners reported that the analysis is suitable when answering many planning questions. In particular, the ability to perform scenarios was welcomed by the practitioners. Therefore, the request to perform on-the-fly scenario building identified by the COST Action TU 1002 project te Brömmelstroet et al. (2016, 2014); Silva et al. (2017) could be confirmed. Many practitioners mentioned that GOAT could support when assessing changes in infrastructure for walking and cycling, mainly when focusing on accessibility effects of new, modified, or deleted street networks. As the tool interprets accessibility solely time-based, the accessibility analyses fall short when changes in walking or cycling comfort should be modeled. The additional spatial data (e.g., noise levels) provides further insights into the quality of street space.

Furthermore, it can be concluded that many of the tool's features are suitable for assessing the effects of land-use changes. Planners valued the ability to assess local accessibility and identify regions not served by a particular amenity. However, the planners also mentioned that the provided analyses only helped in some of their work and asked for ongoing expansion of the tool. The involvement of practitioners from both urban and transport planning, as well as the general mutual understanding when using GOAT, showed that accessibility can serve as a shared language between often disconnected disciplines, as suggested by Büttner et al. (2018). The usability of the software is vital. During the development, there was constantly the challenge to balance additional functionality and the ease of using the tool. As a result, GOAT might be much easier to use than a classical desktop GIS but is significantly more complex than an easy web map. Accordingly, GOAT can only be used effectively with approximately one day of training. This training can be realized via online tutorials but furthermore through in-person training. Despite the high efforts in making the tool more straightforward, the usability can still be significantly improved. A challenge of the co-creative involvement of the practitioners was that some reported improvements in terms of usability contradicted statements from other users. In general, it is suggested to make separated usability tests that use common methods such as contextual inquiry or session recording. Overall it is concluded that utility cannot be assessed independently from usability. Both criteria in this case study are, instead, often highly interrelated.

During the workshops, the need to combine the training of operating GOAT and practical teaching of the accessibility concept was seen. Many of the involved practitioners have heard of accessibility before, but none of them has used an accessibility instrument before. Similar to the observations of Boisjoly & El-Geneidy (2017) accessibility is generally a known concept in the planning practice, but many have not used accessibility metrics in practice. The study can be seen as a tiny step to make the accessibility concept more known in the local planning practice. Accordingly, the benefits of engagement with the planning practice, which were raised by previous research te Brömmelstroet et al. (2014); Silva et al. (2017), could be confirmed. Although the engagement with citizens using the tool was not tested, the tool is seen as too complex to be easily used by non-professionals. Meanwhile, it is seen as very beneficial to use GOAT in workshops with citizens and political decision-makers while being operated by a planning professional. The concept of seeing the professional as *'chaufeur'* is common from studies using participatory GIS Haklay & Tobón (2003).

The interoperability with existing systems (e.g., desktop GIS, transport models), is an aspect seen as necessary for adopting accessibility instruments in practice. By using standard data formats such as from the Open Geospatial Consortium Open Geospatial Consortium (2022) or by developing software plugins, interoperability can be strengthened. Overall, the continous exchange with the planning practice was a rewarding experience from the authors' perspective and it is suggested to continue on this path.

It is essential to underline the limitations of the presented study. First, the identified use cases were also influenced by the capabilities of GOAT. Many planners knew the scope of the software before and therefore were focusing on solvable planning questions. Accordingly, there might be many more relevant planning questions in the field. Second, the tool was, so far, primarily used in synthetic workshops settings. However, the use of planning software is usually characterized by planners using the software alone. Long-lasting and continuous feedback from planners using GOAT would be needed to produce a more solid picture. Furthermore, the focus was on documenting the experience in worksheets during the workshops. There was also prepared an online survey. However, only very few practitioners participated. Accordingly, the results were not used for the study. Therefore, a collection of anonymous feedback and eventually more honest feedback was not realized. An apparent methodological weakness of the study is that the tool developers themselves carried out the assessment. Self-assessment was great to bring the experience directly into the tool development. However, it also comes with a bias despite following a good scientific practice. It is suggested that independent colleagues assess the usefulness of the instrument in the future.

An eventually trivial aspect is the cost of implementing an accessibility instrument such as GOAT in practice. Despite being an open source tool, it needs to be maintained, hosted, and equipped with the necessary data. Accordingly, it is suggested that future development aiming for fast adoption of accessibility instruments should always keep the necessary resources in mind needed for operating in a real-world environment and the willingness to pay for the analyses. Also, even if mass adopted, the market for accessibility instruments will be a niche with few users compared to other fields in software development. Furthermore, it is crucial to find new in-roads in other domains to tap into new use cases (e.g., real estate development). Finding more use cases might be an appealing idea, not only from the idea of spreading accessibility analyses, but it can generate more resources for better tool development by joining forces in the future.

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Awareness and knowledge levels of engineering and planning students and practitioners about the 15-minute city concept in a developing country

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ABSTRACT

This study aimed at understanding the awareness and knowledge levels of planning and engineering students and practitioners about the 15-Minute City concept (FMC). The three main objectives were to determine the awareness levels, factors affecting the awareness levels and the knowledge level about FMC. A questionnaire survey was conducted in Lahore, Pakistan, which included questions on the respondents' demographics, and their awareness and knowledge about FMC. The collected data were analyzed using various statistical analysis techniques to achieve the objectives of the study. The results indicated that a high number of respondents did not have awareness about the FMC concept. Ordinal regression model indicated that type of degree and numbers of seminars attended had a significant influence on the awareness levels. Those having or pursuing planning degrees had higher awareness about FMC than those with engineering degrees. Those who attended more number of seminars on urban and transport planning had higher levels of awareness about FMC as compared to those with lower number of seminars. Civil and Transportation Engineers play an important role in the planning and development of cities, however, they were found to have lower awareness levels. The results of this study can be used to determine how the awareness level of planners and engineers can be increased about more sustainable solutions including FMC.

1. Introduction

Travel demand is increasing with the ever-expanding cities causing urban planners and policy makers to find ways to cater this rising demand. In the recent years, more than half of the worlds' population is living in the urban areas and the cities are becoming increasingly dense (United Nations, 2018). It has been projected that around 68% of the total population of the world would be living in the cities if the present growth of the cities continued by the end of 2050 (United Nations, 2019). The past policies mainly focused on increasing people's mobility giving rise to car-dependent cities which resulted in several negative consequences including traffic congestion, air and noise pollution, and accidents etc. (Profillidis et al., 2014). Therefore, it is the utmost priority for the urban planners and policy makers to make the cities more sustainable, inclusive, resilient, and safe for the residents where they can access the necessities to live a comfortable life with convenience using non-motorized transport systems.

In order to forgo the mobility-based planning and to promote the accessibility-based planning, innovative ways of reinventing cities are being explored such as "15-Minute City (FMC)" and superblocks etc. (Eggimann, 2022). Recently, the idea of FMC has been gaining popularity. The basic idea of the FMC is originally drawn from the concept of "neighborhood unit" which was developed in 1923 for the city of Chicago, in which the main idea was to promote the accessibility for compact residential units where the proximity between the services and the homes can be achieved in order to give an idea of "the sense of belonging" to a community in a place (Gaglione et al., 2022). The policy makers are proposing transformations in search of more humane and sustainable cities which can allow the change in the current urban paradigm where private vehicles play an important and essential role in urban planning. Hence, policy makers are trying to maximize the accessibility to local amenities such as public transport options, healthcare, education centers, employment centers, and recreational centers which can be reached by walking or bicycling. However, it is pertinent to mention that a lot of challenges are there when it comes to the implementation of the FMC concept because of the inequity in the history of urban development. The issues of social polarization, and spatial mismatch vary from one city to another across different countries. For example, people who are living in big cities such as Tokyo or New York can get all their daily needs within a 15-minutes traveling as compared with the residents who live in small or medium-sized cities because of

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the inequity in the urban development (Bramson & Hori, 2021; Chen & Crooks, 2021). These cities with accessibility to all the necessary amenities within 15 minutes represent a new possibility for the re-organization of the urban systems which can be effectively used in order to address many of the recent challenges such as health crisis (pandemics), energy savings and aging populations (Strappa et al., 2020; de Valderrama et al., 2020), and GHG emissions (Allam et al., 2022).

The mayor of Paris, Anne Hidalgo" was the one who propagated the idea of the FMC for the re-organization of the urban structure in order to create extensive green areas for the pedestrians which are currently being used by the cars to allow the inhabitants to reach the essential urban services either by walking or bicycling (Duany, 2021). Other cities such as Milan and New York have also started to transform the cities into FMCs. Some other prominent examples are Barcelona – with the *Superblock* organization, and Milan with a plan called *La città a 15 minuti* (de Valderrama et al., 2020; Pinto & Akhavan, 2022).

The idea of FMC provides an opportunity for making the streets car-free and increasing the utilization of the open spaces for the promotion of pedestrian and bicycling routes for the city inhabitants. It can also help in reducing the long queues of inhabitants at essential services such as procurement of local foods at markets. In other words, the idea of FMC has rediscovered the conception of city designs for the improvement of the livability of the areas near homes, and have raised the "walking appeal", an idea which has been propagated by some of the institutional and political domains in the scientific community (Doubleday et al., 2021).

The emergence of the COVID-19 pandemic has also highlighted the need for proximity-based planning. The current urban planning approach is based on car-dependent policies in most of the developing cities including Lahore, which limits the access to basic necessities during pandemics due to health protocols. Further, it leads to inequity during pandemics since public transport use declines and everyone does not have access to private vehicles. Active modes gained popularity during the pandemic since long commuting distances and public transport use have been found to be associated with the transmission of coronavirus (Ando et al., 2021). These circumstances urged urban planners and researchers to explore innovative urban planning approaches to ensure access to basic necessities during pandemics. FMC is one such approach which has been proposed as a response to the pandemic (Moreno et al., 2021). Since the concept of FMC had already been partially applied in Milan, Italy, the response to the COVID-19 pandemic was quick leading to better proximity to essential services (Fabris et al., 2020). The cities need to be reinvented in the wake of the pandemic (Florida et al., 2021) and the concept of FMC may act as the front line of city defense against the harms caused by the COVID-19 pandemic.

In order to make Lahore a sustainable city, the national transport policy of Pakistan was developed which aims at prioritizing active modes and improving accessibility (Planning Commission, 2018). Hence, innovative planning approaches such as FMC can help achieve these goals. The Lahore city has various features which can facilitate the implementation of the FMC concept. For example, it has a relatively high population density, and a developed road network. The city, however, does not have sufficient parks and relaxing spaces for its population (Al-Rashi et al., 2020). In addition, pedestrian and bicycle facilities are either non-existent or in poor condition (Aslam et al., 2018). Contrary to the national transport policy, the movement of private vehicles is still being facilitated throughout the city of Lahore. Most development projects typically follow car-centric policies and impede the movement of other road users. In addition, signal-free corridors are being developed which encourage high vehicle speeds and maneuverability, restrict the right-of-way for active travel and, therefore, compromise on the mobility and accessibility of bicyclists and pedestrians (Alwan & Hadi, 2021). These developments indicate that the relevant authorities as well as engineers and planners may not have sufficient awareness and knowledge about the recent sustainable planning approaches such as FMC.

It is important for the planners and engineers to first understand the FMC concept in order to implement it. Lack of awareness and knowledge about such concepts may lead to the continuation of car-dependent policies. To the best of the authors knowledge, there are no studies which aimed at determining the awareness about FMC. This is the first study of its kind which aims at determining the awareness and knowledge levels of the engineering and planning students and practitioners about FMC. This study differentiated between awareness and knowledge about FMC. The awareness was determined based on whether or not people had heard of FMC and their understanding about its basic concept. The knowledge of the aware respondents was determined based on their understanding about certain specific aspects of FMC. This study had the following objectives:

1 To determine the awareness level of engineers and planners about the 15-Minute City concept
2 To determine the factors affecting the awareness level of engineers and planners about the 15-Minute City concept
3 To evaluate the knowledge of engineers and planners about the 15-Minute City concept

This study is an initial step toward a large scale study which involves (a) determining the awareness level of engineers and planners about FMC in developing cities, (b) determining the applicability of the existing definition of FMC to developing cities and whether any modifications are required, (c) evaluating whether a particular developing city is an FMC or not, and (d) proposing a framework to apply FMC concept to the developing cities.

The rest of the manuscript is divided into the following manner. Section 2 explains the methodology. The next section presents the results and their interpretation. The discussion on the results and the recommendations are presented in Section 4.

2. Methods

2.1. Questionnaire

A questionnaire was designed keeping in view the objectives of the study. The first part of the questionnaire consisted of demographic questions such as gender, age, and type of undergraduate degree etc. The second part contained the following three questions aimed at determining the awareness levels of the respondents.

i Have you ever heard of "15-Minute City"?
ii "15-Minute City" promotes:

a) Active modes (walking / bicycling), b) Motorized transport

iii Choose the most appropriate definition of '15-Minute City"

a) The "15-Minute City" concept is a way to ensure that everyone living in a city should have access to essential urban services within a 15-minutes walk or bike.
b) The "15-Minute City" concept is a way to ensure high mobility such that everyone living in a city should be able to access essential urban services within a 15-minutes car drive.

The third and last part consisted of 5-point Likert type questions aimed at determining the knowledge level of the respondents such as "the 15-Minute City concept preserves environment by reducing fuel consumption and emissions", "the 15-Minute City concept improves overall public health", and "the 15-Minute City concept promotes mixed land-use" etc.

2.2. Sample and questionnaire administration

The sample consisted of engineering and planning students and practitioners in the Lahore city. More specifically, Civil/Transportation Engineering, and City & Regional Planning students and practitioners were targeted in this study. There are several universities in Lahore, however, only few of them offer Civil/Transportation Engineering and City & Regional Planning programs. Students from three universities were mainly targeted since they have high number of students, good job placement, and the targeted undergraduate programs. In addition, their undergraduate programs have been running for several years and are accredited by the relevant accreditation bodies. These universities include University of Engineering and Technology (UET), University of Management and Technology (UMT), and National University of Computer and Emerging Sciences (NUCES). UET offers undergraduate degrees in all three programs i.e., Civil, Transportation Engineering and City & Regional Planning. UMT offers undergraduate programs in Civil Engineering and City & Regional Planning. Whereas, NUCES offers an undergraduate degree in Civil Engineering only. There are other universities which offer these undergraduate programs, however, many of those are still struggling to get accredited by the relevant authorities and have low student enrollment. Therefore, those were not included in this study. A convenience sampling approach was adopted where the respondents were contacted through personal contacts, emails, and social networking platforms to fill an online questionnaire. It took about 6 minutes to complete the survey. All the respondents were informed about the purpose of the survey and no personal identifying details were collected. The survey was conducted during June 2022.

2.3. Analysis methods

Initially, descriptive analysis of the demographic questions was conducted. The first objective was achieved by asking three specific questions to determine the awareness levels of the respondents. The awareness level was divided into three categories i.e., none, low, and high. The second objective was achieved by constructing an ordinal regression model with awareness level being the dependent variable and the socio-demographic variables as the independent variables. The third objective was accomplished by asking some specific 5-point Likert type questions to the respondents who had either low or high level of awareness about the 15-Minute City concept. The underlying factor called as “knowledge” was obtained after conducting factor analysis on the Likert data. The factor scores were then computed using the regression approach. Non-parametric statistical tests were performed to evaluate the effects of demographic variables on the factor scores. All the analysis was conducted on SPSS v. 20.

3. Results

3.1. Overview of the sample

A total of four hundred and three (403) complete responses were obtained. Most of the respondents were male which can be attributed to the fact that female population is quite low in engineering disciplines in Pakistan (Table 1). The sample mainly consisted of younger population with very few above the age of 40 years. The sample predominantly comprised engineers because City & Regional Planning program is not so common and is offered by only few universities in Lahore as compared to engineering programs. Most of the respondents had studied at least one course on urban or transportation planning.

3.2. Objective 1: awareness level

Initially, awareness level of the respondents was determined using three questions about 15-Minute City. A summary of the responses to the questions is shown in Table 2. The awareness levels of the respondents were then determined using the scheme shown in Fig. 1. About 57% of the respondents declared that they have never heard of the term “15-Minute City”. Those who answered the first question wrong were considered to have no awareness about the concept. Those who answered the either of the second or third question correctly were considered to have low awareness and those answering all the questions correctly were believed to have high awareness about 15-Minute City. Fig. 2 shows that about 57% of the respondents had no awareness, 8% had low awareness, and 35% had high awareness about the FMC concept. Further the breakdown of the awareness levels for the demographic variables is shown in Fig. 3. It can be seen that gender, ownership, age, and university seem to have no effect on the awareness levels. Whereas, type of undergraduate degree and number of seminars attended seem to have a considerable impact on the awareness levels of the respondents.

3.3. Objective 2: factors affecting the awareness level

An ordinal regression model with Probit link function was developed to determine the factors affecting the awareness level of the respondents. Awareness level was entered as the dependent variable, whereas all the demographic variables were entered as the explanatory variables. However, only degree type and number of seminars attended were found to be significant. Therefore, the final model with only two significant variables is presented here. The significant chi-square statistic indicates that the model is a significant improvement over the intercept-only model (Table 3). Pearson (χ^2 = 2.088, df = 4, p = 0.720) and Deviance statistics (χ^2 = 3.018, df = 4, p = 0.555) were non-significant and the Con and Snell, Nagelkerke, and McFadden r-square were 0.147, 0.177, and 0.089, respectively. The test of parallel lines was non-significant (χ^2 = 1.494, df = 2, p = 0.474) suggesting that the corresponding regression coefficients were equal across all levels of the outcome variable. Parameter estimates for the ordinal regression model as shown in Table 4. The sign of the coefficients indicates direct or indirect relationships between continuous explanatory variables and the awareness level. The relative values of the coefficients for the categories of categorical explanatory variables can help in determining their effects. The sign of a coefficient for a category of a categorical explanatory variable indicates the effect of a particular category with respect to the reference category. Degree type and number of seminars attended were found to be the significant variables. The sign of the coefficient for degree type indicated that those with planning degrees are more likely to have high awareness about FMC as compared to those with engineering degrees. Furthermore, the sign for number of seminars attended indicated that those with higher number of seminars had higher level of awareness as compared to those with lower number of seminars.

3.4. Objective 3: knowledge level

The knowledge level of the respondents who were aware with the FMC concept was evaluated using 5-point Likert type items (N = 174). Most of the respondents agreed with the items as evident from the distribution of the responses shown in Fig. 4.

Exploratory factor analysis with maximum likelihood estimation was conducted on the Likert data to obtain the underlying factor called “knowledge” (Table 5). The factor explained about 68.140% of the variance. All the item loadings were considerable and no cross-loadings were observed. The sampling adequacy (Kaiser-Meyer-Olkin = 0.939), Bartlett’s test of sphericity ($p < 0.001$), and the determinant of the correlation matrix (= 0.001) were satisfactory. The Cronbach alpha was also adequate (= 0.945). Further, the factor scores were computed using regression approach.

Non-parametrical tests i.e., Kruskal-Wallis test and Mann-Whitney U test were conducted on the factor scores to compare the knowledge level of various groups. Females, practitioners, public university graduates, and more seminar attendees had higher knowledge levels compared to males, students, private university graduates, and less seminar

Table 1
Demographic information of the sample.

Variable	Category	Frequency	Percentage
Gender	Male	339	84.1
	Female	64	15.9
Profession	Student	280	69.5
	Practitioner	123	30.5
University	Public University	253	62.8
	Private University	150	37.2
Undergraduate degree	Civil/Transport Engineering	304	75.4
	City & Regional Planning	99	24.6
Age	<22	160	39.7
	22-25	161	40.0
	26-40	75	18.6
	>40	7	1.7
Courses studied on	0	61	15.1
urban/transport	1-2	231	57.3
planning	>2	111	27.5
Seminars attended on	0	183	45.4
urban/transport	1-2	156	38.7
planning	>2	64	15.9

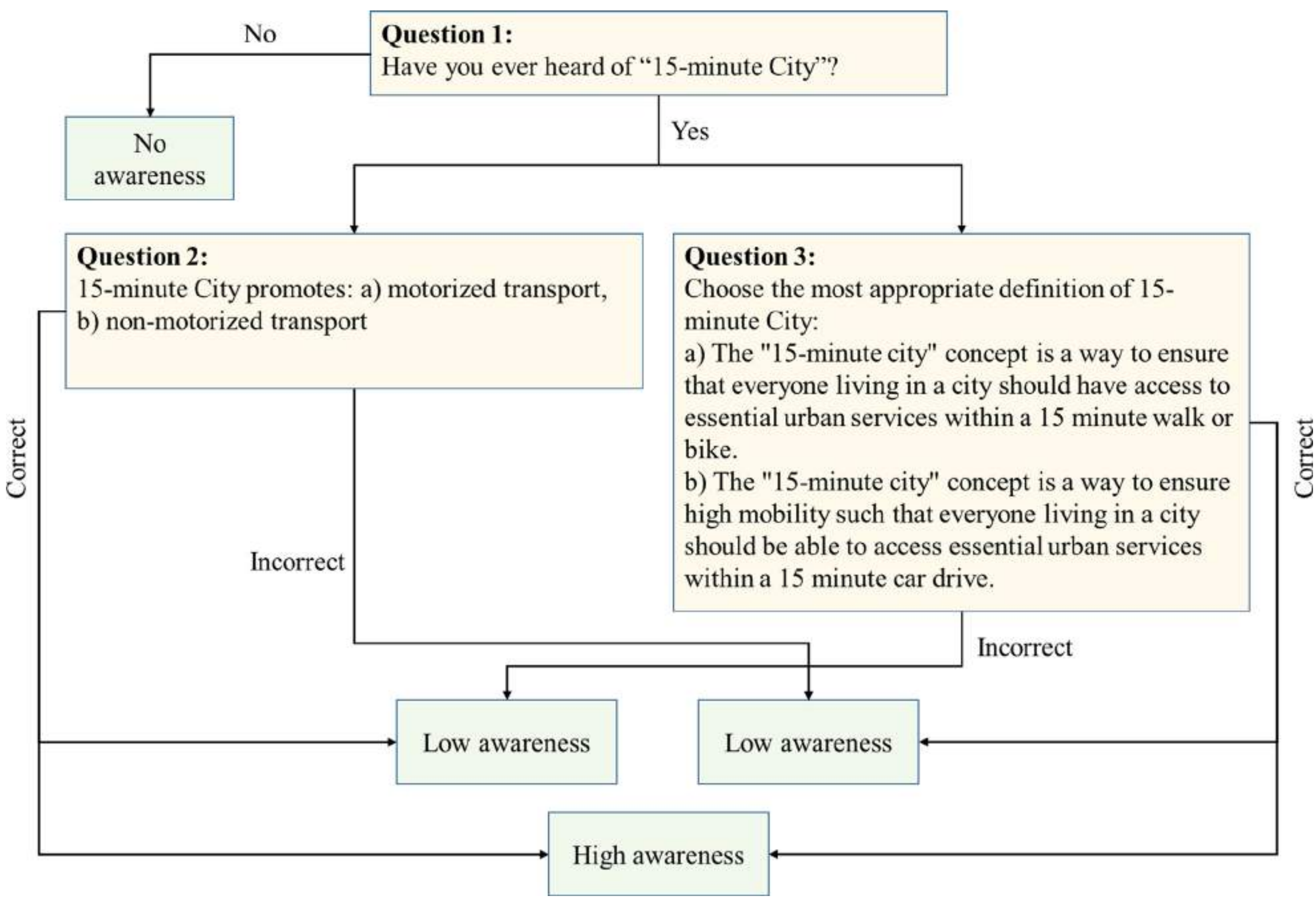

Fig. 1. Schematic diagram showing the process to determine the awareness levels.

attendees, respectively. However, Mann-Whitney U test found the effects of gender (U = 10455.5, p = 0.646), profession (U = 15415.5, p = 0.093), university (18000.5, p = 0.388), and number of seminars attended (U = 18167.0, p = 0.091) on knowledge to be insignificant. In addition, Kruskal-Wallis test indicated that age did not have a significant effect on the knowledge level of the respondents (χ^2 =2.906, p = 0.234). Whereas, type of undergraduate degree and number of courses were found to have significant effects on the underlying factor. City & Regional Planning graduates had a higher level of knowledge about FMC as compared to Engineering graduates (U = 12071.5, p = 0.003*). Those who attended at least one course on urban or transport planning had higher level of knowledge as compared to those who did not attend any such course (U = 8782.5, p = 0.049*).

4. Discussion

This study aimed at understanding the awareness and knowledge level of planning and engineering students and practitioners about the 15-Minute City concept. The three main objectives were to determine the awareness levels, factors affecting the awareness levels and the

Table 2
Distribution of responses to the awareness-related questions.

Question	Category	Frequency	Percent
Have you ever heard of "15-Minute City"?	Yes	174	43.2
	No	229	56.8
"15-Minute City" promotes	Active modes	312	77.4
	Motorized transport	91	22.6
Definition of 15-Minute City	True	333	82.6
	False	70	17.4

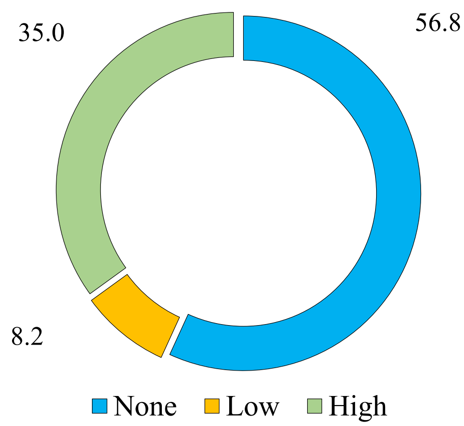

Fig. 2. Distribution of awareness levels about the 15-Minute City concept.

Table 3
Model fitting information.

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	97.148			
Final	32.906	64.242	2	.000

knowledge level about FMC. A questionnaire survey was conducted in Lahore, Pakistan, which included questions on demographics, awareness, and knowledge about FMC. The collected data was analyzed using various statistical analysis techniques such as ordinal regression, factor analysis, and various non-parametrical tests to achieve the objectives of the study.

The results indicated that a high number of respondents did not have awareness about the FMC concept. It could be attributed to the fact that sustainability and non-motorized modes have often not been the focus of transportation planning and engineering curricula (Balsas, 2001). Further, descriptive analysis indicated that type of university, profession, and age seem to have no effect on awareness levels. The ordinal regression model indicated that type of degree and numbers of seminars attended had a significant influence on the awareness levels. However, other demographic variables including number courses attended on transport and urban planning were not significant. The result that Civil Engineers had lower awareness about the FMC concept can be attributed to the fact that the existing curricula particularly that of Civil Engineering does not contain core courses on Sustainability (Chau, 2007). Akyazi et al. (2020) also suggested that sustainable transport be included in the Civil Engineering curriculum to face the future challenges. Further, courses on sustainable transportation in Civil Engineering programs are mostly offered at graduate level (Wu et al., 2014). Websites of the Civil Engineering departments of various universities in Lahore were visited to determine the number of courses related to urban planning. It was found that the curriculum was packed with too many engineering design courses and there was mainly only one transport planning or urban planning course in the curriculum. It is obvious that such vast urban planning content cannot be covered in a single course. It has been reported that education through courses about environmental awareness can produce graduates who are advocate of sustainable transportation policies (Kim et al., 2016). On the other hand, the results of this study indicate that number of courses attended on transportation and urban planning did not have a significant effect on the awareness levels about the FMC. This may indicate that the current courses being taught may not be up-to-date and may not be delivering the recent concepts such as FMC. In addition, Handy et al. (2002) also found the content of planning courses to be highly variable. The seminars, however, seem to be effective and need to be continued for professional development of planners and engineers by imparting them the latest knowledge about the advancements regarding FMC. Other studies have also reported seminars to be effective in conveying important concepts interactively (Al'Adawi et al., 2017). Among those who were aware of the FMC concept, number of courses studied on urban and transport planning had a significant effect on their knowledge levels further indicating that courses with up-to-date contents can increase the awareness and knowledge about the latest proposals and practices related to sustainable solutions such as FMC.

Considering the effectiveness of seminars on transport and urban planning, special seminars must be arranged for engineers to enhance their understanding of FMC. Courses with up-to-date contents can be introduced for Civil and Transport Engineers for their better understanding of more sustainable solutions such as FMC. Since the current Civil Engineering curriculum is overburdened with courses on the design of physical infrastructure, elective courses could be introduced to spark the interest of students. In addition, the contents of the existing courses on urban and transportation engineering can be modified to include

Table 5
Exploratory factor analysis on the Likert data (maximum likelihood estimation).

	Factor Knowledge
The 15-Minute City concept preserves environment by reducing fuel consumption and emissions	.913
The 15-Minute City concept improves overall physical health	.898
The 15-Minute City concept promotes equitable societies	.876
The 15-Minute City concept promotes proximity-based planning	.805
The 15-Minute City concept improves urban fabric with the help of technology	.785
The 15-Minute City concept reduces dependency on motorized transport	.781
The 15-Minute City concept promotes mixed land-use	.769
The 15-Minute City concept promotes compact societies	.760

Table 4
Parameter estimates for the ordinal regression model.

		Estimate	Std. Error	Wald	df	Sig.
Threshold	No awareness	-.553	.127	18.872	1	.000
	Low awareness	-.311	.126	6.093	1	.014
Location	Engineering (Civil/Transport)	-.540	.155	12.149	1	.000
	City & Regional Planning	0				
	Seminars attended = 0	-.734	.138	28.119	1	.000
	Seminars attended ≥ 1	0				

Reference category for the dependent variable: High awareness.

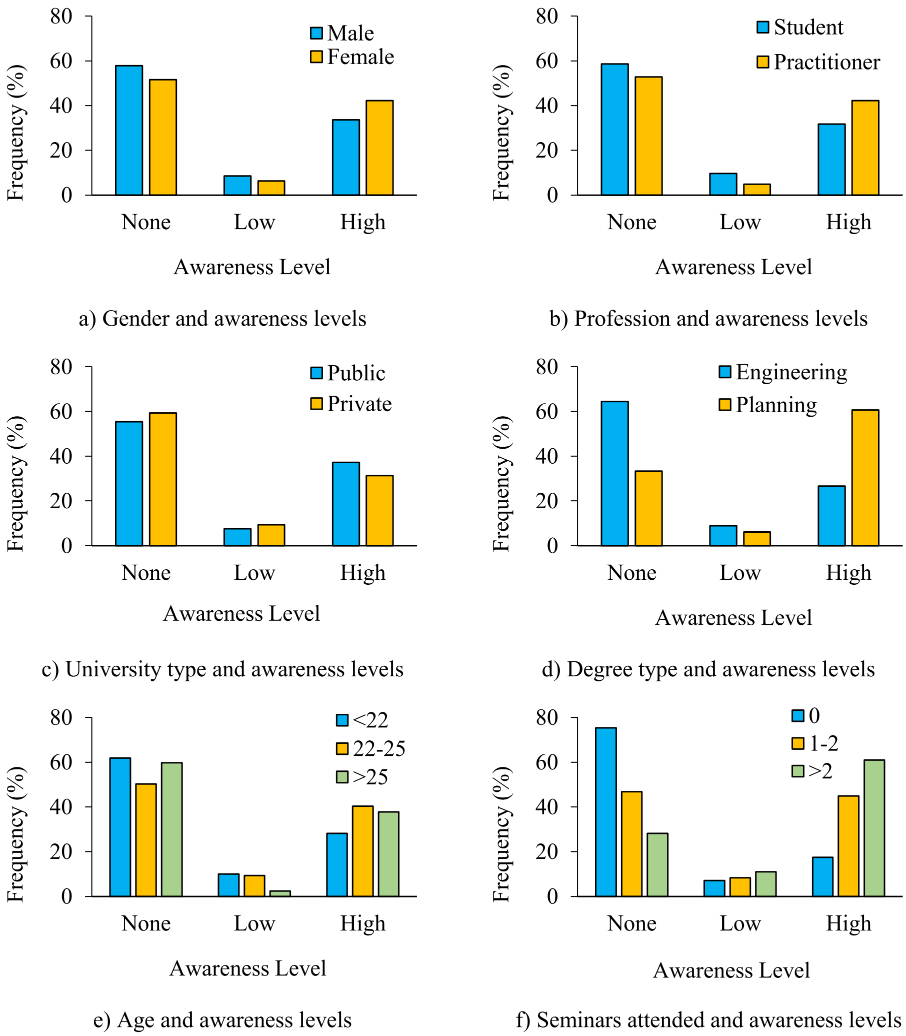

Fig. 3. Breakdown of awareness levels with respect to demographic variables.

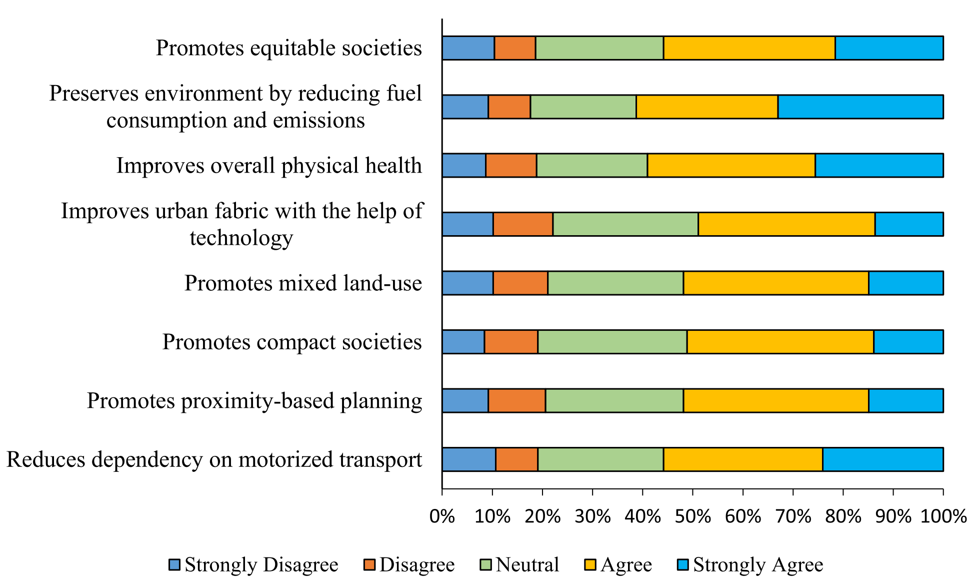

Fig. 4. Distribution of responses for the items measuring knowledge level.

the latest developments in urban planning. Furthermore, project-based learning has been found to be an effective way to increase engineering students' understanding of sustainability concepts in transportation (Fini et al., 2018) and can be adopted.

5. Conclusions

The traditional car-oriented urban planning approach has resulted in cities with more number of cars, more air and noise pollution, and several other negative consequences. Urban sprawl has also been observed in most developing cities around the world. In addition, the COVID-19 pandemic exposed the vulnerability of the existing car-oriented planning approaches. The health protocols limited the movement of people arising the need for the accessibility to basic necessities by walk or bicycle. All the negative consequences of car-oriented policies coupled with the effects of COVID-19 pandemic urged engineers and planners to propose creative and innovative planning approaches such as 15-Minute City. Various countries are aiming at developing FMCs by improving access to basic necessities by walking and bicycling. However, the car-oriented planning approach is still being followed in Lahore. This indicates that the engineers and planners involved in the development of Lahore may need to acquaint themselves with the recent more sustainable urban planning approaches. Therefore, this study aimed at understanding the awareness and knowledge level of planning and engineering students and practitioners about the FMC concept. The three main objectives were to determine the awareness levels, factors affecting the awareness levels and the knowledge level about FMC. A questionnaire survey was conducted in Lahore, Pakistan, which included questions on demographics, awareness, and knowledge about FMC. The collected data was analyzed using various statistical analysis techniques such as ordinal regression, factor analysis, and various non-parametrical tests to achieve the objectives of the study.

The results indicated that about 57% of the respondents had no awareness, 8% had low awareness, and 35% had high awareness about the FMC concept. The ordinal regression model indicated that degree type and number of seminars attended the significant predictors of awareness levels among engineers and planners about FMC. Those with City & Regional Planning degrees were found to be more likely to have high awareness about FMC as compared to those with engineering degrees. Those who had attended higher number of seminars were more likely to have higher level of awareness as compared to those who had attended lower number of seminars. Further, City & Regional Planning graduates were found to have a higher level of knowledge about FMC as compared to Engineering graduates. Those who attended at least one course on urban or transport planning had higher level of knowledge as compared to those who did not attend any such course.

A further study could be conducted on exploring the contents of the courses being taught to the prospective engineers and planners. There might be other factors besides awareness levels affecting the planning approaches being adopted in Lahore, which can be determined in a future study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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City logistics: Challenges and opportunities for technology providers

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A R T I C L E I N F O

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Autonomous deliveries
Stakeholder collaboration

A B S T R A C T

Current last-mile logistics operations are inefficient. The economic competitiveness of logistics service providers is affected by distinct factors, such as the limited time windows they are given to deliver freight in increasingly complex urban environments. This paper presents the different challenges that the sector faces to make its operations more sustainable, from both economic and environmental perspectives. Then, an exhaustive list of measures and initiatives is presented and for each of them, the impact on the different agents involved in last-mile operations is analyzed. This study is expected to help understand the relations between the different actors and design compensatory mechanisms between the parties that mostly benefit from the measures and the most affected ones. Finally, a particular focus is set on the technological developments that are expected to shape the evolution of last-mile operations in the medium or long term. As in the passenger mobility industry, digitization, the emergence of more innovative and modular vehicles, and automation are trends that will undoubtedly affect the market. To maximize the impact of these new technologies, balanced and fair governance schemes and compensatory mechanisms between agents should be designed. The authors believe that the EIT Urban Mobility framework is perfectly adequate to improve this required collaboration between all agents. As a first step towards an increased sustainability of last-mile operations, win-win and agreed measures should be implemented to set the ground for more innovative and disruptive solutions that will emerge in future years.

1. Introduction

Providing people with a reliable and robust transportation system is fundamental to ensure the efficiency of a given city or metropolitan area. Goods are also moved, and ensuring that this can be done efficiently is a key aspect to support the economic attractiveness of a given region. Nowadays, goods are most of the time manufactured out of a city, they are transported to inner neighborhoods, and the resulting waste is then evacuated from the city center to the outskirts. This situation is the result of the sprawl of industrial activity towards less dense areas. It is interesting to recall that this is a quite recent trend and that, throughout history, cities have almost always been considered as centers of production and residence, with mixed land use.

When considering the whole supply chain of a good from the manufacturer (which can be located in Asia) to the final customer (located in cities, as the world population is becoming increasingly urban), the last mile refers to the trip of a good between the last distribution center run by the carrier and the final customer. It can be part of a business-to-business (B2B) or business-to-consumer (B2C) transaction. This generic term of “last-mile logistics” describes very different realities, ranging from the courier express parcel (CEP) market (e-commerce, mail collection, and delivery) to retail (shop) replenishment, food delivery, delivery of construction materials, or garbage collection. Unfortunately, even if this is a fundamental aspect of the economic life of a city, the movements of goods and the relations between the different stakeholders involved in these operations are still quite unknown at the moment, especially when compared to the passenger mobility market in which the situation is evolving rapidly and innovation is flourishing. It seems that last-mile logistics have attracted less interest from city practitioners. Nevertheless, the situation has evolved over the last few years. With the development of sustainable urban logistics plans (SULPs), considered as complementary to the sustainable urban mobility plans (SUMPs) and promoted by the European Commission, planners are expected to become increasingly aware of city logistics challenges.

The main objective of this paper is to propose an overview of how logistics operators are currently dealing with the last mile and describe the main tendencies that will shape this activity in future years. The remainder of this paper is organized as follows. The first part addresses the state of the market and the different challenges that the sector will have to face to increase its sustainability, either economic or environmental. Then, an exhaustive list of measures, including how each one of them impacts the operations and behavior of the different stakeholders, is proposed. Finally, the third and last section presents the technological developments that will be needed to support these measures.

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2. Urban last-mile logistics challenges

In this section, we intend to build an exhaustive panorama of the last-mile logistics market current situation. We identify the main reasons why last-mile operations show a clear lack of efficiency and analyze how the increasing fragmentation of the market and the rise of e-commerce are barriers to improvement.

2.1. Low efficiency of last-mile logistics operations

Urban last-mile logistics are a significant source of traffic and air pollution. The impact of commercial vehicles in traffic may vary depending on the methodology and the area under study, but they represent more than 20% of the total vehicle kilometers traveled in a city (Dablanc, 2007; Russo & Comi, 2012). Their relative contribution to air pollution is generally estimated to be higher (approximately 25% of the total greenhouse gas emissions) because of the aging fleet of vehicles (Dablanc, 2007; Russo & Comi, 2012). These figures show the great importance and huge economic weight of the logistics sector in cities. However, the economic competitiveness and productivity of these operations are still low. Segura et al. (2020) estimated that the last mile represents up to 40% of the total logistics costs (in the Spanish case).

This very low efficiency of urban last-mile logistics can be explained by the fact that carriers have to move and work in an increasingly complex urban environment that is not adapted to their operations (Lindholm & Blinge, 2014). The low cruising speeds in urban areas, vehicle size limitations, and temporal route constraints cause the resource consumption in the last-mile distribution to be high compared to other legs of the transport chain. Tozzi et al. (2013) reported that the average occupancy rate of the commercial fleet in Parma (Italy) was only 30%, as 74% of deliveries must be performed during peak traffic hours. The access restrictions and time windows imposed by local authorities and receivers significantly worsen the efficiency of the supply chain. Figliozzi (2007) estimated that only 51% of driver shifts are spent overcoming the local distance between consecutive customers in the urban delivery route. The complementary fraction is required for loading and unloading operations (32%), resting times (6%), and moving freight from distribution centers to the final delivery area (11%). Indeed, the logistics sprawl has been accentuated in many metropolitan areas as noisy and heavy activities have been relocated to freight villages outside of city centers. Dablanc & Rakotonarivo (2010) studied the evolution of distribution center locations in the Paris (France) metropolitan area between 1974 and 2008. They concluded that the distance that the driver needs to cover from the distribution center to access the first client of the route has increased by 10 km in 30 years. In the case of fleet electrification, this tendency could be a real challenge because of the limited vehicle range with the current battery technology.

Foltyński (2019) and Dablanc & Beziat (2015) ascribed these problems to the low standardization of handling operations and packages (average palletization rate of 5.44%), strong volatility of the market throughout the year (56% of the deliveries during Christmas period), and the lack of loading/unloading (L/U) parking slots (25% of parking is either on double lane or illegal on the curb, bike tracks).

In the particular case of the B2C e-commerce, one of the main challenges is to lower the number of first attempt delivery failures that occur when the carrier comes to the customer's house and nobody is there to receive the parcel. This failure rate, estimated to be approximately 20% in European cities (Eurobarometer, 2013; Van Duin et al., 2016) forces the driver to repeat the delivery without charging any extra fee to the customer.

2.2. Many agents with different objectives and a difficult cooperation

The low efficiency of logistics service providers commented before is also related to the perception that logistics is "an adjusting variable" for many agents involved in the supply chain Dablanc (2007). The freight distribution market involves many stakeholders that pursue very different and, most of the time, antagonistic objectives. Therefore, it seems unrealistic to put in practice innovative solutions addressing the current urban distribution challenges if we do not consider the economic impact of solutions on the profitability of each stakeholder. Carriers have to deal with three different interlocutors: the shipper and receiver, which have economic power, and the public administration, which can impose regulatory decisions with different objectives. The carrier agent, that is, the agent that moves freight, must fulfill the decisions of purchase–sale agreements between shippers and receivers. The relationship between shippers and receivers is essentially economic. They want their goods to be carried from the shipper logistics facility to the receiver's location with specific distribution times, time windows, and shipment sizes. These logistic attributes that result from economic shipper–receiver decisions may vary in every shipment, which limits the carrier's power of action (Holguín-Veras et al., 2014). In addition, the general trend promoted by local governments to decrease the space dedicated to private vehicles (including delivery trucks and vans), and "give the streets back to people" (Bertolini, 2020) will have huge and unpredictable consequences over the carrier's economic competitiveness. In a 15-minute city, how could local shops be efficiently replenished if all the streets are pedestrian and delivery trucks not allowed?

The main driver that pushes public administration to regulate the sector is the reduction of induced externalities. In smaller cities, the main preoccupation is the improvement in safety and reduction of noise levels. In a bigger and denser metropolis, safety and noise are two important considerations, but concerns about air quality have to be added to the list (Lindholm & Blinge, 2014). In contrast, the top three priorities of freight operators reported by Perera & Thompson (2021) are cost minimization, travel time minimization (obviously linked to cost minimization), and reliability. In the survey conducted in the latter study, only 5% of the interviewed freight operators considered the reduction of externalities as the main driver of their actions. Designing policies and organizational solutions that can both reduce externalities and ensure economic profitability for freight operators (beyond some subsidies that may exist during pilot initiatives) is a current research topic. Without this economic viability, carriers' business models are not likely to change (Taniguchi, 2014).

Moreover, public authorities have not fully addressed the issues raised by last-mile logistics. Lindholm & Blinge (2014) conducted a study in Swedish municipalities in which it was reported that only three cities had a person especially dedicated to freight transportation. Despite the importance of freight movement, 88% of the city planners surveyed spent less than 10% of their time on freight-related issues. For most city representatives, last-mile low efficiency is "a matter that the business itself needs to address," and "freight is mainly handled through restriction" (Lindholm & Binge, 2014). In the regulatory framework, all agents expect measures to be led by the other side. City governments assign leadership in this matter to logistics service providers, while the latter are waiting for municipalities to facilitate (and even subsidize) new services before starting a business (Dablanc, 2007).

One of the main reasons that can explain this deteriorated relationship between private carriers and public authorities is the lack of open data, especially when compared with passenger transport. Lindholm & Blinge (2014) highlighted that only 30% of the city representatives in charge of freight-related issues had statistics regarding freight transport in their own municipality. Gathering such data could help to better understand the challenges raised by last-mile operations and provide start-ups and researchers with reliable and extensive data to create new solutions. In this sense, there is a broad consensus within the research community that more vertical cooperation between logistics operators, shippers, receivers, and public administration is necessary.

Finally, the market has entered a phase of deep reconfiguration. Historical post operators (in which the sustainability component can be more easily integrated because they are public companies most of the time), are struggling to be economically sustainable. In France, in 2020, two billion letters less than in 2019 were distributed (Chocron, 2021). Since 2017, the universal postal service offered by La Poste has been in deficit, and this deficit could reach 1 billion euros by 2025 (Chocron, 2021), which questions its existence. These historical operators clearly need to change their business models; e-commerce could be an opportunity (increased business volumes) as well as a threat to them because their supply chains have to be reconsidered. The last-mile universe is increasingly fragmented, especially in the case of CEP operations. Because of low entrance barriers (one just needs to buy a van to start delivering some parcels), competition is increasing, and subcontracting business relationships are gaining momentum. In this context of fragmentation, the horizontal collaboration between carriers, bringing everyone together around a table to improve the sustainability of the operations, will be a huge challenge in future years.

2.3. The rise of e-commerce

Retail e-commerce sales worldwide are expected to grow from $2.3 trillion in 2017 to $4.5 trillion by the end of 2021 (eMarketer, 2019), approximately 16% of total retail sales. These estimations were made before the Covid-19 pandemic, during which the use of e-commerce skyrocketed. Marketplaces, that is, third parties that aggregate and commercialize products by internet from many providers, are capturing an increasing number of customers because they offer better prices, free or discounted shipping, and a broader variety of products (UPS, 2018). The increasing volume generated by online shopping exacerbates the issues highlighted in the previous sections. More will be demanded from a system that is not capable of efficiently dealing with the current demand, especially in the CEP market. This is similar to asking a child to run before he/she can stand up and walk.

The convenience of online shopping will contribute to the fragmentation of demand: smaller parcels will be ordered more frequently, increasing freight vehicle traffic. E-shoppers are increasingly demanding, especially in terms of time horizon (same-day or 24-hour home deliveries). In Mexico City, Muñoz-Villamizar et al. (2021) highlighted that fast shipping could result in 15% increase in carbon dioxide emissions and 68% increase in operational costs because this delivery mode reduces the consolidation of demanded goods (the delivery vans run half empty). The impact of food delivery platforms, whose usage has surged in the last few years, on traffic and emissions is still under investigation (Allen et al., 2021). To be environmentally sustainable, the food should be delivered using low-emission vehicles (such as bikes), which is not always the case at the moment and is raising great concerns.

In addition, e-shoppers are not necessarily willing to change their habits to make the system more sustainable. In Germany, even if the parcel locker network is dense and efficient, 90% of customers prefer to have their parcels delivered at home (Morganti et al., 2014a). If the delivery does not suit him/her, the e-shopper will just order from another e-commerce platform offering better conditions.

The impact of the Covid-19 pandemic on the use of e-commerce was tremendous. In a survey conducted by Holguín-Veras et al. (2020), 27% of the respondents declared that they switched from buying in stores to buying online during the pandemic. The sanitary crisis had an impact on people's behavior. Nevertheless, the long-term consequences of the pandemic on e-commerce habits are currently unknown.

Beyond this effect of the Covid-19 crisis, the impact of e-commerce on the behavior of shopping customers is a controversial topic within the research community, which still needs to be investigated. Worldwide, 28% of Amazon shoppers declared they go less often to retail stores because of online shopping (eMarketer, 2019); that is, e-commerce will substitute local retail stores, which is not desired by municipalities if they want to maintain vibrant and livable neighborhoods. However, this result is counterbalanced by other studies, in which the real impact of e-commerce seems to be much more complex. In some cases, e-shopping is seen as complementary to retail stores (Cao et al., 2010; Farag et al., 2006; Lee et al., 2017; UPS, 2018) or even a great opportunity for local retail shops.

To sum up and conclude this first section, very distinct tendencies ranging from new urban planning models to the emergence of e-commerce are hugely impacting carriers' operations, making them more and more complex. This will eventually result in an increase of the final cost of freight transport (worsening the level of service), and its associated externalities if no measures are taken. At a governance level, the movement of commercial vehicles in urban areas is the result of decisions taken by many different stakeholders with opposite objectives (Holguin-Veras et al., 2014), mainly shippers, receivers, local authorities, and carriers. Most of the time, logistic practices that increase shipper profitability or receiver utility are usually those that generate the worst impacts on society and the environment.

3. Last-mile improvement initiatives

Different measures and initiatives have been developed, not only to increase the cost efficiency of last-mile logistics but also to alleviate the negative social and environmental impacts. The deployment of a wide range of initiatives entails an equilibrium between individual and social profitability. This equilibrium, usually attained by regulations set by local authorities and administrations, must consider the overall impacts of logistics services among the agents involved in the system. The social benefits of the distribution activity must be balanced with the negative externalities generated by commercial fleets. In this process, it is crucial to enable economic mechanisms to control and adjust each stakeholder's profitability, i.e. economic incentives may compensate for the negative effects of public measures on affected agents or the low economic return of eco-innovation concepts. Failing in the estimation of the impact experienced by each agent and the economic compensation mechanism usually leads to claims about the nature of the initiative or its failure.

The novel initiatives undertaken by different stakeholders are usually classified into the following groups of measures: (i) logistic infrastructure, (ii) new technologies, and (iii) new organizational schemes. These initiatives in the last-mile distribution have been tested under different research and innovation programs worldwide, demonstrating the feasibility of the new concepts in controlled situations with targeted agents. Nevertheless, the scalability of these measures, especially those related to new organizational schemes that imply collaboration between agents, do not meet the expected target values and present variability. These controversial results are, in part, due to the different levels of stakeholder engagement. Another reason could be the natural reluctance of some stakeholders (mainly carriers) to share data and collaborate with other companies competing for the same market. The latter issue would become important when obtaining data to monitor the results of ongoing measures in freight systems. Thus, there is no consistent set of predefined effective measures to improve the current freight situation in a city. The success of each initiative, especially of those related to new organizational schemes, depends on stakeholder collaboration rather than on the technical specifications or operations of the improved system.

The objective of this section is to compile last-mile logistics initiatives that have been emerging these last few years and analyze them based on the agent responsible for their development (shipper, intermediary marketplace, carriers, receivers, and local authorities), along with the cross-effect on other stakeholders. The innovations needed to enhance the considered initiative, in terms of infrastructure, technology or organizational scheme, are also presented. For a more detailed breakdown of policy-related measures promoted by public agencies, readers are encouraged to consult Holguin-Veras et al. (2018a, 2018b). In the following tables, '+' (respectively '-') means that the implemented measure has a positive (respectively negative) impact on the considered stakeholder.

Table 1
Shipper-led innovations.

Concept	Impact on stakeholder (S: Shipper, M: Marketplace, Ca: Carrier, R: Receiver, LA: Local Authority)						Needed innovation		
	S	M	Ca	R (B2C)	R (B2B)	LA	Infrastructure	Technologies	Organizational scheme
Multiple commercialization channels (physical/digital)	+	+	–	+	–	–		Digital marketplaces	Vertical collaboration S/Ca
Demand forecasting	+	+	+	+	+	+		Demand forecasting algorithms	
Returnable packaging and recollection channels	–		–	–	–	+		Reusable packaging Tracking technology	Reverse supply chain

3.1. Shippers

Shippers are product manufacturers or service providers that need to distribute goods and freight through physical networks. They aim to maximize the revenues of product sales while satisfying the expected requirements of potential customers. Shippers have expanded the traditional sales channels and touchpoints with final customers (via retail shops and/or e-commerce) and the combination of product characteristics (specific attributes or extras that can be selected). This customization process, in addition to pull-production and just-in-time strategies, has forced the externalization of logistics operations through LSPs and carriers with dedicated fleets (see Table 1). These agents can provide more efficient and adaptive services by aggregating the demand peaks of multiple shippers.

Carriers and LSPs are now responsible for providing a wide spectrum of logistic solutions to meet the final customer requirements: regular versus express deliveries, distribution in time windows (Zhang et al., 2020), alternative locations to home deliveries using lockers or dropping boxes (Morganti et al., 2014b), and reverse logistic operations for returns (see Table 1). This range of commercialization and distribution channels clearly benefits the producer position in the market. However, it strains the work of LSPs, increases the negative impact of more frequent transport services on the environment, and affects the livability of cities. Moreover, the variable peak demands resulting from the temporal needs of individual customers critically stress the production chain.

Therefore, producers have been promoting new initiatives to forecast customer demand, implementing artificial intelligence (AI) schemes, and new smart home devices. Nowadays, important brands (LG, Samsung) have launched household appliances capable of monitoring the inventory of groceries, chemical products at home, and order new shipments when necessary. The historical analysis of these orders or the consumption rates will become crucial information to plan the logistic shipments of products for the next few days. The increasing interest in the circular economy forces carriers to design new reverse logistics (from the final customer to the manufacturer/producer) to reduce waste and/or foster product recycling (Yang et al., 2021).

3.2. Marketplace companies

The goal of this agent is to become the commercialization channel of the highest number of producers, retailers, or even traditional shops. The aggregation of multiple products and potential customers into a single purchasing platform gives marketplace companies a dominant position in the market (see Table 2). These agents may internalize those parts of the supply chain previously outsourced to LSPs and introduce added value in terms of new services distributed to/from final customers (Janjevic & Winkenbach, 2020). The biggest marketplaces are expected to sign trust-vendor agreements with individuals (B2C) or companies (B2B) to perform unattended deliveries by means of digital door keys. This will also expand the service catalog by picking up objects that require any type of process (laundry, product repair, returns).

3.3. Carriers and logistic service providers (LSPs)

The objective of this agent is to run a physical network that enables goods to arrive at the location of the receivers. Although most of the effects caused by the last-mile distribution are related to the operation of carriers, this agent has a limited range of decisions. In fact, shippers and receivers impose the vast majority of requirements that carriers must fulfill to provide a more reliable service to final customers. Hence, carriers deploy new systems capable of providing tracking information of deliveries or the installation of alternate location facilities (dropping boxes or collaborative retail shops, see Table 3). Although these systems are required by other agents, they may also result in a reduction in delivery failures and, consequently, in the operational cost of carriers. They will also make the distribution more efficient with the deployment of routing optimization algorithms (Crainic et al., 2009; Janjevic et al., 2020), considering real traffic data and loading/unloading (L/U) parking occupancy and the amount of product to be picked up at destinations (on-street waste or second-hand clothes containers).

The pressure imposed by local governments to reach target emission goals has encouraged carriers to purchase eco-friendly vehicles with alternative powertrains, such as electric cargo bikes, full electric vehicles (Caggiani et al., 2021), and fuel-cell trucks (Toyota, 2021, Daimler Truck unveils fuel cell concept truck, 2020). Despite a smaller energy consumption cost and broader use in restricted zones, electric or hydrogen vehicles have not always justified net cost savings owing to the high capital purchasing cost and the restrictions in terms of maximal kilometer range with a loaded battery. These constraints are causing the utilization of two commercial fleets in cities with historical centers, one for accessing the city and another, of smaller capacity, for performing deliveries to customers (see Table 3). Several carriers are exploring strategies for pre-classifying parcels to be distributed by the same vehicle at the shipper location, with the development of standardized small urban containers or small vehicles. These containers or small vehicles are transported in heavy trucks accessing the city, thereby reduc-

Table 2
Marketplace-led innovations.

Concept	Impact on stakeholder (S: Shipper, M: Marketplace, Ca: Carrier, R: Receiver, LA: Local Authority)						Needed innovation		
	S	M	Ca	R (B2C)	R (B2B)	LA	Infrastructure	Technologies	Organizational scheme
Aggregation of multiple producers	+	+	+	+	–	–		Scalable digital marketplaces	
Internalization of logistic operations		+ –	–						

Table 3
Carrier-led innovations.

Concept	Impact on stakeholder (S: Shipper, M: Marketplace, Ca: Carrier, R: Receiver, LA: Local Authority)						Needed innovation		
	S	M	Ca	R (B2C)	R (B2B)	LA	Infrastructure	Technologies	Organizational scheme
Driver education program			+ –			+			Vertical collaboration LA/Ca
Time information and tracking	+	+	+ –	+	+	+		Data treatment system	Vertical collaboration S/R RGPD compliance
Alternative delivery locations (lockers, local shops…)			+ –	+ –	+	+	Integration of lockers in urban landscape	Agnostic parcel locker tech.	Horizontal collaboration (deliveries in same locker) Vertical collaboration Ca/R (B2B)
Route optimization (depending on traffic, L/U parking slot)			+	+		+	L/U parking slot digitization	Dynamic en-route routing	Vertical collaboration Ca/LA
Low-emission vehicle			–			+	Micro-hub network (for e-cargobikes) Deployment of recharging stations (for e-vehicles)	Modular vehicles More efficient e-vans Fast recharging stations	Vertical collaboration Ca/LA
Standardized urban containers	–		+			+		Vehicle trailer concept	Common classification and palletization Vertical collaboration S/Ca
Automation			+	+		–	Vertiports Infrastructure mapping	Orchestration systems Air delivery drones Ground autonomous delivery robots	Collaboration Ca/LA New regulation
Off-peak distribution			+		–	+ –		More silent vehicles	Vertical collaboration Ca/R
Use PT capacity during off-peak hours			+ –			+	Adaptation of PT infrastructure to freight handling	Flexible freight handling system	Vertical collaboration Ca/LA
Use city "blue layer" (waterway, seaside…)			+ –			+	Freight multimodal hubs	Autonomous freight boat Efficient transshipment system	
Underground "hyperloop"			+ –	+	+	+ –	Freight "hyperloop" infrastructure	Standardized container Orchestration tools	Horizontal collaboration Standardized sending protocols Vertical collaboration Ca/LA/R

ing costs and time (the mobile depot concept in Marujo et al., 2018 and Verlinde et al., 2014).

A promising concept that may change the current paradigm of city logistics is the automatization of commercial ground vehicles (Chen et al., 2021) and drones. Despite the higher purchasing cost, this technology reduces the human workload in the physical distribution and the relaxation of constraints associated with driver shifts. Although driverless technologies are becoming more mature, the crucial challenge is not the vehicle itself, nor the trip, but how these unmanned vehicles will deliver or pick up parcels to/from final destinations without human assistance. Carriers are also willing to reduce the impact of congestion and crowded L/U parking operations in dense cities by changing the time of service and transportation mode. Several successful results have been obtained in off-peak or night delivery programs in terms of cost reduction and emission savings. Nevertheless, receivers must accept deliveries out of the normal period by means of public–private campaigns promoted or incentivized by local authorities. In addition, there are initiatives to transport freight through the city "blue layer" (rivers, channels, or seafront), public transport networks (Thompson & Taniguchi, 2014; Kikuta et al., 2012; Nuzzolo et al., 2008), or even underground paths to alleviate road networks from commercial vehicles. Despite the promising results for specific large freight demand attractors, the generalization of these improvement concepts to all distribution chains presents challenges in terms of accessibility and load breaks (see Table 3).

3.4. Receivers

Although receivers are not responsible for any physical operation in the supply chain, their decisions in terms of the number of products purchased, reception times, and delivery address clearly affect the entire distribution system. Shop associations in city districts (B2B) or different departments in big pole attractors (B2B or business-to-administration) are performing receiver-led consolidation programs, in which demand requests of individual shipments are centralized in a neutral body or mobility manager (see Table 4). Hence, the aggregation of these requests can be served with a significantly lower number of vehicle routes. Based on these collaborative practices, receivers may benefit from lower transportation costs because the number of shipments is reduced. In recent decades, these shop associations have also organized home deliveries to compete with internet marketplaces, sharing the cost of drivers or offering micro-jobs via crowd-sourced deliveries (Buldeo Rai et al., 2017).

3.5. Local authorities

They are responsible for deploying public infrastructure, enabling the freight flows derived from economic transactions in the city. At the same time, they face the challenge of alleviating the negative effects on citizens and the environment. Therefore, public policy-oriented initiatives focus on balancing the welfare of citizens with the economic activities of stakeholders involved in urban distribution. Possible initiatives can be summarized as follows: (i) promotion of new pathways and logistics facilities (relocation of logistics centers), (ii) adaptation of urban spaces to urban logistics operations, (iii) flexible management logistics facilities, (iv) network and parking pricing, (v) access restrictions, noise compliance, and (vi) land use management (see Table 5).

Nevertheless, city councils are also in favor of public–private partnerships to promote new organizational schemes between stakeholders to reduce access to commercial vehicles in city centers. In fact, public

Table 4
Receiver-led innovations.

Concept	Impact on stakeholder (S: Shipper, M: Marketplace, Ca: Carrier, R: Receiver, LA: Local Authority)						Innovation		
	S	M	Ca	R (B2C)	R (B2B)	LA	Infrastructure	Technologies	Organizational scheme
Crowd-sourced last-mile logistics			–	+ –		+ –			Horizontal collaboration R/R Vertical collaboration S/R
Receiver-led consolidation strategies	+		+	+ –	+ –	+			Horizontal collaboration R/R

Table 5
Local authority-led innovations.

Concept	Impact on stakeholder (S: Shipper, M: Marketplace, Ca: Carrier, R: Receiver, LA: Local Authority)						Innovation		
	S	M	Ca	R (B2C)	R (B2B)	LA	Infrastructure	Technologies	Organizational scheme
Access restrictions			–			+	Relocation of logistic centers		Vertical collaboration Ca/LA
Road and parking pricing			–			+	Monitoring sensors	Pricing management system	
Urban consolidation center			+ –			+	Creation of urban freight facilities	Data exchange platform	Horizontal collaboration Ca/Ca Vertical collaboration LA/Ca
Adaptive infrastructure to urban logistics (L/U parking slots, geometric constraints removal)			+			–	L/U parking slots Removal of geometric constraints	Parking slot management system	Vertical collaboration LA/Ca

authorities can promote or compel by regulating the implementation of these new logistics practices, but the success of each measure depends on stakeholder engagement. The most promising strategies that imply vertical collaboration among stakeholders are as follows.

- Consolidation strategies. The basic idea is to consolidate freight trips before the last distribution leg in an existing or new economical urban facility (carrier-led). In carrier-led consolidation, freight from different carriers arrives at urban facilities, known as urban consolidation centers (UCC). The cargo will be loaded in exclusive or shared vehicles with a load factor higher than the regular distribution (HALLO project, 2021; SMUD project, 2020). Despite the positive results from the city perspective, the crucial issue is a successful business model of the agent that runs the UCC and last-mile service (Allen et al., 2012; Browne, Sweet, Woodburn, & Allen, 2005; SMILE project, 2015). In the receiver-led strategy, the goal is to coordinate freight arrivals in the same shipments, so that the existence of a dedicated facility is not required (Holguín-Veras & Sánchez-Díaz, 2016; van Rooijen & Quak, 2010).
- Off-peak distribution. City councils may lead vertical collaborative programs between different agents to increase the acceptance of receivers to switch to non-peak periods or use of time slots. This strategy does not require significant incentives when carriers can perform unattended deliveries (McKinnon & Tallam, 2003). It has obtained outstanding results in terms of emission and operational cost savings in different demonstrations in New York, Bogotá, Copenhagen, Barcelona, and Brussels.

In the future, it is expected that local authorities will undertake educational programs for citizens, retailers, and carriers to introduce them to sustainable logistics and behavioral practices.

Many innovative measures can be envisioned to improve last-mile logistics considering the challenges presented in Section 1. These innovations are led by a given agent but have an impact on the rest of stakeholders present in the supply chain, meaning that compensatory mechanisms should be designed. Disruptions that mostly rely on policy and governance innovation have been largely studied by the research community. However, even if policy plays a key role, some of these initiatives cannot be implemented without the application of particular technologies to the given context of last-mile logistics. To the best of our knowledge, this aspect needs further investigation and will be the object of Section 4.

4. Last-mile logistics technological challenges

The technological challenges that the last-mile industry will have to face in future years are not fundamentally different from those that appear in passenger mobility. The authors identified three main transformation and improvement opportunities: (i) digitization of the logistics sector to generate better monitoring of the last-mile operations, (ii) development of more sustainable and flexible delivery vehicles, and (iii) automation of last-mile operations. Each of these opportunities will be further detailed in the following sections.

4.1. Digitization of last-mile operations

The first main technological developments that will affect the last-mile industry are the emergence of the Internet of Things (IoT) and shared data platforms. They will depict the "big picture," providing information to establish global optimization schemes, resulting in a decrease in both operational costs and externalities. In the particular case of last-mile operations, the technologies at stake are radio frequency identification (RFID) chips (Rey et al., 2021), which will ensure a much better traceability of goods along the supply chain, low-cost GPS devices (Nuzzolo et al., 2020; Taniguchi et al., 2016) to monitor the real-time location of delivery vehicles accurately, and a network of wireless sensors that could be used, for example, to monitor the occupation of the different L/U parking spots. By connecting different sources of information, logistics operators will be able to (i) optimize the use of its assets, (ii) decrease the significance of human error, and (iii) increase transport control (Rey et al., 2021). IoT will enable the carrier to have an exhaustive real-time overview of the state of its fleet. In addition, implementing IoT and taking advantage of its assets could generate new revenue streams for the carrier. As an example, SEUR, an important CEP company in Spain, equipped its city vehicles with sensors to measure real-time air contamination (SEUR, 2020). If adequately shared and analyzed with local public authorities, these data could be very valuable.

The expansion of IoT within the logistics sector will generate a huge amount of (high-quality) real-time data, which, if adequately processed, could result in important operational improvements. To analyze these data efficiently, new algorithms, including machine learning and artificial intelligence (AI) techniques, should be investigated and implemented. Roca-Riu et al. (2015) developed a parking slot assignment system for urban distribution. The objective is to use optimization algorithms to maximize the usage of urban L/U parking spots with a slot reservation system. To implement these numerical methods in a real-life use case, parking spots must be equipped with IoT sensors to track their real-time occupation. In addition, collecting, storing, and analyzing real-time data will enable logistics operators to optimize the routing and scheduling of their operations (Taniguchi et al., 2020). Real-time vehicle location can be crossed with traffic data for more efficient routing, thus avoiding congestion.

As previously described in Section 2.3, one of the major challenges of last-mile operations is the clear lack of collaboration between the different agents that play a role in this market. To foster this collaboration, which could result in efficiency improvements for the carriers (Estrada & Roca-Riu, 2017), the authors see a huge potential for integrated digital platforms for last-mile operations (Taniguchi et al., 2018). The usage of such a platform would result in a better spatial consolidation of the demand (shared between all logistics operators participating in the project), that is, a decrease in operational costs.

Nevertheless, to obtain support from carriers, the platform and the way it is managed (governance scheme) should be completely transparent and trustworthy (Hribernik et al., 2020). As described in Section 2.3, in such a competitive market as is the last-mile industry, (not) sharing data is of strategic importance for the carriers. To achieve this reliability and trustworthiness, blockchain technology, which is currently a very active research topic, could be used. Irannezhad (2020) highlighted that, in the case of maritime transport management, the use of this technology could improve the efficiency, transparency, and trustworthiness of different actors. He then showed that the governance of such a blockchain-based digital platform is a key element for successful implementation. Three types of governance schemes can be used and depending on the different characteristics of the considered market, a solution could be more suitable.

In last-mile logistics, the potential of blockchain has been less investigated. To the best of our knowledge, Hribernik et al. (2020) were the first to present a decision framework for horizontal collaboration between CEP carriers. When compared to maritime transport, in which some pilots have already been conducted (Irannezhad, 2020), the last-mile market seems to be even more fragmented. One of the main challenges will be to attract medium-sized carriers to these platforms, as they have limited resources for innovation projects and are not necessarily aware of the technological implications. To illustrate this, it is worth noting that the penetration of IoT is much higher in large logistics companies (Rey et al., 2021). Everything indicates that the same type of results can be obtained in the case of blockchain. In an online survey they developed, Hackius & Petersen (2017) emphasized that the main barriers to its adoption by logistics companies are regulatory uncertainty and the fact that “different partners must join forces,” that is, the necessity of a close collaboration between the agents involved in the market. Middle-level managers seem to be less enthusiastic than senior executives (Hackius & Peterson, 2017). There is also a discrepancy that depends on the practitioner’s background. While logisticians have difficulties obtaining a clear idea of the benefits of blockchain and there is a lack of convincing use cases, consultants and scientists are more concerned about the maturity of this technology. More research on the benefits and risks of such blockchain-based platforms is needed (Hribernik et al., 2020)).

4.2. Innovative vehicles

The electrification process experienced by commercial fleets presents significant potential for reducing the air pollution (Giordano et al., 2018) and noise (Campello-Vicente et al., 2017) generated by frequent freight shipments in urban areas (ZEUS project, 2020). Van Duin, Tavasszy, & Quak (2013) estimated that the electrification of the delivery vehicle fleet in Amsterdam (the Netherlands) could reduce the sector’s carbon dioxide emissions by 90%. However, even if the perception of electric vehicles within logistics companies is favorable (Wolff & Madlener, 2019), the penetration of electric vans and trucks in the last-mile industry seems to be very slow. In 2015, only 0.5% of the 1.7 million newly registered commercial vans in Europe (including last-mile logistics and service vehicles) were electric, and today 97% of the last-mile fleet uses diesel engines (Morganti & Browne, 2018). The most important barrier to the adoption of electric vehicles is the high cost of ownership (Feng & Figliozzi, 2013; Morganti & Browne, 2018; Van Duin, Tavasszy, & Quak, 2013; Scoranno et al., 2021). In a survey conducted by Morganti & Browne (2018), English and French urban freight operators raised that the redesign of the current supply chain was one of the main concerns. Beyond purely economic and rational considerations, one of the main barriers is the lack of understanding of the technology and “psychological” issues (fear of change).

In recent years, environmental concerns have also motivated the development of non-motorized vehicles, adapted to the last-mile distribution and urban space limitations (electric cargo bikes, bicycles, trolleys; see Nocerino et al., 2016). Although some of these vehicles can be assisted by electric engines, they are allowed to run along sidewalks and pedestrian areas. Apart from the promising emission savings, these vehicles would become a more time-competitive solution than regular vans in restricted areas of historical city centers, where the gage of one-direction streets is limited.

The freight industry has not only fostered the launch of innovative solutions in the tractor element or vehicle powertrain, but also in the receptacle that holds products for convenience of movement (truck box, trailer, or container). In this sense, the tendency is to standardize or create modular freight receptacles in order to speed up handling operations at urban terminals or adjust the size of the trailer. Several vehicle manufacturers are attempting to replicate the principles of the European modular system in heavy trucks (regulated by Directive 96/53/EC) to light commercial vehicles in urban environments. As a result, freight may be loaded into urban-designed containers at distribution centers that can be easily transferred from heavy vehicles (operating the long-haul network) to light vehicles or devices that will perform last-mile deliveries. Modularity may allow different vehicle layouts and sizes to adapt better to the shapes, volumes, and characteristics of the shipments. Indeed, there are initiatives aimed at developing a set of interchangeable modular urban trailers to be powered by common electric tractors (EDAG, 2019).

The previous concepts are being developed together with the last developments of vehicle connectivity with the infrastructure (V2I), travelers (V2P), and other vehicles (V2V) (Fossen et al., 2017). This connectivity may lead to the (semi-)automatization of driving operations, thereby increasing the traffic safety and productivity of resources. Two alternatives provide different latency performances, and data flow at an affordable cost. The first is the ITS-G5, or intelligent transport system, promoted by vehicle manufacturers, which operates in the short range (5 GHz), does not require a licensed spectrum but the deployment of a dedicated field infrastructure, and ensures the minimum latency needed in safety-critical applications. The second one is 5 G, the fifth generation of mobile networks, which could be another option for implementing vehicular connectivity. It has short and long range, high data transfer rates, very low latency, and improved security.

4.3. Automation

In last-mile operations, personal costs represent approximately 80% of the total operational costs of the vehicle (Observatory of Road Freight Transport Costs in Catalonia, Bedoya & Torre, 2021). This figure is a key element in understanding the recent enthusiasm of the last-mile industry for autonomous technologies that have the potential to cut both the carrier’s operational costs (Jennings & Figliozzi, 2019, 2020) and externalities (Figliozzi, 2020). Baum et al. (2019) identified 39 different designs for automated ground micro-vehicles. In addition to this already-long list, air delivery drones are currently raising a great interest within the research community. However, the market is not yet mature, and business models involving this type of technology need further assessment (Lemardelé et al., 2021).

Last-mile supply chains must be adapted to foster an efficient use of these autonomous delivery vehicles (either on the ground or in the air). Because they are medium-sized electric vehicles with limited battery capacity, they have a low range of action. Currently, carriers' distribution centers are located in the outskirts of the city (Dablanc & Rakotonarivo, 2010), and the distance between the distribution center and the final customers cannot directly be covered by autonomous delivery vehicles, especially the smaller ones. As a consequence, there could be new cooperative delivery patterns involving trucks and ground autonomous delivery vehicles (Boysen et al., 2018) or trucks and air delivery drones (Murray & Chu, 2015). This is an opportunity for manufacturers to design vehicles that are more adapted to these collaboration schemes.

In addition, at the moment, autonomous technologies are only able to deal with smaller parcels and, even if the technology were ready, it is not clear whether future regulations will allow larger parcel transportation. This implies that carriers have to increase the complexity of their supply chain by creating two distinct distribution strategies depending on the characteristics of the parcel that is to be delivered. This increased complexity could be a barrier to the implementation of autonomous technologies.

Finally, business models and adequate use cases must be further investigated for wide deployment. Müller et al. (2019) analyzed the emergence of air-delivery drones. Currently, air delivery drones operate only in niche markets, such as in the delivery of medicines to isolated areas (after a natural catastrophe, for example), or in some pilots of e-commerce parcel delivery in rural areas. The automobile industry and other manufacturing companies are integrating drones in the supply chain, but these are still pilots involving the limited transport of small misplaced pieces. In some cases, these pieces are transported from a supplier to the factory, and the drone flies over an external road outside both companies (Bertran & Petit, 2019).

The main question concerning the air delivery drone technology is to determine whether the techno-economic pressure (the development of the information and communication technology, the emergence of e-commerce that generates smaller parcels and instant or same-day deliveries) and the socio-political pressure (the need to reduce contamination and congestion) will counterbalance the low acceptance of drones by public authorities and citizens. Noise and safety issues remain a major barrier to the introduction of air delivery drones in densely populated urban areas. Because air drones operate in niches in which the customer willingness to pay is higher (instant e-commerce deliveries, for example), the capital invested in this technology can generate more margins than in the standard mass last-mile delivery market that relies on delivery trucks and vans. These high margins attract non-conventional or market players that are not necessarily aware of all logistics constraints. Mostly because of some very restrictive regulation barriers and safety/insurance challenges, the use of drones does not seem competitive in the mass last-mile market. However, the multiplication of successful use cases, such as truck-launched delivery drones in rural areas or for fast emergency response, will contribute to the maturity of the technology, which seems to be today in its stabilization phase (Müller et al., 2019). The ability of drones to disrupt the mass last-mile market is yet to be seen.

5. Conclusions

Last-mile operations in urban environments are currently very inefficient, both from an economic and environmental perspective. The main reasons for this inefficiency are the requirements for the carriers to operate during very restrictive time windows (that most of the time coincide with traffic peak hours), the long distances between the distribution centers and the main service regions, and a lack of loading/unloading parking spots. To solve these issues, high-level cooperation between the stakeholders (shippers, marketplaces, carriers, receivers, and public authorities) is needed, but this is hardly achieved at the moment. The agents pursue different goals (most of the time contradictory), and because of a very intense competition, a lack of trust between each one is observed. In this context of low efficiency, the rise of e-commerce could be seen both as a threat (the freight movements will strain even more some supply chains that are not optimized), and an opportunity (public authorities may be increasingly willing to collaborate and improve operations to avoid externalities).

To make city logistics operations more sustainable, many measures have been proposed within the research community. Each of these initiatives affects the involved agents in different ways, and to guarantee an adequate implementation, some compensatory mechanisms for the most impacted parties need to be designed. Policy and governance aspects are fundamental and have been extensively investigated in the literature. Nevertheless, some technological developments are also needed to guarantee a successful implementation.

As in the passenger mobility industry, digitization greatly affects carrier operations. The efficient combination of IoT, numerical optimization techniques (including big data or machine learning), and the blockchain technology is expected to significantly improve last-mile operations. The emergence of more sustainable and more flexible vehicles, including autonomous robots, will help carriers adapt to increasingly complicated urban environments in which modularity is one of the keys. Here, the participation of manufacturers in providing innovative vehicle concepts is essential. It can be expected that the cost of ownership of electric vehicles will decrease in the future owing to an increase in the demand for this type of vehicle, rendering them more and more economically competitive.

The major barrier to the implementation of many of the initiatives presented in this paper will certainly be the current lack of cooperation between stakeholders. To help improve this, the EIT Urban Mobility, an innovation and knowledge community integrating all involved actors, has a major role to play. Because technology is not an end in itself, it must be tailored to the actual needs of cities to make them more livable and design equilibrated and fair governance schemes. The promotion of successful use cases through innovation projects will undoubtedly help convince the different agents of the validity of the measures presented in this paper. The EIT Urban Mobility, by bringing together local authorities, research institutions and private institutions, seems to be the best framework to help improve last-mile logistics operations. It is worth noting the implication of the EIT Urban Mobility community that has been co-funding several logistics-related innovation projects in the last few years (EIT Urban Mobility, 2021a). 14 start-ups with activities related to last-mile logistics have also been participating in the EIT Urban Mobility acceleration program (EIT Urban Mobility, 2021b). This effort should be pursued in the future.

As presented in this paper, many challenges are still to be overcome. To move towards more sustainable operations, implementing radical, disruptive (and most of the time controversial) measures in the next few years may not be the adequate approach, above all in a so fragmented market. Cities in which the last-mile logistics market is not mature enough should first focus on consensual measures that could have a positive impact on all stakeholders. Some of these measures could be training programs for drivers, the improvement of traceability all along the supply chain, data sharing to help improve routing or demand modeling and prediction (see Section 3). These measures are win-win for all agents. Since no compensatory schemes would be needed, these measures would be better accepted and easier to implement. Once these first steps have been done and trust has been established between the different parties, more innovative operational models could be implemented.

Finally, because replicability is a key aspect to be considered in last-mile logistics, one of the major concerns of the community should be to conduct efficient ex ante and ex post analysis of the different projects and pilots to understand the reasons for success or failure. The authors have no doubt that the newly created Journal of Urban Mobility will be of great help in this purpose.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Connecting people and places: Analysis of perceived pedestrian accessibility to railway stations by Bavarian case studies

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ABSTRACT

Walking connects different modes of transport and acts as the main feeder for public transport. Nonetheless, ensuring high-quality accessibility for pedestrians to railway stations is seldom evaluated beyond measurable factors such as walking distance and time. Although several studies found differences in calculated and perceived accessibility, little research has so far focused on the factors that are influencing perceived pedestrian accessibility and thus causing these differences. In order to contribute to the current efforts of conceptualizing perceived accessibility, this study explores the factors which determine whether or not people walk to train stations. Potential influencing factors were first derived from a literature review and clustered into six quality criteria (directness, simplicity, traffic safety, security, comfort and built environment). Then, on-site and online surveys were conducted in five Bavarian towns (Germany) to understand the importance of the identified factors and how this differs between different people and places. The results confirm that above all comfort, safety and security factors play an important role for pedestrian accessibility. In addition, significant differences were found between different age groups and city sizes.

1. Introduction

All trips begin on foot. Walking is especially important for public transport trips: walking overall serves as the main feeder for public transport and thus also for the railway system. Although the proportion of pedestrians can vary considerably, in Europe typically, more than 50% of trips to and from railway stations are made on foot (Ceder, 1998; La Paix and Geurs, 2014). Travellers that reach the railway station by car, bicycle or bus, still have to walk the last metres to the platform. In general, public transport is only attractive if the whole trip chain is competitive with other modes of transport, especially cars (Keijer and Rietveld, 2000). Thus adequate pedestrian infrastructure to and at public transport stops is crucial to foster public transport usage. Evidently, walking is a key element of railway stations and mobility hubs: it allows different transport modes and nodes to be connected, thereby enabling intermodality and promoting sustainable mobility. Apart from the feeder role it has to public transport, active mobility brings many health benefits for its users (Lin et al., 2015). Moreover, walking is for free, uses urban space efficiently, is environmentally friendly, allows for easy interaction with other people, strengthens the local economy and requires comparatively little investment (FGSV, 2014; Jou, 2011).

Pedestrian accessibility can be defined as the ease with which certain destinations can be reached by walking (Koenig, 1980; Niemeier, 1997). To firstly analyse and secondly enable the ease of reaching the stations in reality, a shift from mobility-based planning to accessibility-based planning is advisable. This shift can already be observed in quite some fields and studies (Handy, 2020; Merlin et al., 2018). The quality of pedestrian accessibility is dependent on the location of the destination, the network connectivity (Geurs and Van Wee, 2004; Kathuria et al., 2019), and the resulting trip duration. However, pedestrian accessibility is not only influenced by time-related factors. A study by Kathuria et al. (2019) shows that the public transport ridership increases with improved walkway quality. The surrounding environment of the walkway also impact the perceived pedestrian accessibility (Bivina et al., 2020; Erath et al., 2021; Gupta et al., 2022; Pueboobpaphan et al., 2022). For example, if a route leads through an unpleasant area, it might feel longer than it actually is (Bahn.Ville-Konsortium, 2010; Ralph et al., 2020). Lastly, the health and well-being of the pedestrian determine whether some routes are accessible or not (Brons et al., 2009; De Vos et al., 2013). If a person is mobility-impaired or has other limitations, some paths may be not accessible at all. Overall, it can be said that good pedestrian accessibility is essential to making walking to railway stations an attractive option.

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This highlights the usefulness of comprehensive accessibility studies in this regard.

While some factors influencing walking, such as distance, footpath width and presence of street lights can easily be measured, others such as the attractiveness of the surrounding environment are harder to evaluate. In fact, even if evaluation criteria for those factors influencing walking are found and measured, it does not necessarily mean that they are *perceived* the same by (all) pedestrians. These differences in calculated and perceived accessibility were posed in several studies and are attracting the interest of a rising number of researchers (such as Curl et al., 2015; Damurski et al., 2020; Lättman et al., 2018; Pot et al., 2021; Ryan and Pereira, 2021; Ryan et al., 2016). In contrast to calculated accessibility (using spatial data to compute accessibility indicators), perceived accessibility describes how people actually experience the potential to participate in spatially dispersed opportunities (Pot et al., 2021) and is attempted to be derived through surveys and mobility behaviour studies. While calculated pedestrian accessibility to transport stations has been discussed at length in literature and is applied in practice, little research has focused on perceived factors influencing pedestrian accessibility (Curl et al., 2015; Ryan and Pereira, 2021).

The purpose of this study is to answer the following research questions: Which factors influence the perceived pedestrian accessibility of railway stations? How does this differentiate for different people and places? Although this exploratory study focuses on perceived pedestrian accessibility to railway stations in Bavaria, the results may also be transferable to pedestrian accessibility to other destinations in other regional contexts. Therewith, this paper aims to contribute to current efforts (e.g. by Pot et al., 2021; Ryan and Pereira, 2021) of conceptualizing perceived accessibility and further advancing the shift from mobility-based to accessibility-based planning (Pot et al., 2021).

This paper is structured as follows: Chapter 2 will start with a literature review, followed by the explanation of the design of this study in Chapter 3. Chapter 4 summarises the results, which are later discussed in Chapter 5 with regard to their relevance for the research question. Finally, Chapter 6 concludes the paper and points out future needs for action – for research and practice.

2. Literature review

The following literature review explores how railway stations interact with the city (Section 2.1), how pedestrian accessibility (to railway stations) can be evaluated (Section 2.2), how measured and perceived pedestrian accessibility differ (Section 2.3), and how this is related to the concept of walkability (Section 2.4). The identified research gaps are summarized in 2.5.

2.1. Functions of railway stations

In contrast to travelling by car, bicycle or foot, public transport does not allow for spontaneous interactions with the external environment, as the routes and entry and exit points are fixed. Thus, railway stations are the portals into places and their opportunities for many people (Bertolini, 2008). In the sense of transit oriented development (Vale, 2015), a railway station has to be well-connected, not only to other nodes on the transport network, but also to its surroundings (Crockett and Hounsell, 2005) - especially for pedestrians (Brons et al., 2009), because at the latest upon entering the station, everyone becomes a pedestrian. In other words, only if network connectivity is met with station accessibility does the public transport system as a whole flourish.

However, reducing a railway station to its mobility function denies its potential as a location in its own right: they are and have to be more than nodes on a transport network (Bertolini, 1996). If designed well, the railway stations are places of service, leisure, commerce and communication (Zemp et al., 2011). While the high accessibility levels ideally given at a railway station attract offices and housing, the high volumes of passengers travelling through railway stations generate demand for retail and gastronomy. Vitalising the surroundings of railway stations in this way also augments the objective and perceived sense of security (Beckmann et al., 1999). Therefore such an intense and diverse functional use not only enhances the overall attractiveness of the location, but also contributes to the local economy around the railway station (Zemp et al., 2011). The many commercial opportunities together with the higher sense of security in turn increase the attractiveness of public transport and spawn higher demand for this mode (Tiwari, 2015). All this makes a railway station a lively place in a city that contributes to a city's character and is more than only a stop on a transit line (Bahn.Ville-Konsortium, 2010; Wulfhorst, 2003).

The importance of walking in enhancing the attractiveness of a railway station is clear: "the larger the number of people that can reach a certain station in a short amount of time, the higher the density of functions around it" (Wenner et al., 2020). The same applies the other way around. Good pedestrian accessibility of the station surroundings thereby increases the catchment area and thus the potential number of public transport passengers (Hillnhütter, 2016).

2.2. Concept of pedestrian accessibility

Accessibility was first defined as the "potential of opportunities for interaction" by Hansen (1959) and later specified by Geurs and Van Wee (2004) as the "extent to which land use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)". Accessibility is characterised by land use, transportation, temporal and individual components (Geurs and Van Wee, 2004). Although there are some overlaps, the first two describe the *place*, while the last two mainly capture how *people* with individual preferences and differing temporal constraints can access destinations. In the context of time-geography (Hägerstrand, 1970), the terms *place-based accessibility* (Hu and Downs, 2019) and *person-based accessibility* (Fransen and Farber, 2019; Järv et al., 2018; Páez et al., 2012) are used to specify these to parts. Individual and temporal factors such as income, age, gender, educational level, car and time availability, as well as the time of the day and year, all influence how people perceive their access to certain destinations (e.g. railway stations) by different modes - and consequently their mobility decisions. According to Handy and Niemeier (1997), "the key is to measure accessibility in terms that matter to people in their assessment of the options available to them". For the transportation component, this means knowing what features of different modes of transport are important to people (Handy and Clifton, 2000).

Pedestrian accessibility outlines the concept for walking specifically, as the accessibility of this mode is determined differently. Pedestrian accessibility is not only influenced by objective, measurable characteristics, but also subjective, perceived characteristics, such as sense of safety or comfort (Lin et al., 2015). Comfort in this sense is defined as the persons level of ease, convenience and contentment while walking (Alfonzo, 2005). Walking attractiveness includes, but is not limited to, unobstructed and safe accessibility with good connectivity, safe crossing opportunities and well-designed footpaths that are easy to walk on (Lo, 2009; Ujang and Zakariya, 2015). There is rising certainty that pedestrian accessibility is strongly connected to perceived quality levels of the land use and transport systems (Arslan et al., 2018; Gkavra et al., 2019; Liang and Cao, 2019) and dependent on individual characteristics, capabilities, attitudes and preferences (Pot et al., 2021). Whether or not an individual chooses to walk to a destination is therefore influenced by various factors, ranging from large elements such as the type of urban form to small elements such as street furniture (Alfonzo, 2005; Arslan et al., 2018) and external conditions such as weather. Due to their slow speed and direct interaction with the environment, pedestrians are generally more aware and sensitive to their surroundings than drivers, which is highly related to the individual walking comfort (Handy et al., 2002). Therefore, a stronger focus on micro-features is needed to fully understand the interactions (Bivina et al., 2020; Clifton et al., 2007).

Pedestrian accessibility in relation to public transport stations has been investigated in recent studies, e.g. by Bivina et al. (2019), Kathuria et al. (2019), Sarker et al. (2019), Bivina et al. (2020), Rossetti et al. (2020), Gupta et al. (2022), and Pueboobpaphan et al. (2022), generating similar results as the general pedestrian accessibility studies. Sarker et al. (2019) found that especially the working population usually chooses the most direct and shortest route. In addition to route directness, micro-scale (e.g. sidewalk availability, surface quality) and meso-scale built environment factors (e.g. population density and land use diversity) were found to have an positive impact on access mode choice (Gupta et al., 2022; Kathuria et al., 2019), while the effects of micro-scale factors were more significant (Bivina et al., 2020). Especially safety and security factors were found as the most influential regarding pedestrian accessibility (Bivina et al., 2019; Gupta et al., 2022). Improving the walking environment can therewith increase the distance people are willing to walk, thus also increasing the service coverage area of stations (Pueboobpaphan et al., 2022) and consequently the ridership numbers (Kathuria et al., 2019).

Rossetti et al. (2020) proposed a method to calculate pedestrian accessibility to railway stations by creating detailed pedestrian isochrones and calculate how many inhabitants have access to the public transport system within a certain time, while Pueboobpaphan et al. (2022) found that acceptable walking distances was less for Bangkok than suggested by standard methods. This again hints at the fact that calculated and perceived accessibility may differ.

2.3. Mismatch between calculated and perceived accessibility

Calculated accessibility refers to the calculation of accessibility by the use of accessibility indicators based on spatial data. This term is e.g. used by Ryan and Pereira (2021), and Pot et al. (2021), while others use terms like *objective accessibility* (Lättman et al., 2018) or *measured accessibility* (Ryan et al., 2016). Anyhow, as all models and indicators are somehow generated by humans, they can never be fully *objective* (Haugen et al., 2012; Ryan and Pereira, 2021; Schwanen and de Jong, 2008). Also, the term *measured* can be misleading, as accessibility itself cannot be measured by a simple device, as e.g. sidewalk width. Instead, technical indicators are needed that somehow *calculate* accessibility by the use of data and certain input parameters. Therefore, the authors decided to go with the term *calculated accessibility*, as it is also recommended by Ryan and Pereira (2021), Pot et al. (2021).

When referring to how individuals perceive their ease of reaching destinations, the terms *subjective accessibility* (Damurski et al., 2020), *perceived accessibility* (Lättman et al., 2018; Pot et al., 2021; Ryan et al., 2016; van der Vlugt et al., 2019), *self-reported accessibility* (Curl et al., 2015; Ryan and Pereira, 2021) or *experienced accessibility* (Chorus and de Jong, 2011) are used. While *subjective accessibility* mainly serves as a counterpart to *objective accessibility, self-reported accessibility* refers to survey results, which is the method used in most studies to derive perceived accessibility, but the term focuses on the method rather than the outcome. Regarding *experienced* and *perceived accessibility*, the authors consider both terms as fitting but decided for *perceived accessibility*, as the majority of existing literature also used this term. Pot et al. (2021) define perceived accessibility as "the perceived potential to participate in spatially dispersed opportunities". This definition is also used in course of this paper, with specification to railway stations.

Regardless of the terminology, several studies found a mismatch between different accessibility metrics (Curl et al., 2015; Damurski et al., 2020; Gebel et al., 2011; Lättman et al., 2018; McCormack et al., 2008; Pot et al., 2021; Ryan and Pereira, 2021; Ryan et al., 2016). While attractiveness of public transport is classified by means of travel time, quality of service, waiting times and comfort, only a few measurable factors such as travel distance and/or travel time are usually considered for walking. Although there are reasons to believe that these factors are not necessarily the most appropriate when it comes to accessibility by active modes (Páez et al., 2020): "Crucial to determining the acceptable distance in a given situation is not only the actual physical distance, but also to a great extent the experienced distance" (Gehl, 1987). In contrast to *place-based accessibility, calculated accessibility* is not excluding the individual and temporal component per definition. But as the perceived factors are not even close to being fully researched, there are only few studies (D'Orso and Migliore, 2018; Erath et al., 2017; Gaglione et al., 2021) considering walkability factors. Thus, there is a tendency to overestimate accessibility levels (Curl et al., 2015; Ryan and Pereira, 2021).

2.4. Walkability

Besides *pedestrian accessibility*, the term *walkability* is often used in literature to make a statement about how walking-friendly an area is. The Walk Score ® index, which is very often used to assess walkability, also uses gravity-based accessibility measures (Hall and Ram, 2018). While the Walk Score ® itself can be considered as an 'objective' measurement, especially when it comes to perceptions, more research can be found in the walkability field than in perceived pedestrian accessibility.

The American-Planning-Association (2006) defines walkability as: "A place in which residents of all ages and abilities feel that it is safe, comfortable, convenient, efficient, and welcoming to walk, not only for recreation but also for utility and transportation". The definition and the term, which already contains the word *ability*, hints at the fact that age and personal abilities have an impact on the walkability. Although those factors are also included in the individual component of accessibility, the term *walkability* puts additional emphasis on the perception of the people walking (as stated in the definition: how people "feel"). In this context, researchers (e.g. Blecic et al., 2015; Fancello et al., 2020; Reyer et al., 2014) also refer to the capability-approach by Nussbaum (2003). According to Sen (1980), *capabilities* cover "what people are actually able to do and to be". The individual capabilities of a person are based on internal and external factors: (1) the ability, persons internal power, detained but not necessarily exercised, to do and to be, and (2) the opportunity, presence of external conditions which make the exercise of that power possible (Blecic et al., 2015). In order that a person is capable of doing something, e.g. walking to the railway station, both the internal and external factors need to be in line. The concept of capability is tightly intertwined with the individual component of accessibility (Vecchio and Martens, 2021), in turn influencing perceived accessibility (Ryan et al., 2019).

Even though there is no standard definition for walkability (Forsyth, 2015) and not all of them include the availability of destinations, plenty the results are also useful for understanding pedestrians perceptions that may also influence perceived pedestrian accessibility.

As for this research the availability of specific destinations, namely railway stations, was of fundamental importance, the term *pedestrian accessibility* is used to describe the walking conditions to those. To emphasise the individual perceptions of the pedestrians, the word *perceived* is added.

2.5. Research gap(s)

Good pedestrian accessibility is paramount in order to encourage people walk to the railway station and increase the users of the railway offer. There is a common agreement, that perceived factors are crucial in this regard and the solely consideration of calculated measures leads to distorted results. However, in order to include the perceived factors in the analysis of accessibility, they must first be explored and fully understood – this is the stage of work that researchers in the field are currently in. To current point in time, it is neither clear which factors are the most important ones when it comes to perceived accessibility nor how this differs for different people and at different places.

3. Research framework and methodology

This research project aims to contribute to this/these research gap(s) and to explore factors influencing perceived pedestrian accessibility to one specific destination: railway stations. Five municipalities are therefore chosen as study areas (Section 3.1). First, a general set of quality criteria (Section 3.2) is derived and developed from literature and subsequently used as a hypothesis framework to evaluate the perceived accessibility. Then, surveys on the perceived pedestrian accessibility are conducted in the selected study areas (Section 3.3). The results are analyzed in order to better understand how individual people at different places perceive accessibility (Section 3.4). The following sections and Fig. 1 give more detail on each part of the methodology.

3.1. Study context

The study was conducted in Bavaria (one of the 16 German federal states). In specific, five Bavarian municipalities were selected: Aichach, Bad Neustadt a.d.Saale, Freilassing, Hilpoltstein and Landshut (see Fig. 2). The focus was on small to medium-sized cities, where the railway station usually plays a bigger role in everyday mobility than in metropolises, which usually have several public transport hubs. The municipalities were chosen as to represent different station typologies in terms of size, passenger numbers and their role in the network. In addition, the willingness of the local authorities to participate was also decisive, as the aim of the project (where this study was part of) was to identify deficits in the pedestrian accessibility of railway stations and to develop concrete measures to improve the situation together with local planners and stakeholders (Pajares et al., 2021). However, this paper focuses solely on the findings in regard to perceived accessibility.

In Bavaria, strengthening local public transport, cycling and walking is a central transport policy goal (Bayerische Staatskanzlei, 2021). The Bavarian railway infrastructure consists of around 6,500 km of track and 1066 stations (Bayerisches Staatsministerium für Wohnen, Bau und Verkehr, 2021b). But, as shown in Fig. 3, 59% of all trips in Bavaria are conducted using private motorised vehicles and only 10% of the trips are made using public transport (infas, 2018). These numbers confirm that in Bavaria public transport in general, and rail transport in particular, are currently not exploited to their full potential.

The low mode share of pedestrians and public transport users in Bavaria could be attributed to shortcomings in pedestrian accessibility, as people are less likely to use the train as the distance between home and station increases (Keijer and Rietveld, 1999). The location of railway stations in Bavaria is a product of history: many are not located in the pedestrian-oriented city centers but rather in outlying districts that are usually more car-oriented and less densely populated.

3.2. Quality criteria

In German as well as international literature, essential quality criteria for pedestrian traffic have been discussed (Alfonzo, 2005; Carr et al., 2010; Lo, 2009; Southworth, 2005). Based on the literature, six overarching quality criteria to evaluate pedestrian accessibility are defined: Directness, Simplicity, Traffic Safety, Security, Comfort, Built Environment. Each quality criterion was assigned a set of indicators. The resulting quality criteria and their corresponding indicators are listed in Fig. 4. The indicators were chosen specifically for the use case of access to railway stations.

The quality criteria, especially comfort and security are significantly influenced by individual perception. Since these cannot be derived directly, the quality criteria are assessed using proxy indicators (e.g. footpath width, lighting). One indicator can have an influence on several quality criteria. For example, the footpath width influences both comfort and traffic safety. The indicators were assigned to the quality criterion for which they are deemed most relevant. The following subsections outline the interplay of the chosen quality criteria and their (proxy) indicators.

3.2.1. Directness

The directness is primarily dependent on the actual length of the route to the railway station, as opposed to the aerial line distance. To provide direct routes to the population, a high local connectivity (ratio of links and nodes) is needed. Major obstacles in terms of directness, besides badly connected neighborhoods, are linear barriers such as fences, railway tracks or busy roads that can only be crossed at certain points. The actual length of the route affects how attractive a route is perceived (Handy and Clifton, 2001; Lo, 2009; Saelens et al., 2003). A comfortable walking distance for the majority of people is around 10 minutes (Calthorpe, 1993), which also seams to be valid for trips to train stations (Daniels and Mulley, 2013; O'Sullivan and Morrall, 1996).

3.2.2. Simplicity

The simplicity of a route depends, among other things, on the number of roads to be crossed. For pedestrian crossings with traffic lights, the waiting time and the duration of the green phase are deciding factors. In addition, a distinction must be made between automatic light signal systems and light signal systems with manual signal request devices. In addition, means of orientation to and from the railway station are important in terms of simplicity, and especially necessary for people who are not familiar with the area. This can be provided by consistent signposting, which also help to counteract overestimation of walking distances (Ralph et al., 2020). Furthermore, lines of sight towards characteristic buildings in the city can significantly improve orientation in public spaces.

3.2.3. Traffic safety

The traffic safety as perceived by pedestrians is determined by the characteristics of the footpath and by the presence of other road users on or near the footpaths. The availability of sidewalks and the spatial buffer between sidewalk and road are therefore important (Kweon et al., 2021). Not only driving cars affect the traffic safety of pedestrians, cyclists on the pavement can also lead to dangerous situations (Mesimäki and Luoma, 2021). In addition, parked cars on the street (or even on the walkway) obstruct the visibility of pedestrians (Oxley et al., 1997).

3.2.4. Security

How protected pedestrians feel from incidents by other humans and crime depends on the liveliness and social control of an area (Arslan et al., 2018; Saelens et al., 2003). Low visibility of sidewalks, e.g. in underpasses (Hillnhütter, 2016) or in areas with dense vegetation (Golan et al., 2019; Lin et al., 2015; Wimbardana et al., 2018) or low lighting levels (Saelens et al., 2003; Wimbardana et al., 2018), leads to decreased perceived security, while a lively environment ("eyes on the street" concept) can increase it (Gehl, 2013; Jacobs, 1961). In addition, cleanliness and appearance of the path and the surrounding environment have an impact hereon (Golan et al., 2019; Saelens et al., 2003).

3.2.5. Comfort

How comfortable it is to walk on a specific path depends on infrastructural criteria, such as footpath width (Alfonzo, 2005), surface (Wimbardana et al., 2018) and guidance (Saelens et al., 2003). Sufficient footpath width is important to ensure comfortable overtaking or crossing of pedestrians. If a footpath leads along a road, footpath width is perceived differently depending on the permitted speed on the road. At high speeds and with high traffic volumes, a spatial separation of road and footpath is therefore vital, also to reduce the noise levels for the pedestrians. If the footpath surface is uneven or contains many potholes, walking on it requires additional attention and may reduce the accessibility for some users. Freedom from barriers is not only of particular importance to people with limited mobility, but also for people with prams or heavy suitcases, for example, to comfortable travel

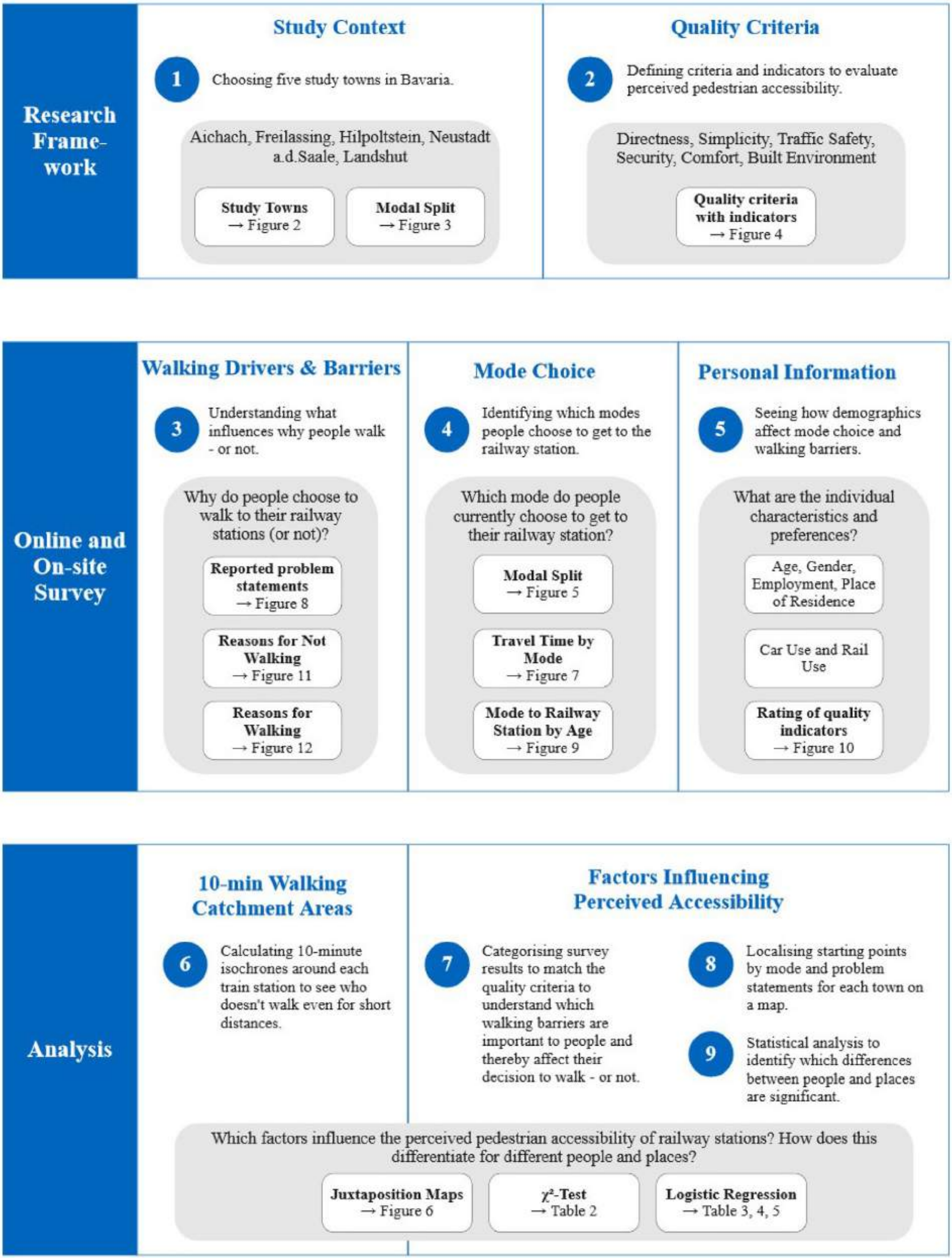


Fig. 1. Methodological steps.

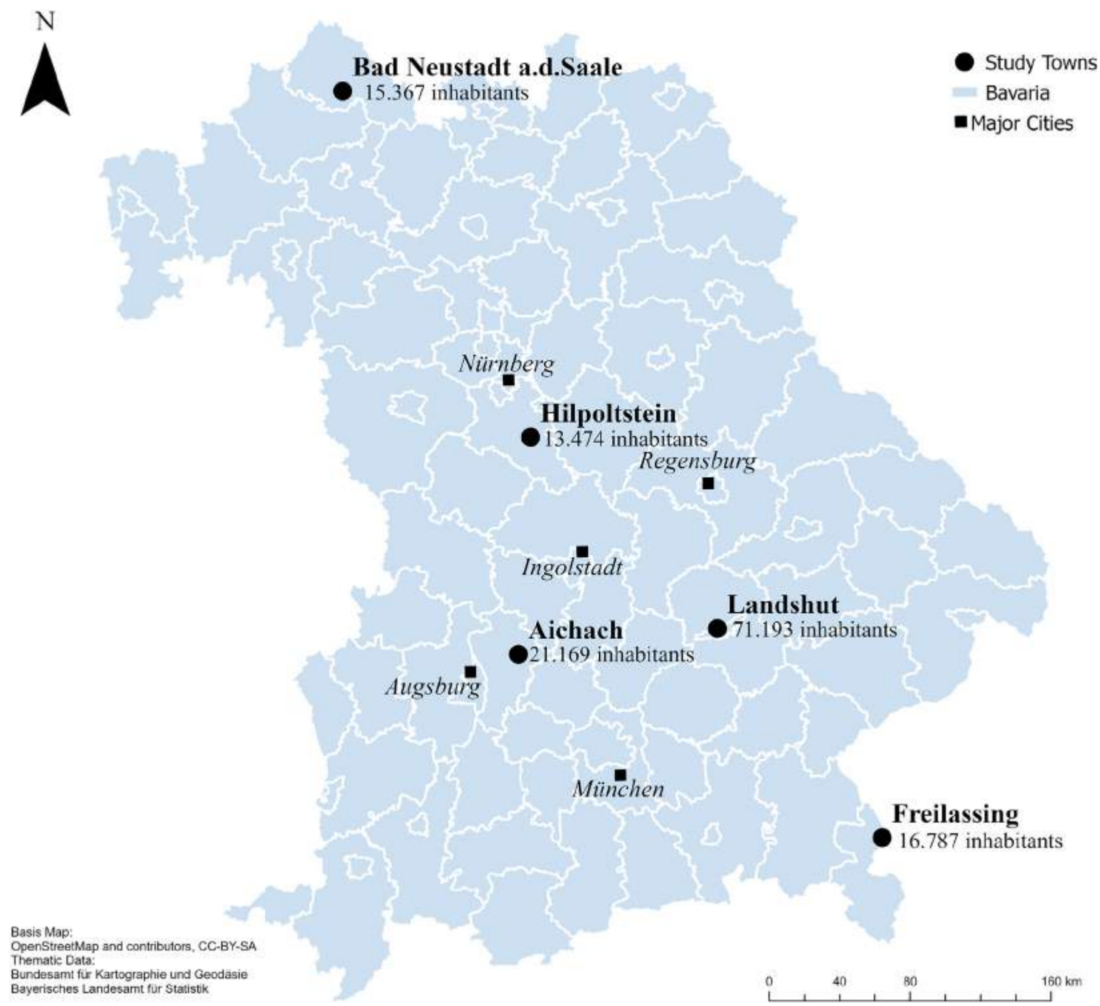


Fig. 2. Selected municipalities in Bavaria.

on footpaths (Zakaria and Ujang, 2015). In addition, walking comfort is influenced by the inclination (Handy and Clifton, 2001) and by the presence of weather protection (e.g. arcades, trees) (Arslan et al., 2018; Pilipenko et al., 2018; Whyte, 1980).

3.2.6. Built environment

How attractive a footpath and consequently walking in-general is perceived by pedestrians, is largely influenced by the built environment in which the footpath is located (Pushkarev and Zupan, 1971; Southworth, 2005). For example, a path through a busy city centre with many shops and people is more entertaining than a path through a deserted industrial area or a boring underpass (Hillnhütter, 2016). Additionally, city centres provide numerous points of interest (POI) to visit and run errands along the way (Lin et al., 2015; Saelens et al., 2003). But not only buildings and people, also natural elements such as street trees and green spaces provide visual and auditory stimuli and have an positive impact on the attractiveness of an area (Golan et al., 2019; Lin et al., 2015).

3.3. Survey

The locals' knowledge about existing weak points in the footpath network is invaluable. Experiences and feelings while walking can not be assimilated other than asking people frequenting those paths on a regular basis. The perceptions of local rail users were gathered using on-site and online surveys. The surveys were conducted in all five municipalities in autumn 2017. The on-site surveys were conducted directly at the railways stations. Five interviewers spend two days on each of the station and surveyed as many persons as possible within this time. The on-site survey was deliberately kept short due to the often limited time available at the railway station. A purposive sampling approach was used. In order to participate, survey candidates had to be frequent rail users (at least once a month) and non-transfer passengers (the stations surveyed had to be the starting or ending point of the train journey). These criteria were asked right at the beginning of the survey. However, occasional customers and transfer passengers were also given the opportunity to name problem areas that came to their attention. The online survey was published on the project's own website and was advertised by the municipal officials. The following questions were asked in both surveys (on-site and online):

General: As perceived accessibility is difficult to grasp, mode choice and specific survey questions are used as proxy to assess perceived accessibility. First, general information about the survey participants and their travel behaviour was recorded:

- Personal information: Age, gender, employment, place of residence
- Car use: Driver's license, car availability
- Rail use: frequency, destinations, purpose (e.g. work, education, shopping)

Non-Walkers: Then, participants were asked which mode of transport they used to reach the railway station. If respondents stated that they did not walk to the railway station, they were asked:

- Why did you not walk to the railway station?

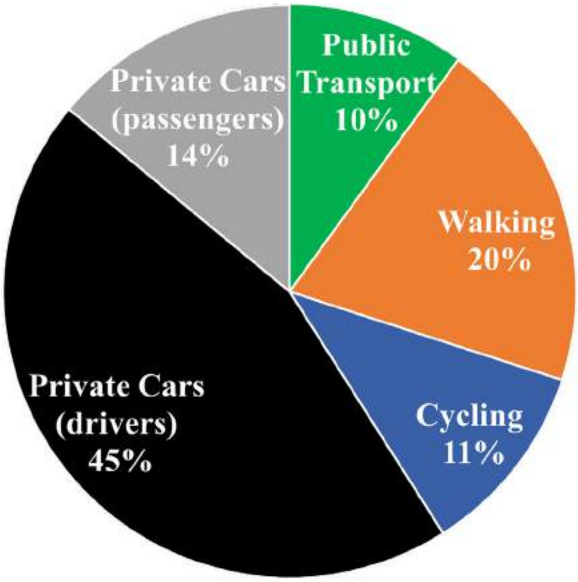


Fig. 3. Modal Split in Bavaria (infas, 2018).

- Why did you choose the other mode of transport?
- Have you ever walked to the railway station?

Walkers: If respondents stated that they walk to the railway station, they were asked:

- Why did you walk to the railway station?
- What would be the maximum distance you are willing to walk to the railway station?
- What and where are weak points on the way to the railway station and at the railway station itself?

In the online survey, problem areas could directly be pinpoint in a web-based tool. In addition, the participants were asked to rate how important different quality indicators for pedestrian accessibility are to them.

3.4. Analysis

For each city, the location-based survey results (starting points, mode of transport to the railway station, reported problem statements) were visualised in a map (see Chapter 4). The reported problem statements were matched with the quality criteria and their respective indicators that were found in the literature (see Chapter 3.2; e.g. the statement "There is no barrier-free access to platform 7." was matched with *Comfort -> Freedom of barriers*). The reported problem statements were visualized by the use of a colour schema (Built Environment: blue, Comfort: yellow, Security: pink, Directness: orange, Simplicity: green, Traffic Safety: red). This colour scheme is used throughout the paper to make it easier to read the graphics and understand the connections. In addition, as proposed by Rossetti et al. (2020), travel-time isochrones (contour-based accessibility measure) were calculated for the five assessed train stations, using 10 minutes walking time and a walking speed of 5 km/h, and thus representing the average time that people are willing to walk to places. For the walking path network, OpenStreetMap data was used (OpenStreetMap-Contributors, 2021). The calculated isochrones were intersected with population data from the Census household survey (Statistische Ämter des Bundes und der Länder, 2011). Therewith, it was assessed if there is a connection between mode choice, walking distance to the railway station and reported problem areas.

If participants started their trip roughly within the 10 minutes walking distance from the railway station and chose a motorised mode, their survey answers were analysed in more detail to understand why. The mode choice differences between walking and cycling were not assessed, as these two active modes usually complement each other, depending on the total trip (chain) length and personal preferences. The answers to the non-location-based survey questions were summarised in diagrams.

In addition, chi-squared-tests and a logistic regression model were used to explore the differences in mode choice and the reasons therefore between places (cities) and people (gender and age). The software Epi Info 7 (Nieves and Jones, 2009) was used therefore. Chi-squared-tests were conducted (see Table 2) to test the association between the potential predictors (age group, gender, city) and the dependent variables (modes). Furthermore, a logistic regression model was built for mode choice, reasons to walk and reasons not to walk. Age groups (<18 - children ; 18 to <30 - junior adults ; 30 to <60 - senior adults ; >60 - elderly), gender (female ; male) and municipalities (>20.000 inhabitants - medium ; <20.000 inhabitants - small) were used as other variables (see Tables 3–5). Children as vulnerable groups were selected as a comparison group for the age groups. The input data were filtered according to the gender and age groups mentioned above.

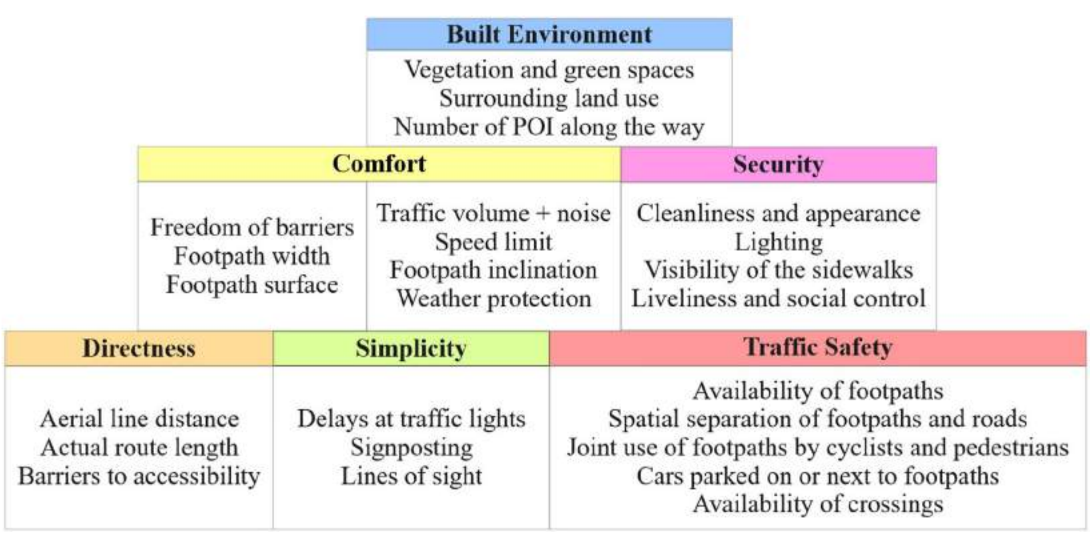


Fig. 4. Six quality criteria for pedestrian accessibility, with their respective indicators.

Table 1
Number of survey participants and descriptive statistics.

Municipality	Inhabitants	# of participants		
		on-site	online	sum
Aichach	21,169	121	15	136
Bad Neustadt a.d. Saale	15,367	85	41	126
Freilassing	16,878	115	118	223
Hilpoltstein	13,474	89	8	97
Landshut	71,193	127	35	162
Sum	**137,990**	**537**	**217**	**754**

Age Groups	Bavaria (Census 2011)	% of participants		
		on-site	online	sum
<18 (children)	17%	38%	2%	24%
18 to <30 (junior adults)	15%	27%	18%	29%
30 to <60 (senior adults)	49%	27%	57%	34%
>60 (elderly)	19%	8%	23%	10%

Gender	Bavaria (Census 2011)	% of participants		
		on-site	online	sum
Male	49%	49%	59%	54%
Female	51%	51%	41%	46%

4. Results

A total of 754 valid questionnaires was gathered (537 on-site and 217 online; see Table 1). According to the calculation method proposed by Kadam and Bhalerao (2010), 384 or more surveys are needed to represent Bavaria and to have a confidence level of 95% that the real value is within ±5% of the surveyed value – under the precondition that the sample is randomized. However, the cities used different advertisement methods, which leads to an unequal distribution of online survey participants per city. To understand how randomized the survey sample is, the distribution of the participants' age groups and genders is compared to the last Bavarian census (Statistische Ämter des Bundes und der Länder, 2011). It reveals that the younger half of survey participants (<30 years) is somewhat over represented in comparison to the census, while the older half of participants (>30 years) is somewhat underrepresented. The reason for this could be that the share of public transport users is also higher among younger people than among older people (Nobis & Kuhnimhof, 2018). In addition, a higher proportion of men participated in the online survey. Since the aim of the study is not to make generalised statements for the whole of Bavaria, but rather to explore how certain people perceive the pedestrian accessibility of railway stations, the sample size achieved is considered sufficient for this purpose, even if not all social groups are equally well represented.

In the following, the results are aggregated from the responses in the on-site and online surveys. The focus lies on the survey questions concerning walking to and from the station.[1] First, the statistical analyses are presented in Tables 2–5, then the results are described by the help of figures.

In four of the five municipalities surveyed, walking is the most important mode of transport to reach the station and was used by 41% of respondents in total. Fig. 5 shows all modes of transport used on the way to the railway station as an average for all five municipalities. A quarter of the surveyed rail users arrive at the station by car. The high proportion of car passengers (not drivers) is particularly striking. Notably, more rail users arrive to the station by bicycle than by public transport. However, it was not investigated separately to what extent this is connected to the local public transport (bus) offer and coordination of the timetables. It can be assumed that a better bus service would also result in a higher proportion of bus users. A small share of 3% uses "other" modes such as taxis or scooters.

[1] Details on the participants' overall travel behaviour can be obtained upon request.

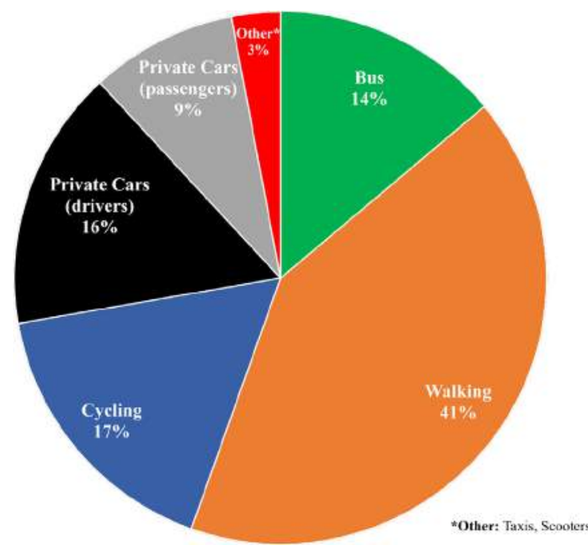


Fig. 5. Modes of transportation used to reach railway stations.

In the following, the factors influencing perceived pedestrian accessibility are presented, each as a summary of all five model municipalities.

4.1. Place

The share of pedestrians (and the overall modal split) depends on how big the town is and where its railway station is located. Although the journey to the station is predominantly made on foot, the composition of the mode of transport choice varies greatly in the five cities studied (see Fig. 6). The statistical analyses (see Table 2 and 3) show that the city size has an influence on the mode choice on the way to the railway station. In small towns, people are 2.41 times more likely to walk because 'it is fast' and they have no alternative (presumably because of the lack of bus connections). In the medium-sized cities, people are 3.22 times more likely to travel by bus.

Smaller towns with central train stations, such as Hilpoltstein and Freilassing, demonstrate very high proportions of pedestrians (56% and 47%). Larger cities such as Landshut, where only a low share of the total population lives within the 10 minute walking catchment area of the railway station, have a lower proportion of pedestrians. This is due to the longer distance that would need to be travelled by foot in order

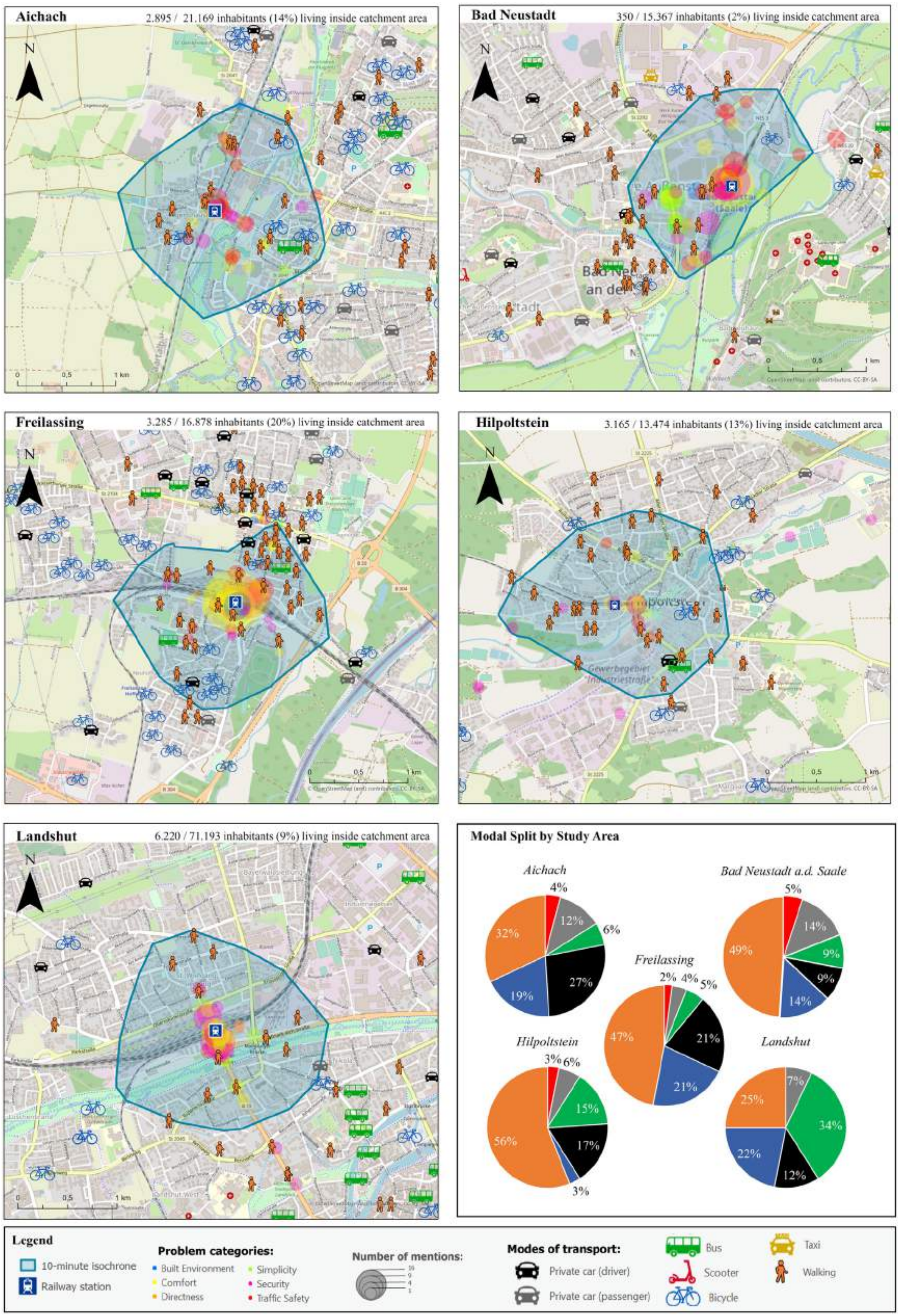


Fig. 6. Catchment areas, starting points, reported problem areas and mode shares for all study areas.

Table 2
Chi-squared test: people, places and mode choice.

		Walking				Cycling			
		total (n = 699) n (%)	**yes (n = 300)** n (%)	**no (n = 399)** n (%)	$\chi^2 - Test$ **p-value**	**total (n = 699** n (%)	**yes (n = 126)** n (%)	**no (n = 573)** n (%)	$\chi^2 - Test$ **p-value**
Age Group	**< 18 (children)**	159 (22.75%)	91 (30.33%)	68 (17.04%)	**< 0.01**	159 (22.75%)	24 (19.05%)	135 (23.56%)	0.16
	18 to < 30 (junior adults)	211 (30.19%)	76 (25.33%)	135 (33.83%)		211 (30.19%)	42 (33.33%)	169 (29.49%)	
	30 to < 60 (senior adults)	255 (36.48%)	95 (31.67%)	160 (40.10%)		255 (36.48%)	52 (41.27%)	203 (35.43%)	
	> 60 (elderly)	74 (10.59%)	38 (12.67%)	36 (9.02%)		74 (10.59%)	8 (6.35%)	66 (11.52%)	
Gender	**female**	332 (47.50%)	142 (47.33%)	190 (47.62%)	0.94	332 (47.50%)	53 (42.06%)	279 (48.69%)	0.18
	male	367 (52.50%)	158 (52.67%)	209 (52.38%)		367 (52.50%)	73 (57.94%)	294 (51.31%)	
Municipality	**medium (> 20.000 inh.)**	271 (38.77%)	79 (26.33%)	192 (48.12%)	**< 0.01**	271 (38.77%)	53 (42.06%)	218 (38.05%)	0.40
	small (< 20.000 inh.)	428 (61.23%)	221 (73.67%)	207 (51.88%)		428 (61.23%)	73 (57.94%)	355 (61.95%)	

		Private Car Driver				Private Car Passenger				Bus			
		total (n = 699) n (%)	**yes (n = 125)** n (%)	**no (n = 574)** n (%)	$\chi^2 - Test$ **p-value**	**total (n = 699)** n (%)	**yes (n = 58)** n (%)	**no (n = 641)** n (%)	$\chi^2 - Test$ **p-value**	**total (n = 699)** n (%)	**yes (n = 90)** n (%)	**no (n = 609)** n (%)	$\chi^2 - Test$ **p-value**
Age Group	**< 18 (children)**	159 (22.75%)	2 (1.60%)	157 (27.35%)	**< 0.01**	159 (22.75%)	16 (27.59%)	143 (22.31%)	**0.07**	159 (22.75%)	26 (28.89%)	133 (21.84%)	**0.02**
	18 to < 30 (junior adults)	211 (30.19%)	34 (27.20%)	177 (30.84%)		211 (30.19%)	24 (41.38%)	187 (29.17%)		211 (30.19%)	35 (38.89%)	176 (28.90%)	
	30 to < 60 (senior adults)	255 (36.48%)	71 (56.80%)	184 (32.06%)		255 (36.48%)	14 (24.14%)	241 (37.6%)		255 (36.48%)	23 (25.56%)	232 (38.10%)	
	> 60 (elderly)	74 (10.59%)	18 (14.40%)	56 (9.76%)		74 (10.59%)	4 (6.90%)	70 (10.92%)		74 (10.59%)	6 (6.67%)	68 (11.17%)	
Gender	**female**	332 (52.50%)	61 (51.20%)	271 (52.79%)	0.75	367 (52.5%)	28 (48.28%)	339 (52.89%)	0.50	367 (52.5%)	44 (48.89%)	323 (53.04%)	0.46
	male	367 (47.50%)	64 (48.80%)	303 (47.21%)		332 (47.5%)	30 (51.72%)	302 (47.11%)		332 (47.5%)	46 (51.11%)	286 (46.96%)	
Municipality	**medium (> 20.000 inh.)**	271 (38.77%)	55 (44.00%)	216 (37.63%)	0.19	271 (38.77%)	27 (46.55%)	244 (38.07%)	0.20	271 (38.77%)	57 (63.33%)	214 (35.14%)	**< 0.01**
	small (< 20.000 inh.)	428 (61.23%)	70 (56.00%)	358 (62.37%)		428 (61.23%)	31 (53.45%)	397 (61.93%)		428 (61.23%)	33 (36.67%)	395 (64.86%)	

Table 3
Logistic regression: people, places and mode choice.

		Walking Odds Ratios (95% C.I.)		**Cycling** Odds Ratios (95% C.I.)	
		Crude	Adjusted Model	Crude	Adjusted Model
Age Group	**(elderly/child)**	0.79 (0.45 - 1.37)	-	0.68 (0.29 - 1.6)	-
	(senior adult/child)	0.44 (0.30 - 0.66)*	0.47 (0.31 - 0.71)*	1.44 (0.85 - 2.45)	-
	(young adult/child)	0.42 (0.28 - 0.64)*	0.49 (0.32 - 0.76)	1.40 (0.81 - 2.42)	-
Gender	**(female/male)**	0.99 (0.73 - 1.33)	-	0.77 (0.52 - 1.13)	-
Municipality	**(small/medium)**	2.59 (1.88 - 3.58)*	2.41 (1.73 - 3.36)*	0.85 (0.57 - 1.25)	-

		Private Car Driver Odds Ratios (95% C.I.)		**Private Car Passenger** Odds Ratios (95% C.I.)		**Bus** Odds Ratios (95% C.I.)	
		Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model
Age Group	**(elderly/child)**	25.22 (5.67 - 112.15)*	25.22 (5.67 - 112.15)*	0.51 (0.16 - 1.58)	-	0.45 (0.18 - 1.15)	-
	(senior adult/child)	30.28 (7.31 - 125.4)*	30.28 (7.31 - 125.40)*	0.52 (0.25 - 1.10)	-	0.51 (0.28 - 0.92)*	0.44 (0.24 - 0.81)*
	(young adult/child)	15.07 (3.56 - 63.74)*	15.07 (3.56 - 63.74)*	1.15 (0.59 - 2.24)	-	1.02 (0.58 - 1.77)	-
Gender	**(female/male)**	1.07 (0.72 - 1.57)	-	1.20 (0.70 - 2.06)	-	1.18 (0.76 - 1.84)	-
Municipality	**(small/medium)**	0.77 (0.52 - 1.14)	-	0.71 (0.41 - 1.21)	-	0.31 (0.20 - 0.50)*	0.31 (0.19 - 0.50)*

* = p-value < 0.05

Table 4
Logistic regression: people, places and reasons not to walk.

		Time-consuming Odds Ratios (95% C.I.)		Tedious Odds Ratios (95% C.I.)		Not enough or bad footpaths Odds Ratios (95% C.I.)		Boring Odds Ratios (95% C.I.)	
		Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model
Age Group	**(elderly/child)**	0.20 (0.04 - 1.17)	-	3.79 (1.17 - 12.3)*	3.79 (1.17 - 12.3)*	NA	-	0.62 (0.15 - 2.62)	-
	(senior adult/child)	0.20 (0.04 - 0.87)*	0.20 (0.04 - 0.87)*	1.23 (0.59 - 2.58)	-	NA	-	0.72 (0.29 - 1.81)	-
	(young adult/child)	0.40 (0.08 - 1.90)	-	1.26 (0.61 - 2.63)	-	NA	-	1.10 (0.46 - 2.63)	-
Gender	**(female/male)**	1.64 (0.77 - 3.46)	-	1.00 (0.60 - 1.67)	-	0.45 (0.19 - 1.04)	-	0.84 (0.45 - 1.59)	-
Municipality	**(small/medium)**	0.83 (0.40 - 1.71)	-	1.27 (0.76 - 2.11)	-	4.64 (1.81 - 11.09)*	4.64 (1.81 - 11.90)*	0.61 (0.32 - 1.16)	-

		Bad weather Odds Ratios (95% C.I.)		Area not nice Odds Ratios (95% C.I.)		Feeling unsafe (crime) Odds Ratios (95% C.I.)		Feeling unsafe (traffic) Odds Ratios (95% C.I.)	
		Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model
Age Group	**(elderly/child)**	0.83 (0.22 - 3.11)	-	5.00 (1.04 - 24.12)*	5 (1.04 - 24.12)*	4.63 (0.69 - 31.05)	-	2.77 (0.50 - 15.49)	-
	(senior adult/child)	1.27 (0.53 - 3.00)	-	2.90 (0.79 - 10.72)	-	3.08 (0.65 - 14.67)	-	1.76 (0.46 - 6.82)	-
	(young adult/child)	1.37 (0.58 - 3.23)	-	1.71 (0.44 - 6.62)	-	5.29 (1.16 - 24.08)*	5.29 (1.16 - 24.08)*	0.80 (0.18 - 3.53)	-
Gender	**(female/male)**	1.14 (0.63 - 2.04)	-	0.64 (0.30 - 1.35)	-	1.67 (0.80 - 3.52)	-	0.63 (0.25 - 1.58)	-
Municipality	**(small/medium)**	0.57 (0.31 - 1.03)	-	1.14 (0.54 - 2.39)	-	1.64 (0.78 - 3.44)	-	1.48 (0.60 - 3.67)	-

* = p-value < 0.05
NA = not enough data

Table 5
Logistic regression: people, places and reasons to walk.

		Free of charge Odds Ratios (95% C.I.)		Fast Odds Ratios (95% C.I.)		No alternative Odds Ratios (95% C.I.)	
		Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model
Age Group	**(elderly/child)**	1.38 (0.60 - 3.17)	-	0.29 (0.10 - 0.80)*	0.29 (0.10 - 0.82)*	0.41 (0.17 - 0.98)*	0.41 (0.17 - 1.00)*
	(senior adult/child)	0.98 (0.52 - 1.82)	-	0.61 (0.25 - 1.46)	-	0.47 (0.25 - 0.89)*	0.51 (0.26 - 0.97)*
	(young adult/child)	1.24 (0.65 - 2.36)	-	0.31 (0.14 - 0.71)*	0.38 (0.16 - 0.89)*	0.39 (0.20 - 0.75)*	0.44 (0.23 - 0.88)*
Gender	**(female/male)**	0.89 (0.55 - 1.46)	-	1.06 (0.58 - 1.92)	-	1.15 (0.70 - 1.88)	-
Municipality	**(small/medium)**	1.28 (0.75 - 2.21)	-	2.71 (1.46 - 5.05)*	2.49 (1.31 - 4.74)*	2.18 (1.22 - 3.88)*	1.95 (1.07 - 3.53)*

		Enjoy walking Odds Ratios (95% C.I.)		Nice area Odds Ratios (95% C.I.)		Form of exercise Odds Ratios (95% C.I.)		While running errands Odds Ratios (95% C.I.)	
		Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model	Crude	Adjusted Model
Age Group	**(elderly/child)**	3.10 (1.06 - 9.08)*	3.10 (1.06 - 9.08)*	1.49 (0.57 - 3.90)	-	3.63 (1.42 - 9.28)*	3.63 (1.42 - 9.28)*	1.16 (0.47 - 2.90)	-
	(senior adult/child)	2.53 (1.25 - 5.13)*	2.53 (1.25 - 5.13)*	0.41 (0.21 - 0.80)*	0.47 (0.24 - 0.93)*	2.96 (1.52 - 5.79)*	2.96 (1.52 - 5.79)*	0.58 (0.30 - 1.09)	-
	(young adult/child)	1.14 (0.58 - 2.23)	-	0.42 (0.21 - 0.82)*	0.45 (0.23 - 0.90)*	1.18 (0.61 - 2.29)	-	0.73 (0.37 - 1.41)	-
Gender	**(female/male)**	1.10 (0.64 - 1.88)	-	2.44 (1.45 - 4.11)*	2.27 (1.32 - 3.88)*	0.92 (0.56 - 1.53)	-	1.29 (0.78 - 2.14)	-
Municipality	**(small/medium)**	1.01 (0.56 - 1.81)	-	0.99 (0.57 - 1.74)	-	0.88 (0.51 - 1.53)	-	0.59 (0.91 - 2.77)	-

* = p-value < 0.05

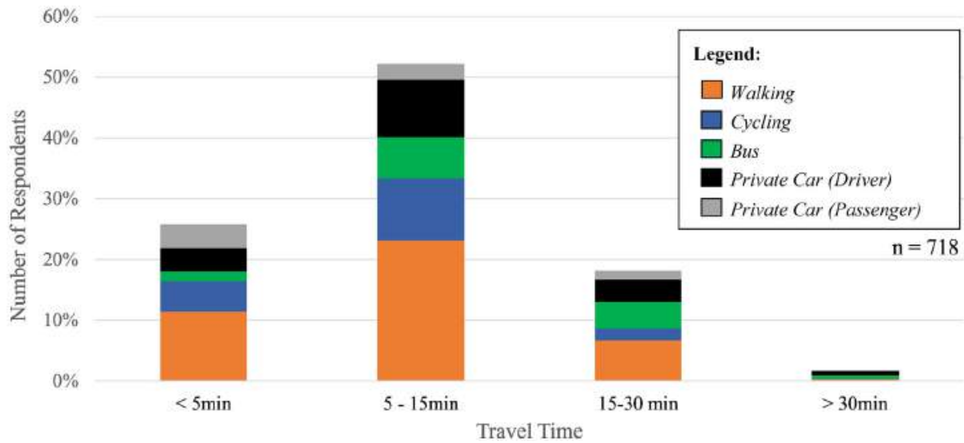


Fig. 7. Travel time required to reach the station, aggregated by mode.

to reach the station. Places such as Aichach, on the other hand, have a large share of rail users that travel to the station by car for the comparatively small size of the town. This may be due to the relatively large free P + R facility with 186 parking spaces (BEG, 2019). Similarly, cities with well-developed B + R facilities, such as Aichach with 168 or Freilassing with 373 bicycle parking spaces, have a higher proportion of cyclists than Bad Neustadt with only 68 bicycle parking spaces (BEG, 2019). This indicates that there is a direct correlation between provided infrastructure and mode choice. Accordingly, it can be assumed that a good walking infrastructure also leads to more pedestrians – or the other way around. In Bad Neustadt, the train station is located next to an industrial area. Thus, only 2% of the population lives within the catchment area. Anyhow, Bad Neustadt has a high share of pedestrians – this may be due to a high proportion of pupils and workers that are commuting to the nearby industrial sites and school campuses.

Fig. 7 shows how much time the respondents need to get to the railway station by their chosen means of transport. More than 50% of the respondents need 5–15 minutes to get to the station, 25% less than 5 minutes and only 2% more than 30 minutes. Journeys of more than 15 minutes are mainly made by bus or car, while 84% of the walking trips were not longer than 15 minutes – which roughly aligns with the numbers found in the literature (see Chapter 3.2.1). But it is noticeable that also many short distances, that could probably have been covered by bicycle or on foot, were travelled by car.

In order to understand the connections between mode choice and the characteristics of the place, Fig. 6 shows all starting points and the respective mode used on the way to the railway station. In addition, the reported problem statements are highlighted. The colour of the circle indicates criteria to which the statement refers (based on Fig. 4), and the size of the circle indicates the number of respondents who mentioned this problem. In total, 860 point-based weaknesses were reported by the participants.[2] The distribution of the problems mentioned per criterion and indicator are summarised in Fig. 8. Many of the weak points are directly located at or in front of the railway station. Especially freedom from barriers was a particular problem at four out of five stations, mentioned not only by elderly respondents but by the whole population. This result is not surprising, as currently only 492 of the 1066 stations in Bavaria are barrier-free (Bayerisches Staatsministerium für Wohnen, Bau und Verkehr, 2021a). Other common issues on the way to and at the railway station were related to security (e.g. dirty appearance of the station, unpleasant underpasses, lack of lighting) and traffic safety (mainly absence of road crossings). For some indicator categories, e.g. “incline” and “visibility of the sidewalk”, no point weaknesses were reported. Interestingly, inadequate or bad footpaths are a significantly more common problem in small towns than in bigger cities.

4.2. People

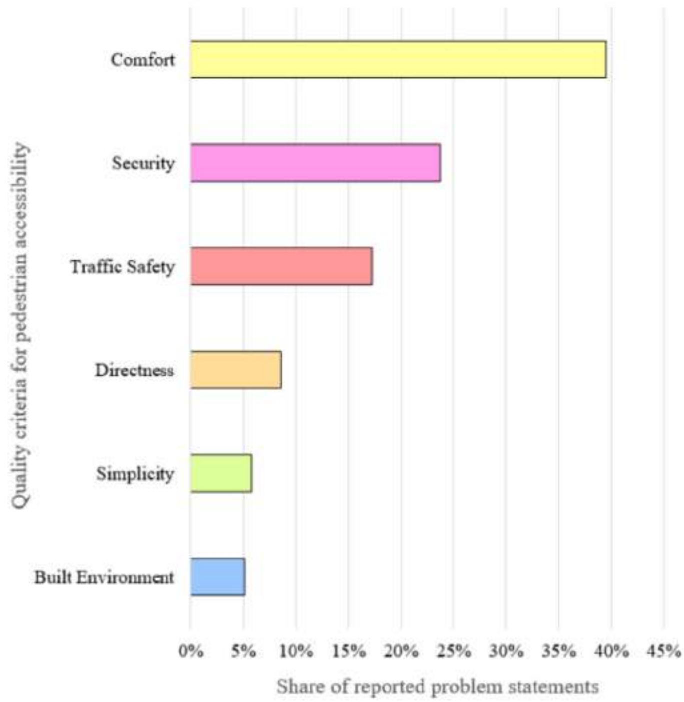
Pedestrians are predominantly found among senior citizens and schoolchildren. Fig. 9 shows the chosen mode of transport in relation to the age of the respondents. Children and elderly have the largest share of walking, while the car and the bicycle are most frequently used by adults. Younger people are the most frequent bus users, and the proportion of bus users decreases steadily with increasing age. Senior adults are 2.27 times less likely to take the bus than children. Between the different gender, mode choice was equally distributed. The only noticeable difference was that men have chosen the bike more often (19%; in contrast to 15% for women; but not significant). Whereas women used the other modes slightly more often. Comparable age- and gender-specific differences were also found in the Germany-wide MiD study (infas, 2018).

When asked about the maximum time people are willing to walk to the station, 40% answered “up to 15 minutes” and another 49% “up to 30 minutes”. The remaining 11% are even willing to walk more than 30 minutes. The discrepancy between the theoretical willingness to walk and the times actually walked suggests that other factors have an influence on this. The assessment reveals that specific point weaknesses, such as poor lighting or unsafe road crossings, present bigger obstacles to perceived pedestrian accessibility than general network connectivity. Comfort, security and safety thus affect route as well as mode choice, for instance some persons claimed to not walk at night due to insufficient street lighting. In this regard, shortcomings were identified in all municipalities surveyed.

Fig. 10 summarises how respondents rated different criteria for walking, with each respondent able to select up to five criteria. Sufficient street lighting at night was rated most important for walking, followed by good street crossings and weatherproof paths (shady in summer, good winter service in winter). Other factors considered important were wide and continuous footpaths, relatively slow moving cars on the route and the presence of other people. The resulting importance of the individual criteria largely corresponds to the proportions of the reported problems. Comfort and security seem to be the most important issues, while the built environment only plays a subordinate role. Directness was not asked about, as we consider this criterion to be rather measured than perceived.

It can clearly be seen that different survey participants perceived the same place differently. Different people have different thresholds of how far they are willing to walk, but also different perceptions of comfort, security and safety. This varies especially due to personal characteristics and individual needs, e.g. mobility-impairedness due to disabilities or heavy suitcases.

[2] All statements in their exact wording (German) can be obtained upon request.



Comfort	Freedom from barriers	31.9%
	Footpath width	2.9%
	Footpath surface	1.7%
	Traffic volume + noise	1.5%
	Weather protection	1.0%
	Speed limit	0.5%
	Footpath inclination	0.0%
Security	Cleanliness and appearance	9.9%
	Lighting	8.8%
	Liveliness and social control	5.0%
	Visibility of the sidewalks	0.0%
Traffic Safety	Availability of crossings	11.9%
	Availability of footpaths	2.2%
	Joint use of footpaths by cyclists and pedestrians	2.1%
	Cars parks on or next to footpaths	0.6%
	Spatial separation of footpaths and roads	0.5%
Directness	Barriers to accessibility	8.6%
	Aerial line distance	0.0%
	Actual route length	0.0%
Simplicity	Delays at traffic lights	4.5%
	Signposting	1.2%
	Lines of sight	0.1%
Built Environment	Surrounding land use	4.2%
	Vegetation and green spaces	0.7%
	Points-of-Interest along the way	0.2%

n = 860

Fig. 8. Reported problem statements, clustered by categories.

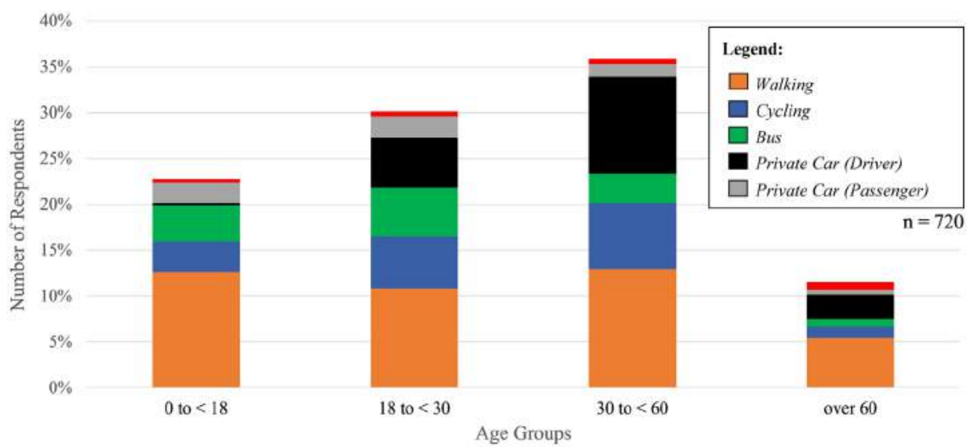


Fig. 9. Mode of transport to railway station, by age.

Fig. 11 summarises the answers of all survey participants who said they do not walk to the station to the questions about the reason therefore. For this purpose, the respondents could affirm or deny various given statements. Time constraints and tediousness were the main reasons given for choosing not to walk to the railway stations. Around half of the respondents that came by car stated that the distance was too far to walk or cycle (in their specific situation). Thus, mode choice is clearly dependent on the route length. For older adults in particular, time is a significantly greater barrier to walking than it is for children (see Table 4). Respectively, elderly are 3.79 times more likely than children not to walk due to tediousness.

But noticeably, the distance does not always determine whether a journey to a railway station is made by car, bicycle or by foot. Also bad weather, boredom, unpleasant areas, unsafe feeling as well as missing or bad footpaths discouraged people from walking – reasons, that are related to comfort, built environment and safety. While unpleasant areas are a barrier especially for older people, young adults are significantly more likely to feel unsafe in terms of crime.

Equally, the reasons why 42% of rail users walk to the station are considered. Fig. 12 shows the questions asked and the corresponding answers. Most respondents walk because it is fast, which is related to the directness. Some participants also see walking as a form of exercise, walk because they enjoy it or simply because they have no (affordable) alternative. Those are reasons, that are not directly linked to the quality criteria but are rather individual conditions and characteristics. Others like the nice area or walk for practical reasons, as they run errands or do activities on the way. Those are linked to the built environment. Interestingly, the built environment seems to be an important factor for mode choice although in terms of pedestrian accessibility, built environment received the lowest priority score. Senior adults and elderly significantly more often walk because they enjoy it and see it as a form of exercise than children (see Table 5). Respectively, young and senior adults walk more often because of the nice area. Same is true for women.

4.3. Individual utilities: connection of place and people

In order to better understand how individual utilities are affected by the place and the peoples' characteristics, the survey results of individual persons whose mode choice is particularly intriguing, was analyzed in depth.

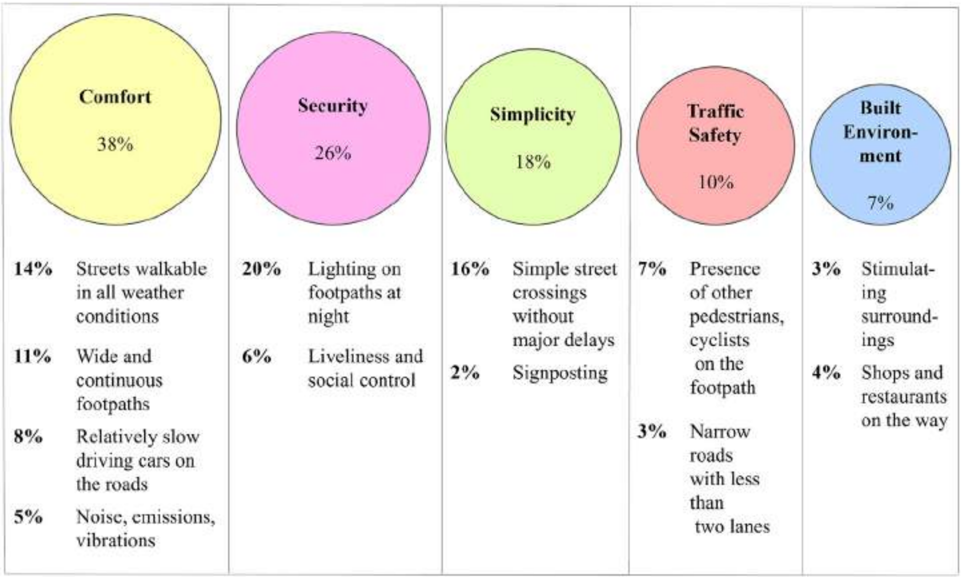


Fig. 10. Prioritisation of pedestrian accessibility criteria.

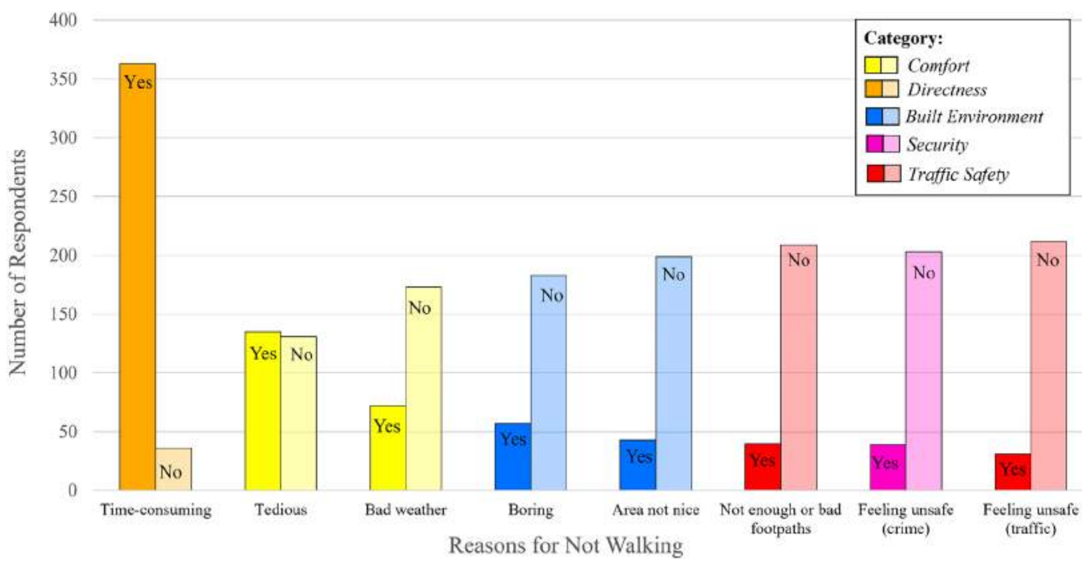


Fig. 11. Reasons why people do not walk to the railway station.

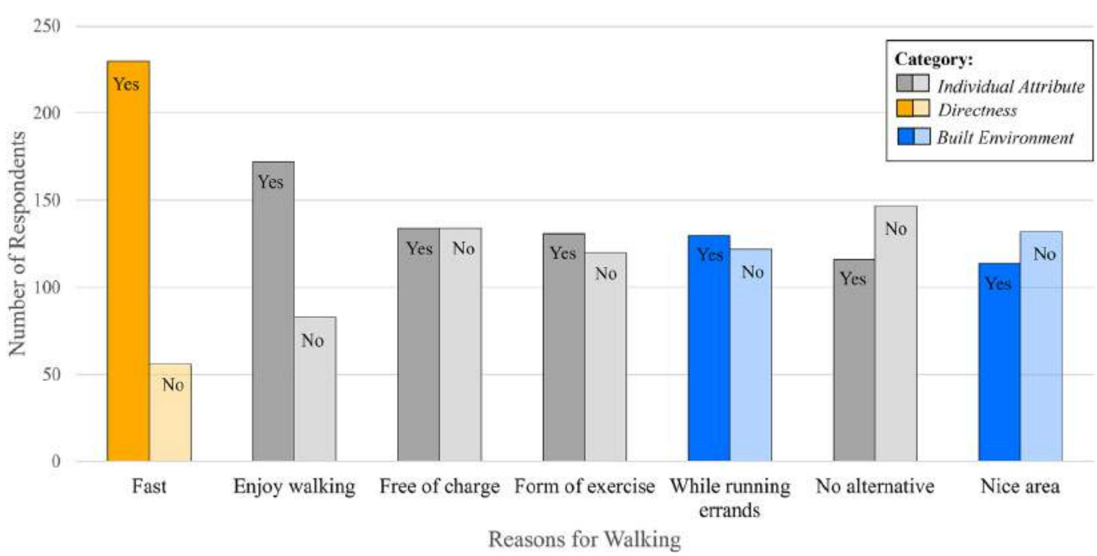


Fig. 12. Reasons why people walk to the railway station.

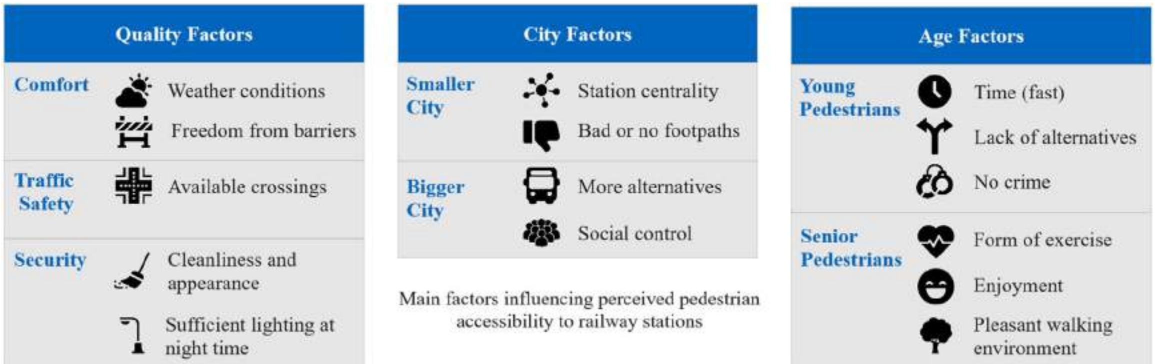


Fig. 13. Main identified factors influencing perceived pedestrian accessibility.

Two persons who started their trip roughly within a 15 minutes walking distance from the train station in Bad Neustadt arrived by taxi. The reason therefor was the carrying of luggage and bad bus connections. But also respondents who started their trip within walking or cycling distance and do not carry heavy luggage use the car or bus for convenience, like one participant in Aichach. In addition, physical limitations (disabilities, illness) hinder people from walking. For example, two persons in Freilassing came to the station by car because they accompanied mobility-impaired persons.

Other reasons for car use were fear of the dark, fear of bike theft or fear of crime in general. For example, one person that lives 10 walking minutes away from Landshuts' station was brought by car as he was afraid of crime. Same applies to one person in Freilassing that preferred the bus therefore.

Some respondents also stated that they walk or cycle primarily when the weather is good, while in bad weather they choose the bus or the car. In some cases also a combination of several reasons can be found, e.g. in Bad Neustadt one person was driving to the station by car due to time, carrying luggage and a baby stroller and in addition, due to bad weather conditions. It is not known whether the omission of one of these criteria would have already resulted in a mode choice change.

Three participants that started their trip roughly within the 10-minute catchment area (two in Hilpoltstein, one in Bad Neustadt and one in Freilassing) have chosen a motorised mode due to bad walking infrastructure, unpleasant route and/or boredom. Interestingly, the two participants from Hilpoltstein started from almost the same place. The route from this starting point to the station was reported by many participants to be unpleasant. Same applies for the routes from the starting points in Bad Neustadt and Freilassing, where bad walking conditions were pinpointed by many other participants. The routes in Bad Neustadt and Hilpoltstein run along busy roads and through monotonous environments which may cause the unpleasant feeling and boredom of the people due to a lack of visual stimuli. The route in Freilassing leads through an car-oriented commercial area with a reported lack of pedestrian infrastructure (missing paths and too few crossing possibilities).

5. Discussion

Within this study, several factors influencing walking were assessed by asking different survey questions. As perceived accessibility can not directly be evaluated, a variety of proxies (mode choice, reasons therefore, rating of pedestrian accessibility criteria, problem statements) were used. Although the answers to most questions show a clear direction for the importance of the six quality criteria, no absolute ranking for the importance of each single factor can be established. The results obtained were very much dependent on the questions asked, which reveals the real problem in this regard: How can we assess perceived accessibility? What question do we need to ask people to find out which factors are the most important? Is there even a universal answer to this, or does perceived accessibility depend primarily on individual capabilities and local external factors? And is there such a thing as the most important factor or is it more about the interactions as a whole?

Due to these still remaining open questions, the authors are aware that this exploratory study does not allow final conclusions to be drawn about the factors influencing perceived pedestrian accessibility to railway stations (in Bavaria), but it does reinforce the assumption (see Section 2.5) that these are largely dependent on people and places (although five different cities were studied here, it is to be expected that further differences will emerge if the study is extended to other places). Anyhow, the comparison of the different questions allows to get a better understanding of the approximate importance of each factor. Factors that were mentioned repeatedly across different questions suggest that they are among the most important. The mismatch between calculated and perceived pedestrian accessibility (Curl et al., 2015; Damurski et al., 2020; Gebel et al., 2011; Lättman et al., 2018; McCormack et al., 2008; Pot et al., 2021; Ryan and Pereira, 2021; Ryan et al., 2016) and the importance of perception in choosing walking as a mode to walk to the railway station (Gehl, 1987; Páez et al., 2020; Pueboobpaphan et al., 2022) could also be confirmed.

Accessibility deficits were identified in all municipalities surveyed, indicating a need for action in this field. This chapter discusses the identified shortcomings and how these can be addressed by future accessibility studies and tackled by the planning practice.

5.1. Time-based factors as prerequisites for walking

Survey participants named time as the most important factor for deciding if they walk or not. Similar to Sarker et al. (2019), it was found that especially the senior adults are more sensitive to time-consumption. Thus, direct and simple walking path networks are prerequisites for walking, although connectivity was rarely mentioned as an concrete issue. The reason for this may also be that simple punctual shortcomings (e.g. unpleasant underpasses, missing street lamps) are easy to grasp while the identification of connectivity issues requires a detailed geographical understanding of the area – and may not be something that participants except to be addressed easily.

But even the best walking path network may not be sufficient if the railway station is located in the 'wrong' place and thus not accessible within an appropriate walking time (which, surprisingly, is even up to 30 minutes for the majority of survey participants – in contrast to the findings of Calthorpe (1993), O'Sullivan and Morrall (1996), and Daniels and Mulley (2013); this high willingness may be due to the lack of alternative transport options, especially in the smaller towns). The size of the town and the centrality of its railway station determine the length, directness and simplicity of its pedestrian routes. A historical obstruction to pedestrian accessibility that remains is the location of many railway stations outside of city centers (see Chapter 3.1), at least in Bavaria.

The solution to this problem is twofold. On the transportation side, supplying attractive pedestrian infrastructure can entice people to travel longer distances by foot (Pueboobpaphan et al., 2022). On the land use side, redeveloping the area around the railway station to include more residential and commercial buildings can bring the origins/destinations closer to the station and therewith shorten travel times. Previous research shows that the more people living and working in close proximity to transit, the more likely it is that they will use the service (Hillnhütter, 2016; Murray et al., 1998; Wenner et al., 2020).

As travel time is paramount, combination of both – building attractive transport infrastructure in the shorter term and redeveloping land in the vicinity of the railway station in the longer term – seems advisable.

5.2. The underestimated role of comfort

However, how time is perceived depends on safety, comfort and environmental aesthetic levels. These results are in line with Pueboobpaphan et al. (2022) who found that pleasant surroundings can increase the willingness to walk. Similarly, areas that are not attractive discourage people from walking. Especially comfort was given a high priority by the survey participants. This result strengthens the certainty that pedestrian accessibility is strongly connected to perceived quality levels of land use and transport (Arslan et al., 2018; Gkavra et al., 2019; Liang and Cao, 2019) but also shows differences to previous studies conducted in India (Bivina et al., 2019; Gupta et al., 2022), in which safety and security were identified as the most influential factors. This may be due to the different spatial contexts, which bring with them different conditions in terms of safety and security. In comparison to India, safety and security may be less bigger issues in Bavaria. This assumption would confirm the hypothesis framework set up in Fig. 4 that sees directness, simplicity and traffic safety as the preconditions for walking. If these prerequisites are fulfilled, comfort and safety are decisive for the attractiveness and perception of the path, with greater attractiveness increasing the willingness to walk - and the built environment as the cherry on the top of the cake.

The calculated catchment areas of 10 minutes thus do not really “catch” the perceived walking conditions. Reported point weaknesses and thus perceived obstacles were primarily comfort and safety factors. In addition, the common destinations/origins of all railway users – the train stations – seam to have severe weaknesses in terms of comfort and security themselves (whereby the comfort issues were mainly caused by the fact that the railway stations are not barrier-free) and are thus mayor bottlenecks in terms of perceived accessibility that could be addressed easily by planning practice. In Bavaria, the issue of the non-barrier-free stations is well known and has been tackled since some years. In this course, also the station of Freilassing was rebuilt in 2021. Therewith, the main obstacle identified in 2017 is now solved. Nevertheless, at this point in time, there are still 492 stations that are not barrier-free and represent a major obstacle in accessing the railway system – not just for the people that walk to the station but for everyone.

For some indicators, e.g. “visibility of the sidewalk”, not a single punctual weakness was reported in the five study areas, although this factor was stated to be important in previous studies (Gehl, 2013; Golan et al., 2019; Hillnhütter, 2016; Jacobs, 1961; Lin et al., 2015; Saelens et al., 2003; Wimbardana et al., 2018). In these cases, the imprecise phrasing chosen by the participants made it difficult for the authors to assign the statement to these specific quality criteria. For example, many participants reported “unpleasant underpasses”. Such a general statement does not allow inferring causation between unpleasantness and dirt or aesthetics. For some people the unpleasantness might also not be linked to a specific feature of the underpass. Those statements were thus categorised as “cleanliness and appearance”. These overlaps and difficulties in delimitation illustrate the ambiguity of transitions between the individual indicators, which often cannot be examined individually but only in connection with other indicators.

In addition, there is a discrepancy between what people stated as their priorities and what they report as problem points in their town. This may be due to the specific local conditions (e.g. the assessed study areas were all topographically flat). Other cities with other walking path networks and other surroundings would certainly generate different punctual weaknesses, as other studies found e.g. that walking in a hilly environment is perceived as barrier (McGinn et al., 2007; Sun et al., 2015). Therefore, a more large-scale study with a wider variety of cities would be needed to validate the results.

Nevertheless, it is clear that perceived factors are of particular importance and should ideally be taken into account when performing accessibility analysis (e.g. by adding them as a generalised cost item to the accessibility formula). There are more criteria that influence pedestrian accessibility but are not mentioned here (e.g. presence of benches (Alfonzo, 2005; Arslan et al., 2018; Hillnhütter, 2016; Whyte, 1980) and aesthetics of building facades (Cervero and Kockelman, 1997; Hillnhütter, 2016; Lin et al., 2015; Lo, 2009; Speck, 2013)). Further studies are needed to obtain a comprehensive picture.

5.3. Travellers’ differing needs and abilities

Mode choice of the participants was not only dependent on the local situation but also very much on the individual characteristics and situations (e.g. age, abilities, carriage of luggage), with age having the strongest influence. Based on the personal situation, in combination with the personal preferences and needs (e.g. in terms of comfort, safety), every person makes its own personal decision on mode choice. Elderly, for example, perceive walking more often as tedious than children, which can be clearly linked to the physical abilities that are changing in the course of ones life. Referring to the capability-approach this means that the internal factors of elderly are not matching with the external factors, which causes this feeling of tediousness. For example, if benches were placed along the path to the station, older people could rest at regular intervals, which would probably make the walk less tedious. Thus, these personal characteristics should be taken into account when making statements of how accessible a place is for certain people (Litman, 2003; Ryan et al., 2019) – and consequently also be reflected in planning practice. As Clifton et al. (2007), Bivina et al. (2020) have pointed out, this also requires a greater focus on micro-features in order to fully understand the needs of individual people and take them into account in the urban setting.

The fact that pedestrians (on the way to the railway station) were in our study case predominantly found among senior citizens and schoolchildren indicates that it could make sense to customise future accessibility analysis according to different user groups and their specific needs. As train stations are important services of general interest, it is particularly important to ensure access for all, which is in line with the individual component of accessibility.

5.4. Temporal and external factors add further complexity

External factors (e.g. weather, time of the day) were stated to have an impact on perceived accessibility, anyhow, only a few studies can be found that took the accessibility effects of nighttime (Chandra et al., 2017; Jehle, 2020) or weather (Erath et al., 2015) into account. These factors are hard to change by planning practice, but can be mitigated through adapted infrastructure (e.g. weather protection, street lamps) and maintenance (e.g. winter service). In accessibility research and application, more attention should be given to external conditions and the temporal component, as lighting at night and weather conditions were among the most important factors for pedestrian accessibility. Thus, perceived accessibility by night and rain can highly differ from perceived accessibility by day and sunshine.

6. Conclusion

This work aimed to understand which factors influence perceived pedestrian accessibility to railway stations and how this may differ for different people and places. It was found that factors related to comfort, traffic safety and security (such as freedom from barriers, availability of street crossings and lighting) are perceived as the most important in terms of pedestrian accessibility. In addition, pedestrian's age as well as the city's size also have a significant influence whether people walk to the railway station or not. With regard to gender, only minor differences were found. Fig. 13 combines the main findings of this study and highlights the factors influencing perceived pedestrian accessibility to railway stations that were identified as the most important ones. Although the importance of several perception factors was determined through various survey questions, these results do not allow quantifying to what extent a specific indicator influences accessibility. But they help in understanding which factors are perceived as important, contribute to the ongoing research on perceived pedestrian accessibility and show where further studies are needed to obtain a more comprehensive picture.

Interestingly, the biggest weaknesses in perceived accessibility to railway stations are found on the stations themselves. But even punctual micro-feature weaknesses such as a broken street light or an unpleasant underpass on a factually short and safe route discourage people from walking to the station. At the same time, it was also found that many people (especially children) are willing to walk long distances to reach the railway station, mostly because they do not have an alternative. So they also accept weaknesses along the way. Older people, on the other hand, care more about the attractiveness of the environment, walk because they enjoy it and see it as a form of exercise, but they also often find it tedious.

The results of the case studies reveal that different people have different needs and abilities based on age, luggage, daytime and weather conditions. These individualities need to be taken into account through people-centred planning in order to provide access to public transport for all. In particular, we see a need for further research into the needs of different user groups. The capability approach can help to assess whether internal and external factors match. In addition, further research in other contexts is needed in order to understand the differences between different places.

The important comfort, safety and individual factors are currently only represented in a few accessibility analyses, which leads to a discrepancy between calculated and perceived pedestrian accessibility. In future, more importance should be attributed to perceived accessibility – of railway stations but also of other destinations. Pedestrian accessibility measures should be enriched by adding an impedance factor for the attractiveness of the route, reflecting the qualities of the paths, trip experience and personal needs. However, to identify the most important quality criteria of pedestrian accessibility and their individual weighing is still a remaining challenge, which may not be possible to solve universally. Ones the crucial factors are found, they can be assessed by the use of proxy indicators. Most of them can be measured or captured objectively (e.g. footpath width, surface, lighting) and then be translated into a quantitative point schema (e.g. no lighting = 0 points; perfect lighting = 100 points). By multiplying the indicators with weights according to their individual importance and then summing them up, an overall attractiveness score can be derived for each path segment. This score can then serve as an impedance factor and be added to the accessibility formula. Ideally, different impedance factors are determined for different user groups, day times and places. However, detailed data on the walking path network and the whole environment are needed therefore. In addition, some indicators (e.g. appearance) may be not 'objectively' measurable. In order to capture those and also to evaluate local context-specific situations and include the individual perceptions of single persons, it seems inevitable to enrich the accessibility analysis by qualitative methods that focus on user-centred feedback.

All in all, this research confirms that ideally all four accessibility components as defined by Geurs and Van Wee (2013) – transportation, land use, temporal and individual – should be included when evaluating perceived accessibility in order to allow comprehensive analyses. In the future – once the perceived accessibility factors are adequately explored – researchers can contribute by developing appropriate measures for perceived pedestrian accessibility that enable planners and policymakers to eradicate the deficiencies in perceived pedestrian accessibility (to railway stations and other destinations). Therefore, the right balance between "rigor (soundness) and their practical relevance (plainness)" (Papa et al., 2015) needs to be found in order to meet the needs from planning practice.

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Electric vehicle charging station accessibility and land use clustering: A case study of the Chicago region

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ABSTRACT

Land use mixing, balanced land uses, and transportation accessibility have previously been indicated as significant impactors of travel behavior, yet this relationship has not been examined in the EVSE accessibility literature. Using an application of the unsupervised machine learning (ML) clustering algorithm Density-based spatial clustering of applications with noise (DBSCAN), this research identifies 34 areas of spatially clustered level-1, level-2, and DC Fast EVSE charging infrastructure in the Chicago Metropolitan Area. Results indicate that charging access is imbalanced across suburban and urban communities and much of this disparity can be tied to EVSE clustering and its associated land use regimes in the metropolitan area. The majority of EVSE clusters are comprised primarily of level-2 charging and exist in isolated commercial developments to the affluent north and west of the city. Only 26% of clusters are associated with mixed land uses that occur in higher-income dense neighborhoods such as Evanston. Level-3 charging forms a smaller proportion of clustered charging across the region but is primarily unclustered. From a travel behavior perspective, this research highlights a need for a wider abundance of public fast charging options for lower socioeconomic communities and not merely utilitarian charging allocations that perpetuate accessibility for the wealthy.

1. Introduction

Driven by concerns about greenhouse gas emissions from fossil fuel vehicles, the electrification of vehicles is considered to have "substantial potential" in reducing climate change damages (Tong & Azevedo, 2020) and improving public health (Pan et al., 2019) when emissions from the power generation sector can be reduced (Horton et al., 2021; Peters, Schnell, Kinney, Naik & Horton, 2020). In recent years, electric vehicle (EV) adoption has become an accelerated priority of world governments including in the United States (Zhang, Greenblatt, MacDougall, Saxena & Prabhakar, 2020; The White House, 2021). Under the Biden Administration, electrification efforts include potential rebates of up to eight-thousand dollars for consumers (Leard & McConnell, 2020) and the complete replacement of the federal vehicle fleet with EVs (Shepardson, 2021). The federal government is also planning to allocate five-billion dollars of electrification infrastructure funding to state governments and two-and-a-half billion dollars for community and corridor level development through the Bipartisan Infrastructure Law (The White House, 2021). Several transportation electrification initiatives also exist at the state level (e.g., California, Illinois, Vermont). For example, "The Reimagining Electric Vehicles in Illinois Act" will provide incentives for EV production to encourage the adoption of 1 million cars by 2030 in Illinois (Illinois General Assembly, 2022). Workshops are currently underway by the National Governors Association for its member states on topics such as charging infrastructure, grid management, and electrification initiatives (Rogotzke, Eucalitto & Gander, 2019).

There are concerns, however, that Electric Vehicle Supply Equipment (EVSE), which are colloquially referred to as "chargers" or "charging stations", are not widely available in every community (Brown, Lommele, Eger & Schayowitz, 2020). In the United States, 80% of EV charging is conducted at home (Office of Energy, Efficiency & Energy, 2021), but not every driver has access to home-based charging (Hardman, Fleming, Khare & Ramadan, 2021). Drivers who live in multifamily rental units often lack suitable access to home-based charging (Fleming, 2018; Lopez-Behar et al., 2019; Wollschlaeger, 2020) which has contributed to a severe homeowner-renter electrification gap (Davis, 2019). In dense urban areas, and especially at high-rise apartment buildings, one-to-one EV charging may also not be feasible without a highly resilient electrical grid (Wang, Meng, Wang & Zhao, 2021) and parking restrictions, make-ready costs, and legal issues create behavioral hesitancies that further impede EV adoption in multi-family properties (Dillon, Hagerman, Swartout & Engel, 2020). EV owners who cannot rely on home-based charging must instead use public EVSE stations.

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There has been substantial research that has examined how EVSE stations should be optimally allocated and placed (Deb, Tammi, Kalita & Mahanta, 2018), but the relationship between EVSE and land use is poorly understood. Land use mixing, balanced land uses, and transportation accessibility have previously been indicated as significant impactors of travel behavior (Kockelman, 1997), but this relationship has not yet been examined in the EVSE accessibility literature (Orsi, 2021; Zhang et al., 2021). The "land-use component" affects the quantity and quality of spatial opportunities at a destination and the demand for these opportunities at origin locations (Geurs & Van Wee, 2004). Dense land uses with mixed activities (i.e., jobs, shopping etc.) can increase the concentration of accessible opportunities in a single area, while disadvantaging the accessibility of less dense communities (Geurs, 2006). It is therefore necessary to examine the spatial heterogeneity (i.e., land use characteristics) of public EVSE (Zhang et al., 2021).

Charging has traditionally been described as taking place at residences during overnight hours, but in order to increase EV-uptake for consumers with diverse travel needs and behaviors, non-residential destination charging has become a key enabler of EV proliferation (Dixon, Bell & Elders, 2018). Destination charging may be conceptualized as a "on-top service" (Schmidt, Staudt & Weinhardt, 2020). In this role, EVSE agglomerates around businesses such as supermarkets, restaurants, and hospitality venues allowing vehicle owners to charge their vehicles while they engage in other activities (Carlton, 2022; Schmidt, Staudt & Weinhardt, 2020). From a land use perspective, this suggests that at least some fraction of public level-1 and level-2 charging may be tied to clustered developments around these services. If these clusters are evenly distributed, then this clustering likely does not equate to a distributive transportation equity problem, but isolated clustering in higher income neighborhoods would represent a trend towards utilitarianism rather than vertical or horizontal equity. Utilitarianism is premised on maximizing transportation investments for the 'greater good' of society using a cost-benefit analysis approach, while potentially ignoring the needs of the least well-off (Pereira, Schwanen, & Banister, 2017). In contrast, Horizontal equity is rooted in the idea that individuals and groups should be treated the same with regard for the distribution of transportation resources, with no group receiving favoritism over the other (Litman, 2002). The vertical equity concept is based on the idea that different groups of people have differing transportation needs based on income and social class, or mobility and ability, and that disadvantaged groups should receive favoritism in the provisioning of resources based on these needs (Litman, 2002).

The clustering of EVSE charging stations is further complicated by the presence of private industry charging infrastructure which comprises the majority of tracked EVSE infrastructure in the United States (Brown, Lommele, Eger, & Schayowitz, 2020). A primary business model of private charging networks involves selling EVSE infrastructure to private businesses who use it to attract EV-owning customers (Klass, 2018). This revenue-centric approach has led private charging infrastructure to be considered "exogenous" to optimization issues in some modeling approaches (Sathaye & Kelley, 2013) with differing attractiveness and cost factors between state and private actors resulting in divergent allocation priorities (Bernardo, Borrell & Perdiguero, 2013). Assuming that EVSE is placed at locations that traditionally cater to higher-income and home-owning individuals, who are the traditional adopters of EVs (Axsen, Goldberg & Bailey, 2016; Gehrke & Reardon, 2021), non-traditional EV adopters may be forced to travel out of their way to reach these locations making EV ownership cost prohibitive for them while increasing their range anxiety. A better alternative is for drivers to have multiple stations in their community and along their travel paths, allowing habitual recharging (Kuby, 2019). Some destination chargers are also semi-private (Schmidt, Staudt & Weinhardt, 2020), and chargers at locations such as hotels and hospitals are more likely to have layers of usage and parking fees that inhibit their use (Viswanathan et al., 2018).

In utilitarian welfare economic approaches that attempt to optimize the placement of facilities such as EVSE, it is often the historically disadvantaged communities who get left behind for the benefit of the majority. Privately owned charging infrastructure, therefore, is possibly not being placed in consideration of the social and mobility equity goals of many central planning agencies. This may lead to inadequately placed charging stations that cluster around certain communities at the exclusion of others, and the environmental benefits gained by these communities may come at the expense of low-income and rural residents which may see increased greenhouse gas emissions from nearby power plants (Ji, Cherry, Bechle, Wu & Marshall, 2012). Additionally, lower income families might have to make cost maximizing choices in their spending behaviors (Hamilton, 2009) and accessing expensive charging options in higher-end retail clusters may be an imposing barrier. These hurdles indicate a need for complimentary charging that is integrated within neighborhoods of varied social and economic compositions and that meet the activity needs of diverse user groups.

Multiple authors (e.g., Canepa, Hardman & Tal, 2019; Hathaway et al., 2021; Karolemeas, Tsigdinos, Tzouras, Nikitas & Bakogiannis, 2021) have described a greater necessity to consider the infrastructure needs of lower-income and traditionally disadvantaged groups when placing EVSE. This, however, leads to a "chicken or the egg" conceptualization problem as discussed by Zink, Valdes & Wuth, 2020. Based on utilitarian welfare economic approaches, increasing the market penetration of EVs in higher adoption brackets may cause a trickle-down effect that increases the development of EV charging for lower income residents in longer term planning scenarios. However, the development of gapless EV charging coverages, even when it may not be initially profitable, may have added benefits that minimize consumer anxieties across a wider swath of society and further increase in EV adoption (Zink, Valdes & Wuth, 2020). Given that charging availability and cost is a greater concern and consideration in communities and regions that have lower adoption rates (Abotalebi, Scott & Ferguson, 2019; Hsu, & Fingerman, 2021; Wang, Yao, & Pan, 2021; Hathaway et al., 2021), under a scenario where EVs are going to be imposed on the populace by market and governmental actors, social justice and environmental concerns would dictate a bottom-up vertical equity approach where chargers need to be available across all communities even if it is not initially profitable. Incentivization programs that target lower income communities and marginal buyers may help improve EV adoption among these groups (Xing, Leard & Li, 2021).

Transportation electrification has the potential to improve acoustic conditions in communities through a reduction in noise pollution (Campello-Vicente, Peral-Orts, Campillo-Davo & Velasco-Sanchez, 2017) and air pollution (Pan et al., 2019), leading to fewer premature deaths and negative health impacts for vulnerable populations (Rizza et al., 2021). However, if low carbon transitions such as transportation electrification are tied to unjust and inequitable practices, it will create further injustices (Sovacool, Martiskainen, Hook & Baker, 2019) for lower income communities and certain racial groups (Holland, Mansur, Muller & Yates, 2019). Concerns have already been raised (e.g., Henderson, 2020) that the mass uptake of EVs will occur in a geographically uneven regime, where the "kinetic elites" of higher income, higher educated neighborhoods will receive preference over others. Various corporate and state interests are pushing transportation electrification on the American citizenry with seemingly little regard for these equity and justice considerations. Illustrative of this, the state of California is requiring that all new vehicles sold in the state be zero-emissions producing by the year 2035 (Hardman & Tal, 2021) even as current research in the state has revealed that there are inequalities in EV adoption and EVSE infrastructure placement along neighborhood and sociodemographic lines (Canepa et al., 2019; Hsu & Fingerman, 2021). California's ZEV mandate has been used as a model to create similar mandates in 11 other states, showing a trend towards forced electrification initiatives by governments in the United States. Therefore, emphasizing transportation equity and justice concepts in the deployment of charging station infrastructures should be given a high priority (Cohen, Shirazi & Curtis, 2017).

This study examines the spatial clustering of public EVSE charging stations, their associated land use characteristics, and how these characteristics impact EVSE accessibility using the Chicago Metropolitan Statistical Area (MSA) as a case study. This MSA is a large urban agglomeration of close to 10,000,000 residents and a major hub of economic activity in the American Midwest. An unsupervised machine learning (ML) clustering algorithm, Density-based Spatial Clustering of Applications with Noise (DBSCAN), is utilized to assess the land use characteristics of EVSE charging stations, and coupled with accessibility and spatial clustering analysis, this study questions: (1) whether charging stations agglomerate around certain land use regimes, (2) whether charging stations are balanced in their spatial distribution across the region, and (3) whether land use clustering may have impacts on accessibility to charging. These research questions are posed with a goal in mind to uncover inequalities in EVSE placement. The results of this study can be used to improve electric mobility outcomes for all communities regardless of their geographic and socioeconomic status within the urban fabric.

2. Material and methods

2.1. Study area

The Chicago Metropolitan Statistical Area (Fig. 1) was chosen for this case study due to its expansive urban sprawl, high number of charging stations, and its history of fractured urbanism that has traditionally favored certain affluent communities over others in transportation development (Farmer, 2011). Collectively, the following counties: Cook, DuPage, Kane, Kendall, Lake, McHenry, Will in Illinois, Lake and Porter in Indiana, and Kenosha in Wisconsin constitute the main urban and suburban extent of the Chicago Metropolitan Statistical Area. Peripheral counties with a predominantly rural character such as Grundy County and DeKalb County in Illinois and Newton and Jasper in Indiana were excluded from this analysis since they are vastly rural in character. The southern part of Chicago, including many of its inner-belt suburbs, has been noted for having disproportionate access to services and amenities compared to the wealthier northern regions of the Chicago Metropolitan Statistical Area. Noted disparities between the southern and northern portions of the metro include inequitable access to trauma care (Wandling, Behrens, Hsia & Crandall, 2016), healthy food (Kolak et al., 2018), public transit (Ermagun & Tilahun, 2020), and pharmacy care (Qato et al., 2014).

Among large metropolitan regions, Chicago has seen a slower EV adoption rates than leading EV-friendly cities such as Los Angeles, New York, and Seattle (Bauer, Hsu, Nicholas & Lutsey, 2021). Market driven siting of EVSE is a common approach in Chicagoland, but some authors (e.g., Ai, Zheng & Chen, 2018) have suggested that equity-based approaches should be considered to make electrification more practical for lower income consumers. As of July 2022, the state of Illinois plans to offer consumers a $4000 rebate to purchase new or used EVs in order to increase adoption (Schoenberg, 2021). The states of Indiana and Wisconsin, which are also part of the metropolitan area, have not yet offered similar rebates or incentives.

2.2. Data

This study uses public EVSE charging station data from the Alternative Fuel Data Center (AFDC). The AFDC is a division of the U.S. Department of Energy that publishes up to date information about al-

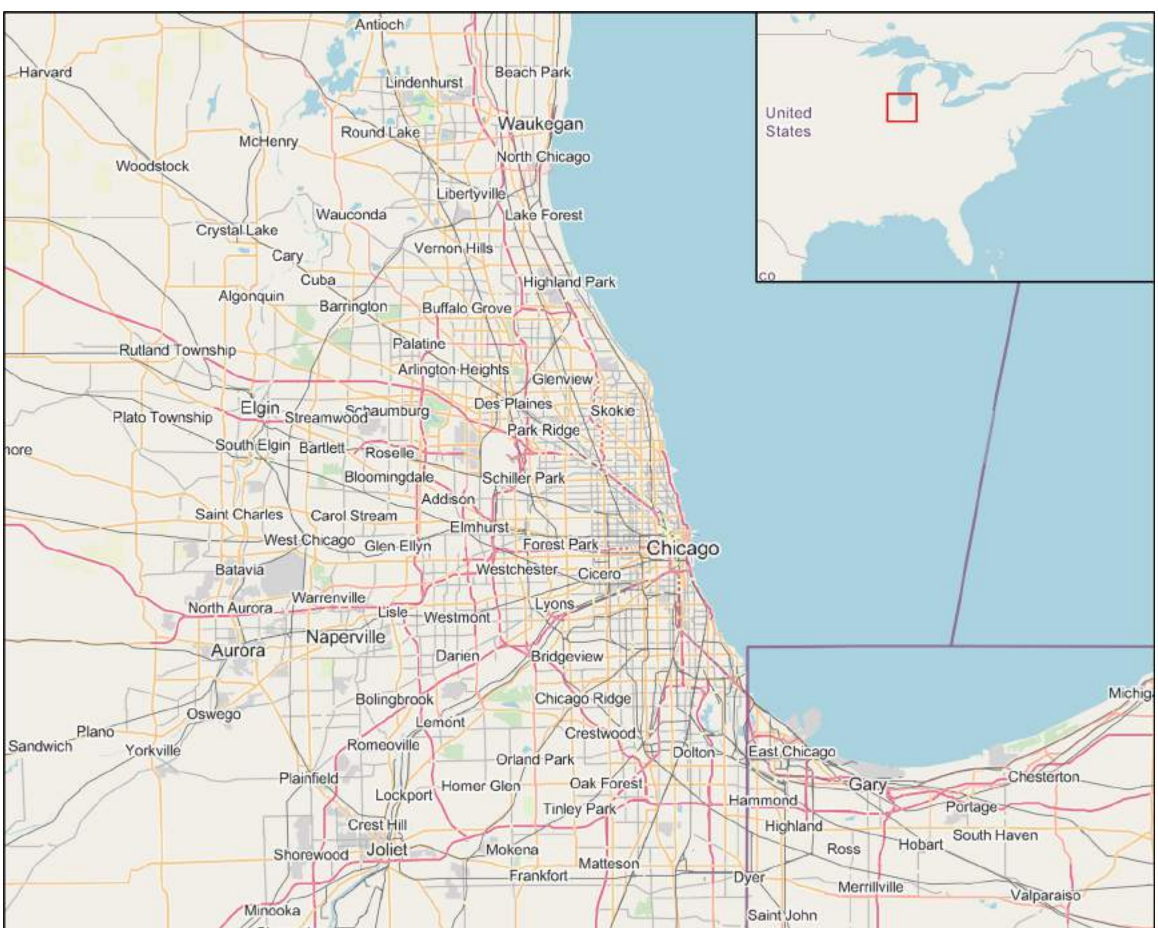

Fig. 1. Chicago Metropolitan Area.

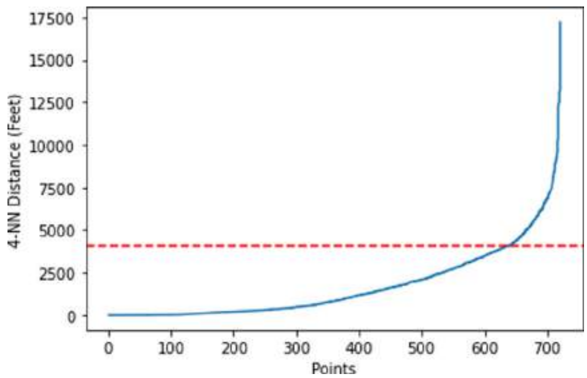

Fig. 2. A K-distance plot of charging stations in the Chicago Metro Area, showing a threshold point at 4000 ft.

ternative fuel use in transportation. One of the products of the AFDC is their "station locator", a database of charging stations across the United States and Canada. The National Renewable Energy Laboratory (NREL) captures data on level-1, level-2, and level-3 charging station locations through service providers, and also through community reporting (Brown, Lommele, Schayowitz & Klotz, 2021). Information on charging stations is updated persistently throughout the year and can be downloaded as a public service through the AFDC. Each charging station record contains information about the types of charging available at the station, the number of outlets at the station, use constraints, and ownership details. The presence of address information as well as geographic coordinates allows station data to be plotted spatially and used in geospatial analysis.

Station data was downloaded for the Chicago Metropolitan Area. In total, there were 721 public EVSE charging stations in the study area, providing 1805 outlets for charging. Level-1, level-2, and level-3 charging stations were considered in this study. Data was collected during May 2021 and analyzed over the subsequent months.

2.3. Procedures for identifying the EVSE clusters, land use regimes, and outliers

Charging station clusters in the Chicago MSA were identified using Density-based spatial clustering of applications with noise (DBSCAN) — an unsupervised machine learning (ML) clustering algorithm developed by Ester, Kriegel, Sander and Xu (1996). This algorithm was originally designed to be used in class identification, or the grouping of data objects into meaningful subclasses. While the AFDC station locator data contains a number of attributes on charging stations including their network status, hours of operation, and connection types, it does not contain any spatial information about the stations beyond their geographic coordinates. In order to assign class labels to each station based on spatial clustering around land use regimes, DBSCAN offers advantages. DBSCAN uses a minimum point (k) density approach to calculate clusters within a distance radius (ε), which can be roughly approximated using a k-distance plot to find a threshold point where the k-distance value is maximized (Ester, Kriegel, Sander, & Xu, 1996). Besides ε, the only other parameter necessary with the DBSCAN algorithm is MinPoints or k. The selection of k is somewhat arbitrary, but it has been found that minimum point values of greater than 4 do not significantly differ from $k = 4$ (Ester, Kriegel, Sander, & Xu, 1996), therefore $k = 4$ charging stations was selected for this study. To establish the distance threshold ε for calculating spatial clusters of at least 4 charging stations, a k-distance plot was created using a k-nearest neighbors matrix for each charging station. The resultant plot is visualized in Fig. 2. A threshold point of approximately 4000 ft was established using this method, and this value was chosen for ε.

Using Python, and the ArcPy and Pandas packages, clusters were calculated using DBSCAN and the aforementioned parameter values of $k = 4$, and $\varepsilon = 4000$ ft. While DBSCAN is useful for detecting spatial clusters of data, it cannot assign class labels to each cluster. Labels need to be manually prescribed after reviewing each cluster. In this case, the associated land use regimes that surrounds each cluster were considered to be the basis of each class label. The DBSCAN calculated clusters were manually reviewed to understand the land use regimes that exist around them. Land use and parcel maps were consulted across the Chicago region, as was the attribute table of charging stations. After manually reviewing these sources, we assigned a class label based on the predominant land uses in the area. In areas with no clearly established land use regime, we applied a "mixed" land use label. These labels are helpful for analyzing each cluster, and for establishing the types of development that private and public decision makers favor in their allocation of EVSE.

2.4. Accessibility analysis

By analyzing accessibility, disparities in charging station equitability can be more fully comprehended and understood in conjunction with land use regimes. Accessibility is a complex subject that is often poorly constructed (Geurs & Van Wee, 2004) even though it is an important outcome of transportation systems (Saif, Zefreh & Torok, 2019). Transportation accessibility is frequently delineated around origin and destination locations and describes the ability to access one location from the other (Curl, Nelson & Anable, 2011). Hansen (1959) defined accessibility as the "potential of opportunities for interaction", a contribution that is tied to the notion that accessibility at a location is proportional to opportunities at nearby locations. Various accessibility measures exist, but Cumulative Opportunities (CO) will be utilized in this study to assess spatial EV charging station opportunities. CO accessibility measure is a simple method to quantify aggregate, place-based accessibility, which is normally represented as absolute values and are easy to compute and perform similar to more theoretically driven gravity-based measure (Palacios & El-Geneidy, 2022) making it a preferred method of accessibility calculation for planners and policymakers (Cheng & Bertolini, 2013). The CO measure is based on the findings of Walter Hansen (1959) and has been refined over the intervening decades, it takes on the following general form:

$$Ai = \sum Oj \cdot f(Cij)$$

Where the accessibility of an origin i (Ai) is calculated as the sum of opportunities at a destination j (Oj) times a cost function of distance or time (Cij).

In this study, accessibility was calculated to charging outlets for each township or community area in the Chicago Metropolitan Area. An averaging approach was applied to the location-based formulation, since there can be more than one potential origin point within a zonal unit i. The rectification is as follows:

$$Ai = \frac{\sum Oj \cdot f(Cij)}{Ni}$$

Ni, in this case, is the number of origin points used to calculate accessibility at a zone i. In this study, 6 origin points were chosen and placed randomly in each zone due to computational limitations. A time function that discounts each opportunity outside of a 15-minute driving threshold of an origin point was used to constrain accessibility. There are many impedance functions that can be used in accessibility calculations (e.g., Kwan, 1998), but the time function used in this study is left purposely simple for the purposes of generalization within the metropolitan area since no publicly available consumer studies of EV charging behavior have been conducted in Chicago or its surrounding metropolitan zone. The 15-minute demarcation was selected based on federal fleet standards for AFV refueling (Daley, Nangle, Boeckman & Miller, 2014). Accessibility is tied to land use and analyzing the clustering of charging stations without also considering which communities have easy driving access to them would be an ill-advised approach.

3. Results and discussion

3.1. EVSE, land use balance, and accessibility

A total of 34 clusters of public EVSE charging stations were located in the Chicago metropolitan area that had densities of at least $k = 4$ chargers within a 4000 feet radius. Fig. 3 depicts the location of these charging stations within the metropolitan area with red marks indicating spatial clustering and white marks indicating non-clustering. Yellow offset boxes are used to visually separate clusters in areas with multiple clusters.

Of the computed clusters, 25 (73%) are latitudinally even with or higher in latitude than Downtown Chicago. Of the remaining clusters of charging, 7 (20.5%) are located in the suburbs to the west-southwest of the downtown core, and only 2 (5.8%) charging clusters are located to the south or southwest of the downtown core area. This represents a severe axial disparity of charging clusters in the greater Chicago region. The South Suburbs and Northwest Indiana do not contain a single cluster of charging infrastructure that meets or exceeds 4 stations. This may reflect private industry charging preferences that favor historically advantaged communities over historically disadvantaged communities. Of the 371 charging stations that are clustered, only 14 (3.7%) do not belong to a corporate charging network. Comparatively, of the 350 unclustered stations, 28 (8%) do not belong to a corporate charging network.

The unbalanced nature of charging stations is even more pronounced when geographic accessibility is considered. Fig. 4 demonstrates a two-panel map that depicts the average number of public charging outlets within 15 min of each township in the Chicago Metropolitan Area and the percentage of these outlets that can be tied to clustered charging. Communities to the North and Northwest of the city limits have the highest average number of charging outlets available within a 15-minute drive time threshold of their boundary. Peripheral areas in the far Northwest Suburbs of the metropolitan area have lower amounts of accessible charging outlets. Unlike the inner-belt suburbs to the north and west of the city, which have more than 144 charging outlets available on average within a short 15-minute drive time, inner-belt suburbs to the south and southeast of Chicago have relatively low amounts of charging. In the South Suburbs and Northwest Indiana, some communities

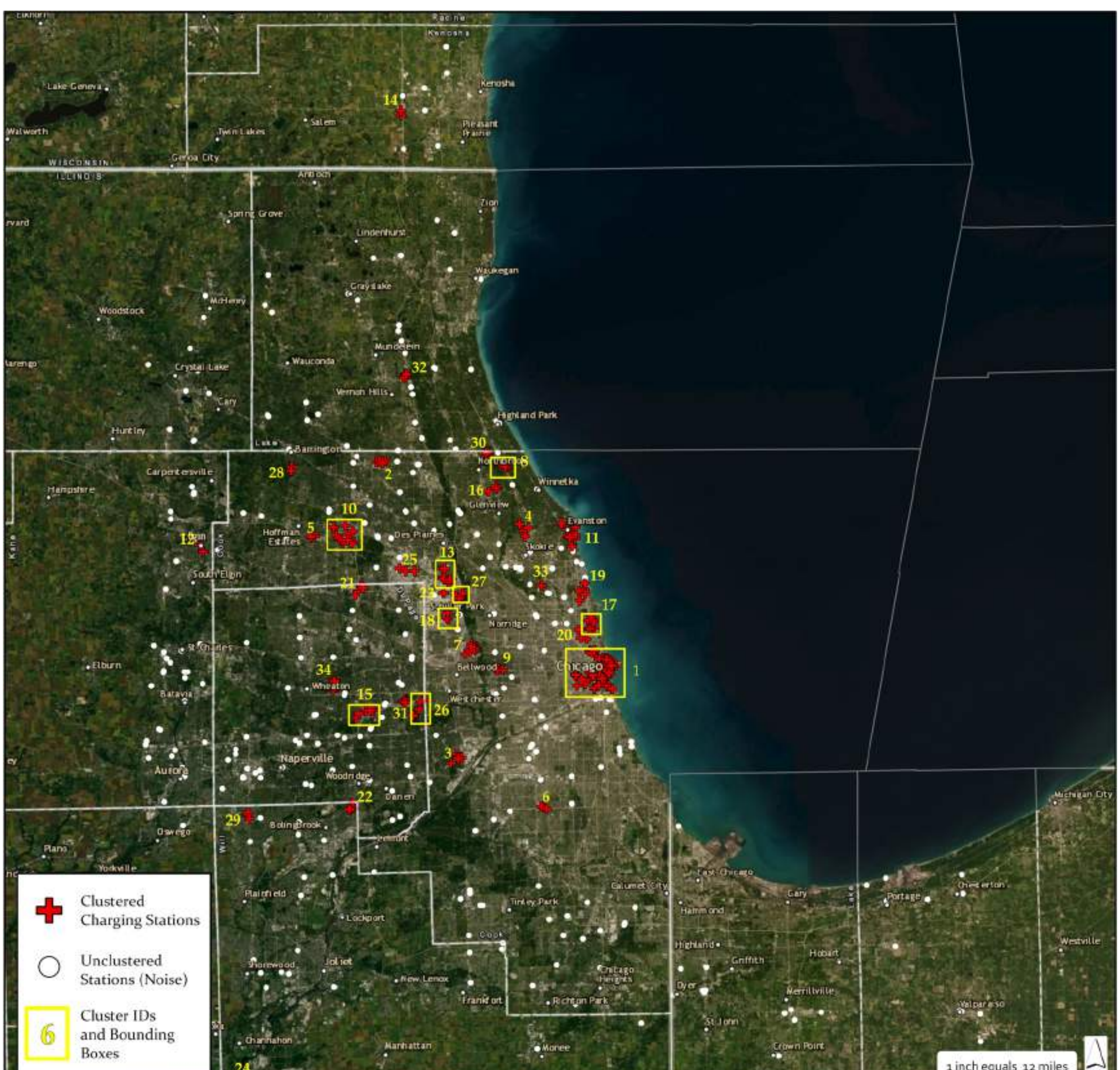

Fig. 3. DBSCAN detected clusters of charging stations in the Chicago Metro Area. Basemap: (ESRI. "World Imagery" [basemap] 2009).

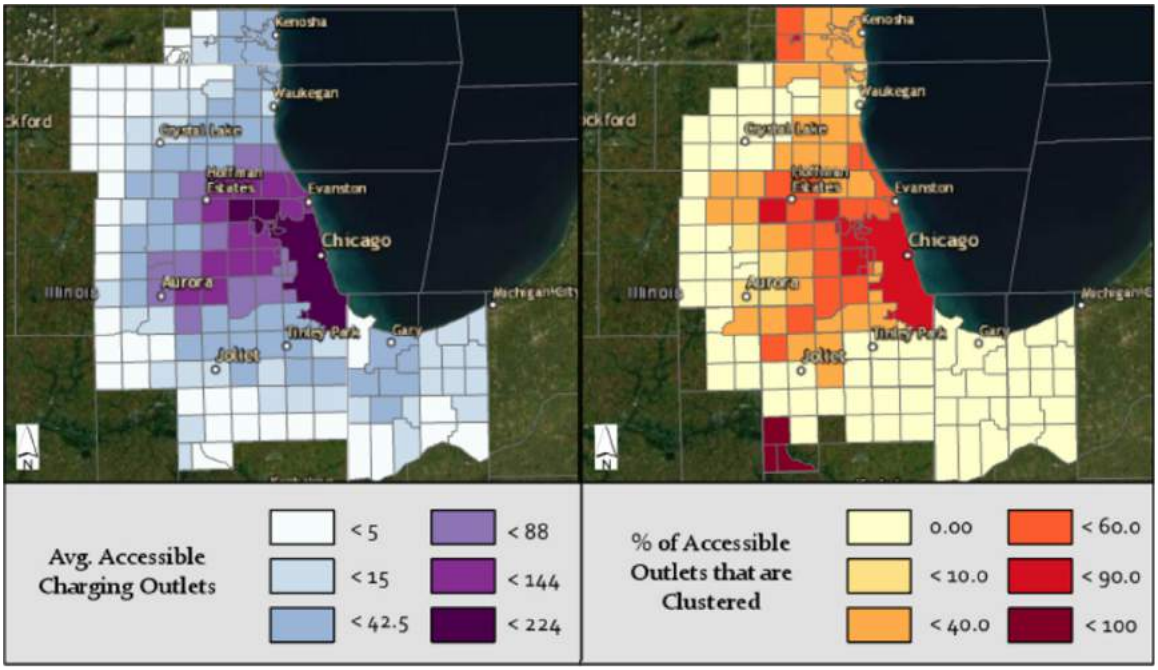

Fig. 4. (Left) A map depicting the average accessible charging outlets by township, (Right) A map depicting the percentage of accessible outlets that are tied to clustered development. Basemap: (ESRI. "World Imagery" [basemap] 2009).

have less than 5 charging outlets available within a 15-minute drive of their boundaries, with most having less than 15 outlets available within that distance threshold.

Between 60 and 90% of charging accessibility to the north and west of the city of Chicago can be tied to clusters of 4 or more charging stations, with the densest area of clustered charging existing within the suburbs surrounding the landscape of O'Hare International Airport. These communities such as Schaumburg and Des Plaines are major commercial and economic centers within the metropolitan area, but the impacts of clustered charging expand well beyond these communities. Townships throughout the western and northern beltway regions surrounding Interstates 290, 294 and 355 owe at least 40% or more of their charging accessibility to clustering. In contrast to this, suburbs to the south and southeast of the city owe none of their accessible charging to clustered developments. This accessibility disparity can be tied to uneven land use balance within the metropolitan region. Since commercial and economic interests favor wealthier communities, it is logical that these communities would also be favored by private EVSE development companies. While EVSE companies do not outright ignore lower income communities, they place far less clustered charging in these areas, which results in diminished accessibility and options for transit users who live in these communities. Though there are un-clustered EVSE options throughout the South Suburbs and Northwest Indiana, it is evident by the lower accessibility in these communities that this infrastructure is considerably less than what would be provided if there were also clustered charging developments. This may force residents without home-based charging to travel outside of their communities to seek better charging options, raising their time and resource expenditures even when this may not be sustainable especially for lower income travelers.

Within the city limits, charging accessibility is more nuanced and varies considerably between community areas. Fig. 5 depicts charging accessibility and clustered charging within the city limits. Neighborhoods close to and surrounding the Central Business District (CBD) have upwards of 224 chargers available within a 15-minute network derived drive time. Between 90 to 100% of this charging can be directly tied to charging clusters. South Side neighborhoods such as Hyde Park, Kenwood, and Pilsen are also included in this area of higher charging accessibility, which may indicate a growing trend of EV development in expanding and gentrifying communities beyond the North Side of Chicago. In contrast, communities on the Southwest Side and far South Side of Chicago have drastically lower amounts of accessible charging. On average, communities on the far South Side have close to zero accessible chargers available to them within 15-minutes, while most communities on the Southwest Side have less than 15 chargers available. Less than half of this charging can be tied to clustered developments.

One major component of Mayor Lori Lightfoot's social equity agenda has been the "Invest South/West" program, which focuses on infrastructure development and community support in the Southwest and South Sides of the city (Gehring, 2021). These parts of the city traditionally have not supported significant numbers of high-income earning populations and have more disadvantages across a number of socioeconomic and social indices (Smith, Sonmez & Zettel, 2021). For this reason, it is not unsurprising that they also have substantially less charging access than areas closer to the CBD and in the more advantaged neighborhoods to the north of the CBD. As in the inner-belt South Suburbs and Northwest Indiana, some of these communities do have access to un-clustered public charging options, but the impact of this EVSE infrastructure is miniscule in comparison to clustered developments elsewhere in the Chicago region.

3.2. EVSE and land use mixing

After the location of clustered charging was determined, a manual review of each cluster was conducted to determine the types of land use regimes and associated development that each EVSE cluster agglomerate around. Table 1 depicts a graphic table of each cluster and its associated land use development. Of the 34 charging clusters, 18 (52%) are associated with commercial development, 9 (26%) are associated with mixed land uses, and the remaining 7 (26%) are associated with some other land use regime. Charging clusters were assigned a commercial label if the majority of charging outlets within the cluster were located at end-consumer retail establishments such as shopping malls, car dealerships, and hospitality establishments. In most cases, clusters of commercial charging densely concentrate around a single large shop-

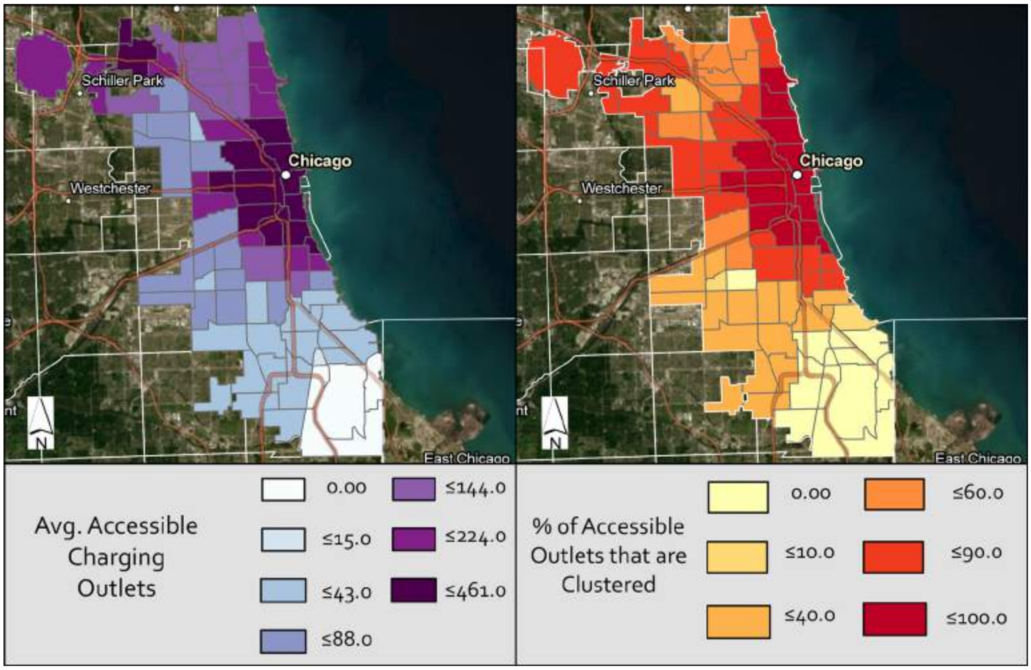

Fig. 5. (Left) A map depicting the average accessible charging outlets by Chicago community area, (Right) A map depicting the percentage of accessible outlets that are tied to clustered development within the city limits. Basemap: (ESRI. "World Imagery" [basemap] 2009).

Table 1
A table of charging clusters in the Chicago Region and their associated land use regimes and charging compositions.

Cluster ID	Associated Feature	Predominant Land Use	# of Charging Stations	# of Charging Outlets	% Level 1	% Level 2	% Level 3
1	Downtown Chicago	Mixed	147	402	2.99	85.57	11.44
2	Arlington Heights Shopping Plazas	Commercial	4	8	0	87.5	12.5
3	Quarry Shopping Center Area	Commercial	5	10	0	60	40
4	Westfield Old Orchard Mall Area	Commercial	4	9	0	88.89	33.33
5	Hoffman Estates Auto Malls	Commercial	6	6	0	66.66	33.33
6	Advocate Christ Medical Center	Medical	5	9	0	100	0
7	Triton College	Education	7	16	0	92.86	7.14
8	Northbrook Office Complexes	Private Offices	4	8	0	100	0
9	Oak Park	Mixed	13	24	0	80.65	19.35
10	Woodfield Mall Area	Commercial	14	31	0	97.37	2.63
11	Evanston/Northwestern University	Mixed	19	38	0	100	0
12	Downtown Elgin	Mixed	4	8	0	82.05	17.95
13	O'Hare International Airport	Airport	9	78	0	100	0
14	Bristol Auto Dealers	Commercial	4	7	0	100	0
15	Yorktown Center Mall Area	Commercial	8	20	0	18.75	81.25
16	Willow Festival Shopping Center	Commercial	4	16	0	68.75	31.25
17	Lake View	Mixed	14	32	0	66.66	33.33
18	O'Hare Oasis	Commercial	4	6	0	88.88	11.11
19	Uptown/Edgewater	Mixed	5	9	0	85.71	14.28
20	DePaul Area	Mixed	4	9	0	100	0
21	Itasca Area	Mixed	5	12	0	55.55	44.44
22	The Promenade Shopping Center	Commercial	5	18	0	100	0
23	O'Hare South Lots	Airport	8	16	0	100	0
24	Exelon Braidwood Station	Power Plant	8	16	0	100	0
25	O'Hare Airport Hotels	Airport	5	15	0	100	0
26	Oak Brook	Mixed	7	24	0	60.71	39.29
27	Rosemont	Commercial	7	28	0	100	0
28	Barrington Auto Dealers	Commercial	5	10	0	100	0
29	Naperville Crossing	Commercial	4	10	0	100	0
30	Northbrook Court Mall	Commercial	5	10	0	100	0
31	Oakbrook Center	Commercial	7	14	0	100	0
32	Hawthorn Mall Area	Commercial	5	9	0	100	0
33	People's Gas Delivery	Commercial	12	24	0	100	0
34	Glen Ellyn	Commercial	4	12	0	100	0

Table 2
A table depicting the average composition of charging stations by cluster type.

Cluster Type	Average Percent Level 1	Average Percent Level 2	Average Percent Level 3
Airport	0	94.44444444	5.555555556
Commercial	0	90.87857573	9.121424272
Education	0	92.85714286	7.142857143
Mixed	0.426439232	72.95413956	26.61942121
Other	0	95.23809524	4.761904762
Unclustered	0.236686391	76.92307692	22.84023669

ping center (such as an enclosed mall) which creates isolation and less land use mixing within surrounding zones. Consumers who visit these commercial developments as part of their daily travel activities may not consider traveling to these locations as burdensome but considering that most of them are far removed from lower-income neighborhoods, the excessive range may be too much for many commuters and vehicle owners to access. Many of the EVSE stations in these developments are located at higher-end car dealerships, restaurants, and stores, which may present additional cost and psychological barriers for lower income consumers.

A surprising finding was the high number of charging clusters that are associated with mixed development. In these clusters, the charging is relatively uniformly distributed between residential and commercial areas, with less segregation compared to commercially oriented clusters. These mixed land use charging clusters were primarily located in established city centers such as Downtown Chicago, Oak Park, and Evanston. In these areas, existing urban development schemes have traditionally favored denser development, and less segregation of land uses. Charging in these areas is close to residences and apartment complexes and can be reached without having to drive to a disjunct shopping center which may offer increased flexibility for vehicle owners. In the long term, this type of clustered development may also result in environmental benefits for residents of these communities especially as adoption increases.

In addition to commercial and mixed land use charging clusters, other clusters were detected in office parks, near airports, educational facilities, and power plants. Each of these clusters features highly concentrated areas of charging that are separated from other land uses and primarily intended to be used by stakeholders in each type of development. Clusters of charging around O'Hare International Airport, for example, were primarily located at parking facilities and hotels associated with the airport. These "semi-private" charging opportunities may not be available to everyday consumers and may be intended only for specialized users, thus impeding their usability by residents from nearby communities. Even if these chargers are available for everyday use, they may have additional costs or restrictions that are not a practical expenditure for cost-conscious consumers.

Compositionally, for clustered and unclustered charging, 87.5% of public EVSE in the Chicagoland region is level-2 charging, which has a recharge rate of between 12 and 30 miles per hour. An additional 12.4% of charging is level-3 (DC Fast) charging, with a much faster recharge rate of up to 15 miles per minute. Less than 1% of charging in the Chicago region is level-1 charging, which can only provide charging at a rate of 3 to 4 miles per hour making it the least efficient. Table 2 depicts the average constitution of each EVSE type across similar clusters of charging. Across all land use cluster types, level-2 charging predominates having slightly less prevalence among mixed land-use charging clusters. Level-1 charging is negligible across cluster types, and level-3 charging constitutes approximately a quarter of the EVSE in mixed land-use clusters. Across the entire Chicagoland region, EVSE that are unclustered, and by virtue of this more isolated than other chargers, are compositionally closely related to mixed land-use clusters of EVSE. This seems to indicate that EVSE that is more dispersed and integrated into the fabric of communities is slightly more diverse than charging that clusters around destinations such as shopping or education centers.

The inconvenience of slower charging for an average user is likely dependent upon their individual travel behavior. Vehicle users with long distance commutes may need to make multiple stops to recharge their vehicles when using level-2 charging, while users who make short-term trips within their neighborhoods may find level-2 charging more convenient. This inconvenience problem is noted by Dixon et al. (2020), who found that for individuals without access to charging at home, the best solution to the charging inconvenience problem is to improve vehicle technology and provide an "abundance of facilities" for charging. Expanding upon this work, we argue that the placement and composition of such facilities is also vital. Considering that level-2 charging can only replenish 12 to 30 miles of electricity per hour, it would be cost prohibitive for users to go out of their way to access this type of EVSE. Even though it may not be optimal from a utilitarian standpoint, maximally distributed EVSE across all socioeconomic communities would help ameliorate range anxiety issues for users from different backgrounds and who have diverse travel needs.

4. Conclusion and future considerations

EVSE charging, land use, and accessibility are interconnected with one another in the metropolitan area of Chicago. Of the 34 DBSCAN derived charging clusters in the region, only 26% are associated with mixed land uses. Clustered charging, therefore, congregates around isolated land use regimes that favor only a singular type of development. These clusters are located primarily near Chicago's CBD, and in the North and Northwest Suburbs. This uneven clustering of EVSE may compel EV owners from neighborhoods with marginal accessibility to travel out of their way to charge their vehicles at these clusters when it would likely be more efficient for them to charge their vehicles closer to their home at businesses and services that they already frequent as part of their daily travel behavior. EV owners who live in older commercial and residential centers of the urban area, where land use mixing is high, are more likely to live close to large EVSE clusters that are well integrated and mixed within the community, providing enhanced flexibility for non-residential charging and potential environmental benefits. Suburbs to the south and southeast of the urban core have deeply inequitable access to charging compared to other inner-belt suburbs, and neighborhoods within the city to the southwest and far south of the CBD have similarly low rates of charging access. Coincidentally, these are also areas that have been cited in other studies as having unequal access to basic amenities such as public transit, healthcare, and healthy food. The differences in charging access between these areas and wealthier communities is wide, and much of these differences can be attributed to the clustering of EVSE. Clustered charging is not inherently negative, but clustering that only occurs primarily in the service of certain privileged communities or the wider utility of society may result in inequitable access to public charging resources and an exacerbation of existing land use imbalances and environmental injustices across lower income communities. Without adequate charging in these communities, adoption rates may struggle to keep pace with market demands, and new geographies of exclusion could arise that systematically disadvantage whole regions from the benefits of EVs.

This research offers an early examination of how EVSE clusters around land uses and communities in Chicago. As EV adoption and proliferation continues to unfold, more research will likely be necessary in this area. This research used a relatively intuitive place-based formulation to calculate accessibility. In the future, advanced accessibility modeling that takes individual travel behavior into account will likely also be necessary, especially in communities that have more adoption constraints. Time and resource constraints will likely also have to be added into these calculations, especially since there are substantial differences in charging times between level-1, level-2, and level-3 charging stations. Understanding how station attributes such as connection type, charge time, network, and price budgeting affects users is a future direction of this research that we believe will add value to the findings from this case study.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Evaluating the accessibility benefits of the new BRT system during the COVID-19 pandemic in Winnipeg, Canada

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Public health

ABSTRACT

Recently, in Winnipeg, the implementation of new bus rapid transit (BRT) system in the middle of the COVID-19 pandemic has raised many concerns, challenging the rationale behind the untimely release. However, the new BRT service can benefit low-income, socio-economically vulnerable, and transit captive passengers who must travel to essential services and work opportunities during the pandemic. This study evaluates whether the new BRT system has positive impacts on accessibility to such essential services during the pandemic. Isochrones with different time budgets as well as times of a day are generated based on high-resolution public transit network via the General Transit Feed Specification (GTFS) data and used for evaluating accessibility benefits before and after the BRT construction. The new BRT service in Winnipeg demonstrates varying accessibility impacts across different parts of the BRT corridor. Areas near dedicated lane-section show a significant increase, whereas areas near non-dedicated lane sections show a decrease in accessibility. Nevertheless, across the whole BRT corridor, the new BRT service presents an overall increase in accessibility to essential services. This demonstrates the positive accessibility benefits of the new BRT service to residents seeking essential services during the COVID-19 pandemic. A decrease in accessibility along some parts suggests the necessity of using local transit improvement strategies (e.g., dedicated lanes) to improve service speed when planning BRT services within urban areas.

1. Introduction

In December 2019, COVID-19 was detected in Wuhan, China, and it has since been one of the most unprecedented challenges in the world (Sohrabi et al., 2020). In Canada, as of March 12, 2020, many provinces have implemented stay-at-home orders or lockdowns to control the spread of the disease. Many schools, universities, and businesses have been closed, and many people were required to work from home. These new policies, along with the fear of infection, have decreased the level and frequency of human mobility in cities, resulting in a decline in public transit demand and its ridership level (Central News Agency, 2020). For example, in Canada, the transit ridership decreased to almost half (- 45.6%) in March 2020 and more than 80% in April and May (Statistics Canada, 2021). In Västra Götaland, Sweden, as a second example, the ridership of trains, trams, and buses saw a drop of 60%, 40%, and 30%, respectively in June 2021 compared to the same time in the previous year (pre-COVID-19) (Jenelius and Cebecauer, 2020).

In the face of the general reduction in mobility and ridership level, some public transit providers have halted specific services and have diminished service span and frequencies (Gkiotsalitis and Cats, 2021). In Canada, all of the largest 25 transit agencies immediately reduced the offered service frequency and capacity in March 2020, while implementing other physical and communication measures to reduce the risk of infection (Diaz et al., 2021). Additionally, almost none of the transit agencies implemented supplemental services or provided access to paratransit services between March 2020 and June 2020 (Diaz et al., 2021). In contrast, Winnipeg Transit unveiled a new public transit service just after 12 days from the stay-at-home order and started running to full capacity (CTV News Winnipeg, 2020a). Although it was welcomed with controversial remarks due to its untimely release (Elisha Dacey 2020), this new BRT service can serve to benefit some people who do not have the luxury of working from home, including low-income, socio-economically vulnerable, and transit-captive *essential workers* (Zimmerman, 2005; Gallagher et al., 2021). Not being able to afford a personal car, essential workers have continued to commute by public transit and have maintained their transit ridership levels despite the potential risk of infection and public health warnings (Liu, Miller and Scheff, 2020; Farber, 2021; Justin George, Kate Rabinowitz, 2021; Kim and Kwan, 2021). Given that low levels of accessi-

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bility can exacerbate the socio-economic and health disadvantages for these groups (Lee and Miller, 2018), it is vital to enhance spatial accessibility, even during a pandemic when the overall ridership declines.

This study aims to investigate the impacts of Winnipeg's new bus rapid transit line (BLUE) on accessibility to essential services during the COVID-19 pandemic. We classify essential services into four categories: 1) health, 2) grocery, 3) finance, and 4) accommodation. The paper examines accessibility to these destinations from centroids of dissemination blocks, which is the smallest geographic unit used by Census Canada[1], that are located within a 500-meter catchment area of the BLUE rapid transit line. This was done to explore the local impacts of the new BRT service on local residents' accessibility along the BRT corridor. We employ a space-time constrained cumulative measure to calculate accessibility benefits pre- and post-BLUE implementation within different time windows on weekdays. Specifically, we consider morning peak, mid-day off-peak, early evening peak, and late evening off-peak hours as our departure times to account for fluctuations in transit schedules (e.g. frequency and headway). Using this detailed approach will help us not only to assess the effects on different segments along the BRT corridor, but also to understand the benefits of offering dedicated bus lanes at some locations.

The rest of the paper is structured as follows: Section 2 will provide discussions on recent research studying the COVID-19 impacts on mobility and accessibility. The following section will describe Winnipeg's new public transit service Section 4 presents the research methodology and explores the impacts of the new BRT service on accessibility Section 5 provides the results, and finally, Section 6 concludes the paper and discusses the limitations and the future steps.

2. Literature review

The COVID-19 pandemic has prompted governments to restrict residents' mobility to mitigate the spread of the virus. The government-imposed restrictions have included the closure of borders, travel bans, lockdowns, and urging people to work and study from home. These governmental interventions as well as people's perceived risk of the disease contributed to behavioural changes in human movement (Warren and Skillman, 2020). Generally, the COVID-19 pandemic has profoundly affected the trip frequency around the world. For example, a study conducted in the United States revealed that the number of out-of-country trips dropped from 28% to 23% and per-person trips fell from 3.7 to 2.7 trips (Lee et al., 2020b). This reduction was also observed in France in both recreational and work-related trips, particularly during peak hours (Pullano et al., 2020). In Canada, since April 2020, there has been a considerable decrease in the number of trips to transit stations, workplaces, and retail and recreational opportunities, while there was a slight increase in the number of trips to essential services such as grocery and pharmacy stores (Google 2021a). The pandemic has also resulted in a dramatic drop in travel distances. For instance, the median of the max-distance mobility in Hong Kong dropped from 2.3 to about 0.2 kilometers and the average trip distance in the US dropped from around 64 to 30 kilometers (Lee et al., 2020b; Warren and Skillman, 2020). Also, movement restrictions during the pandemic have reduced traffic congestion and therefore resulted in a considerable rise in the spatial extent and average level of personal vehicle speeding relative to the before COVID-19 speeding pattern (Lee, Porr and Miller, 2020; Stiles et al., 2021).

Recent studies have examined the travel mode choice during the pandemic and observed a shift away from public transit (Abdullah et al., 2020; Bhaduri et al., 2020; Dingil and Esztergár-Kiss, 2021). They indicate that most passenger's preference has shifted from public transport to private vehicle and non-motorized vehicles (Anwari et al., 2021). For example, there has been a significant increase in bike trips and cycling kilometers per day in Switzerland (Molloy et al., 2021). As a result of the overall decline in public transit use, ridership has notably decreased (Ahangari, Chavis and Jeihani, 2020; Jenelius and Cebecauer, 2020; Wilbur et al., 2020). For instance, in New York, there has been an 80% drop in subway and commuter rail ridership, and a 50% drop in bus ridership (Gao et al., 2020). Although the mode preference has shifted to personal cars, public transit has been remained popular in some trips during the pandemic (Anwari et al., 2021). Considering low-income people who are most reliant on public transportation to reach their destination (Liu, Miller, and Scheff, 2020), it is important to enhance the accessibility by public transit during the pandemic (Wilbur et al., 2020).

Accessibility, which is a key concept in land use and transportation planning, refers to the ease with which potential opportunities can be reached using a travel mode (Handy and Niemeier, 1997). In contrast, *mobility* refers to the ability to move along (Morris, Dumble and Wigan, 1979). Among different accessibility measures, such as opportunity-based, gravity-based, utility-based, and space-time measures (Geurs & Van Wee, 2004), most studies tend to use the cumulative-opportunity measure, also called isochronic measure, as it is easier to interpret, communicate, and can be applied to different modes of travel (). It evaluates accessibility by counting the opportunities that can be accessed from a specific location within a determined threshold (Boisjoly and El-Geneidy, 2017). Numerous researchers have been studying accessibility within urban areas due to its profound impacts on land values (El-Geneidy and Levinson, 2006), employment rates (Tyndall, 2017), transit use (Owen and Levinson, 2015), and social equity (Allen and Farber, 2020). Recently, a variety of studies have been carried out to assess accessibility in different contexts during the COVID-19 pandemic (Kang et al., 2020; Allen and Farber, 2021; ; Paez and Higgins, 2021; Pereira et al., 2021). For instance, a study conducted in Illinois evaluated the spatial accessibility of COVID-19 healthcare resources to identify areas with a low level of spatial accessibility that requires additional health resources (Kang et al., 2020). Another study evaluated the accessibility to vaccination sites and their variation across the population to promote the equity of access (Paez and Higgins, 2021).

Despite several studies on changes in human mobility and accessibility during the pandemic (de Haas et al., 2020; Wilbur et al., 2020; Anwari et al., 2021; Kim and Kwan, 2021; Matson et al., 2021), little attention has been paid to assessing the accessibility benefits of new public transit infrastructures offered during the pandemic, particularly while focusing on accessibility to different essential services. Additionally, it is hard to find studies that focused on assessing the local benefits experienced by different segments of the corridor over the span of the day. To fill these gaps, this study considers the City of Winnipeg as a case analysis to better understand how a new public transit service can benefit individuals' accessibility to specific essential services during the COVID-19 pandemic.

3. New public transit service in Winnipeg: BLUE BRT and Southwest Transitway

Winnipeg Transit has proposed the concept of Transitway since the 1970s to connect downtown with Southwest Winnipeg (Winnipeg Transit, 2021b). In April 2012, the Southwest Transitway Stage 1 was commissioned to complete the dedicated roadway. However, there were two main drawbacks to this service, which led to significant changes in travel time. Firstly, due to the population growth and increased ridership, passengers often experienced pass-ups, which refers to when the arrived bus is full and passengers must wait for the next bus (Kavanagh, 2019).

[1] A dissemination block, for which population and dwelling counts are disseminated, is defined as a region bounded on all sides by roads or boundaries of standard geographic areas (Statistics Canada, 2018).

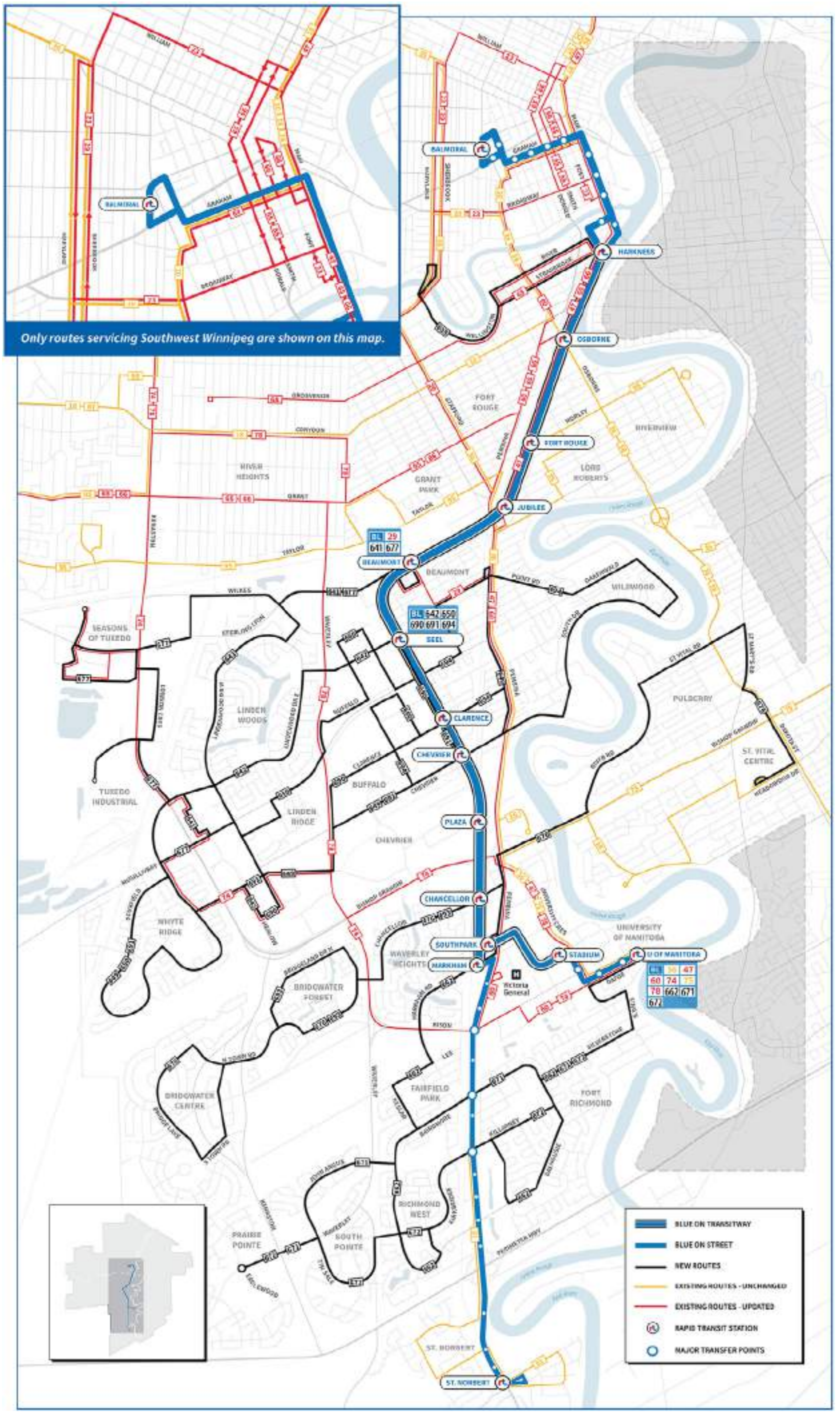

Fig. 1. The map of the new spine route (BLUE BRT) + feeder routes (black routes) network and Southwest Transitway (a bold blue line) (Winnipeg Transit, 2021a).

Secondly, it suffered from poor on-time performance as it could not meet coordinated schedules because of the traffic congestion.

To meet challenges associated with the bus routes in Southwest Winnipeg, Winnipeg Transit adopted a new plan for the Southwest Transitway Stage 2 in March 2016 and proposed a new spine and feeder service model to the public in April 2019 (see Fig. 1). The neighbourhood feeder routes in this network were planned to connect passengers from local neighbourhoods to the Southwest Transitway stations where they can transfer to the spine route, named BLUE rapid transit line.

Finally, the new Southwest Transitway including the BLUE BRT was launched in April 2020 during the COVID-19 pandemic. It started to operate under a full schedule despite the closure of the University of Manitoba and other non-essential businesses, and a 70 percent reduction in the number of passengers (Kavanagh, 2020). Consequently, the untimely release and the financial burden of this new service have led to controversial remarks among Wininipegers (Winnipeg Transit, 2021a).

This new Southwest Transitway, including the BLUE rapid transit line, is a high-speed dedicated roadway for buses traveling between Downtown, the University of Manitoba, and St. Norbert, but without a transit signal priority system (see Fig. 1) (Winnipeg Transit, 2021b). It addresses the shortcomings of the previous transit service and enhances the overall performance of the transportation network by offering an efficient, fast, and frequent transit service. By construction of this network, some new transit routes have begun service, while some corridors have been replaced or have ceased operation. In addition to these changes to the transit routes, enhancing on-time performance, maintaining headway spacing, increasing staff establishment, operation frequency, and the number of articulated buses and stations could have contributed to

Table 1
Selected essential services.

Health	Grocery	Finance	Accommodation
Health and Personal Care Stores (Eye Care, Drug Stores, pharmacies, etc.)	Grocery Stores (Supermarkets, Markets, Convenience Stores, etc.)	Depository Credit Intermediation (BMO, TD, Scotia Bank, RBC, etc.)	Hotel and Motels
Offices of other Health Practitioners (Chiropractor, Physiotherapy, Massage, etc.)	General Merchandise Stores, including Warehouse Clubs and Supercenters (Dollarama, Walmart, Costco, etc.)	Accounting, Tax Preparation, Bookkeeping, and Payroll Services (H&R Block, Liberty Tax Service, etc.)	
Other Ambulatory Health Care Services (Hearing, Therapy, etc.)	Grocery and Related Product Merchant Wholesalers (Tea Stores)	Non-Depository Credit Intermediation (Money Mart, Pawnshops, Cash Money Services, etc.)	
General Medical and Surgical Hospitals (Hospitals)	Specialty Food Stores (Meat Shops, Frozen Foods, Delis, etc.)	Agencies, Brokerages, and other Insurance Related Activities (Allstate, Co-operators, etc.)	
Offices of Dentists (Dentists, Orthodontists, etc.)			
Offices of Physicians (Medical Clinics, and Health Services)			
Specialty (except Psychiatric and Substance Abuse) Hospitals (Gynecology, Lab Services, etc.)			

the accessibility improvements (Winnipeg Transit, 2021b). Accordingly, to evaluate these radical changes in the Southwest Transitway network and take into account the concerns in the local community, it is vital to assess the impact of the new BRT service on residents' accessibility during the pandemic and over the span of the day.

4. Method

4.1. Data

4.1.1. Transportation

To create a multimodal transport network dataset, we integrate the walking (e.g., sidewalk) network with the public transit network. We obtain street network data from OpenStreetMap (OSM), a collaborative street map database around the globe, to build the walking network (OpenStreetMap 2021). As per the public transit network, we utilize General Transit Feed Specification (GTFS) data which is typically used for estimating the travel time by transit from one point to many other points (Farber et al., 2014). The GTFS is a common data format for public transit data that contains information about public transit schedules, fares, routes, stops, and associated geographic information (e.g., locations of stops and shapes of routes) ((Google 2021b). We collect Winnipeg Transit GTFS feeds for before and after the new BRT periods directly from an open-source GTFS collection website: OpenMobilityData (OpenMobilityData 2021). To investigate the accessibility changes and conduct a fair evaluation on accessibility benefits of the new BRT, we select April 20, 2020, as a date after the BLUE BRT implementation when it was operating on a full schedule without any service reduction (CTV News Winnipeg, 2020b). Correspondingly, we choose April 22, 2019, as a date before the BLUE BRT implementation.

4.1.2. Essential services

Essential services refer to critical infrastructure services that must stay open during a disaster or an emergency as they ensure human health, welfare, and economic wellbeing (Government of Canada 2021a). For instance, grocery and convenience stores are among the essential services since food availability has a substantial effect on community health (Kar et al., 2021). To specify essential services which can be open during the lockdown, the Winnipeg government listed essential businesses, including accommodations, transportation, retail and wholesale, research, and finance (Gerbrandt, 2020). Accordingly, in this study, we consider four types of essential services: 1) financial, 2) healthcare, 3) grocery, and 4) accommodation and obtain their location data from the SafeGraph (SafeGraph, 2021), which is a dataset containing 6 million points of interest across the US and Canada (Ossola, 2020). A detailed description of the selected essential services is presented in Table 1 Fig. 2. presents the geographic distributions of these essential services in Winnipeg.

4.2. Creating multimodal transit network and generating isochrones

This study aims to gauge the accessibility by deploying the space-time constrained cumulative measure within the travel time isochrones. To this end, we employ OpenTripPlanner (OTP) and *otpr* R package (Young, 2020) for generating isochrone polygons which indicate locations that can be accessed from a specific origin (e.g., home, centroids of dissemination blocks) within a predetermined travel time (e.g., 30 minutes, 1 hour) or less and measuring accessibility (O'Sullivan et al., 2000a). OTP is a free open-source trip planner that analyzes the transportation network and helps passengers to plan a trip with multiple modes of transportation (OpenTripPlanner 2021). Using the *otpr* R package, we can send queries to the relevant OTP API resource and retrieve useful R objects (RDocumentation, 2019).

Based on the collected multimodal transportation network data highlighted in the previous section, we create and query our own multimodal journey planner using a local OTP server. The first step to generate an isochrone area is building an OTP network graph for streets and transit services and launching the OTP instance on a local machine (Young, 2021). Once an OTP instance has been started, we use the OTP server to delineate an isochrone polygon representing the geographic areas that can be reached from an origin via walking and public transit networks given a specified time budget. Travel times account for first-mile walking time from a trip start point to the public transit station, waiting (initial/transfer) and in-vehicle travel time, and last-mile walking from the stop to the final destination (e.g., essential service location) (Stępniak et al., 2019).

In the public transit industry, a 400-meter buffer around the transit line serves as a common identifier for the service area, which is the area from which most residents can walk to reach the transit. However, generated service areas in several Canadian cities showed that most passengers' walking distance to bus transit services is around 500 meters. For instance, the service area for the city of Saskatoon is 532 meters which represents the 85th percentile of walking distance to public transit stops in the city (Bree, Fuller and Diab, 2020). Accordingly, we use the centroids of dissemination blocks located with a 500-meter catchment area of the new BLUE rapid transit corridor for our trip starting points (Government of Canada 2021b). To investigate the impacts of transit lane reservation (i.e., dedicated (separated) lane) on accessibility, we split our trip origins (centroids of the dissemination blocks) into two categories based on their proximity to the dedicated or non-dedicated lane sections of the BLUE BRT corridor and use for the analysis.

Due to the lack of observed travel behaviour data and an ideal cut-off time (Xi, Miller and Saxe, 2018), we consider four different travel time budgets to create isochrone polygons. According to Canada's 2016 Census, the average commuting duration in Winnipeg is 24 minutes (Statistics Canada, 2019). We, therefore, choose 30 minutes as a standard travel time cut-off for measuring local accessibility. We also choose a 60-minute cutoff time since it is a standard time budget for measuring regional-level accessibility (Lee and Miller, 2018). As a part of the sen-

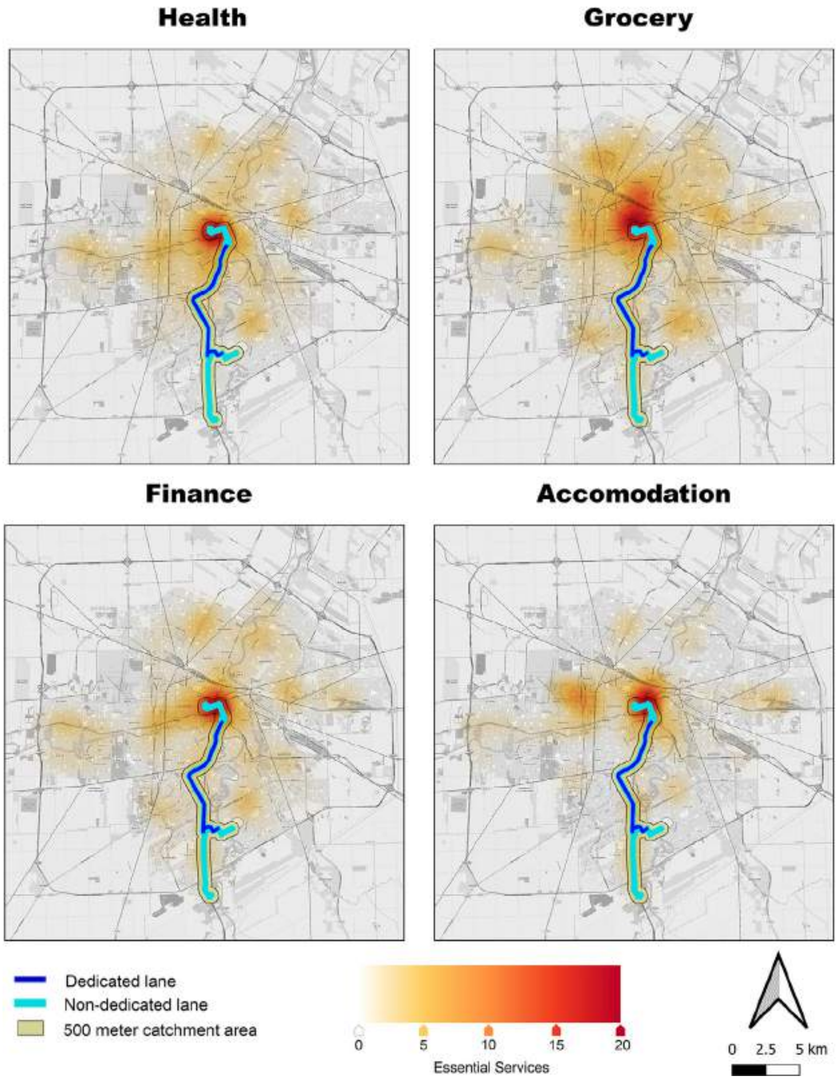

Fig. 2. Geographic distributions of essential services in the city of Winnipeg.

sitivity analysis and to take into account those able or eager to travel to more distant destinations, we select two additional time limits, 45 and 75 minutes.

As our travel time windows, we select morning peak (7 - 9 AM), mid-day off-peak (11 AM - 1 PM), early evening peak (3:30 - 5:30 PM), and late evening off-peak duration (7 - 9 PM) based on Winnipeg Transit's schedules to take into account the variability in the public transit schedules and frequency which can have a profound impact on the total travel time due to the factors such as missed connections and prolonged transfer times (Cooke and Halsey, 1966; Farber et al., 2014; Kim and Lee, 2019; Winnipeg Transit, 2021a). Lastly, to address possible variances in accessibility depending on the trip starting times within a time window, we choose the 15-minute temporal resolution for generating isochrones within a specific time window as it offers a lower computational time with reasonable precision when measuring transit-based accessibility (Stępniak et al., 2019). For example, during the morning peak time (7 - 9 AM), we create a total of nine isochrones based upon different departure times with 15-min intervals, including 7:00, 7:15, 7:30, 7:45, 8:00, 8:15, 8:30, 8:45, 9:00 AM.

4.3. Calculate the cumulative accessibility measure

This study deploys the cumulative accessibility approach (O'Sullivan et al., 2000a; El-Geneidy and Levinson, 2006; Lee and Miller, 2018, 2019; Kim and Lee, 2019) to count the total number of potential opportunities that are accessible from an origin within a specific time limit. For each trip origin (i.e., dissemination block centroid) and time budget (i.e., 30, 45, 60, 75 minutes), we generate nine isochrones for a given time window (e.g., 7 - 9 AM). We then compute the cumulative accessibility index for each isochrone using the *otp_evaluate_surface()* function in the *otpr* R package. *otpr* sums the number of essential services located within an isochrone, producing the cumulative accessibility index for each type of essential service: financial, health, grocery, and accommodation (Young, 2020). The average of the cumulative accessibility across all nine isochrones within a time window is calculated and used as a benchmark when measuring accessibility benefits before and after the BRT introduction.

5. Results

5.1. Space-time accessibility maps

In this section, we visualize space-time accessibility maps before and after the construction of the BLUE rapid transit line. Due to the space limitation, we select 8 AM and 12 PM as representative peak and non-peak hours respectively. To illustrate the impacts of lane designation (with vs. without dedicated lane) on accessibility, we select two sample starting points within the 500-meter catchment area of the dedicated and non-dedicated lanes Fig. 3. illustrates the space-time accessible areas within different time budgets at 8 AM pre and post the new BRT introduction. As can be seen, although the area of accessible regions became larger for the origin located within the dedicated lane section, the

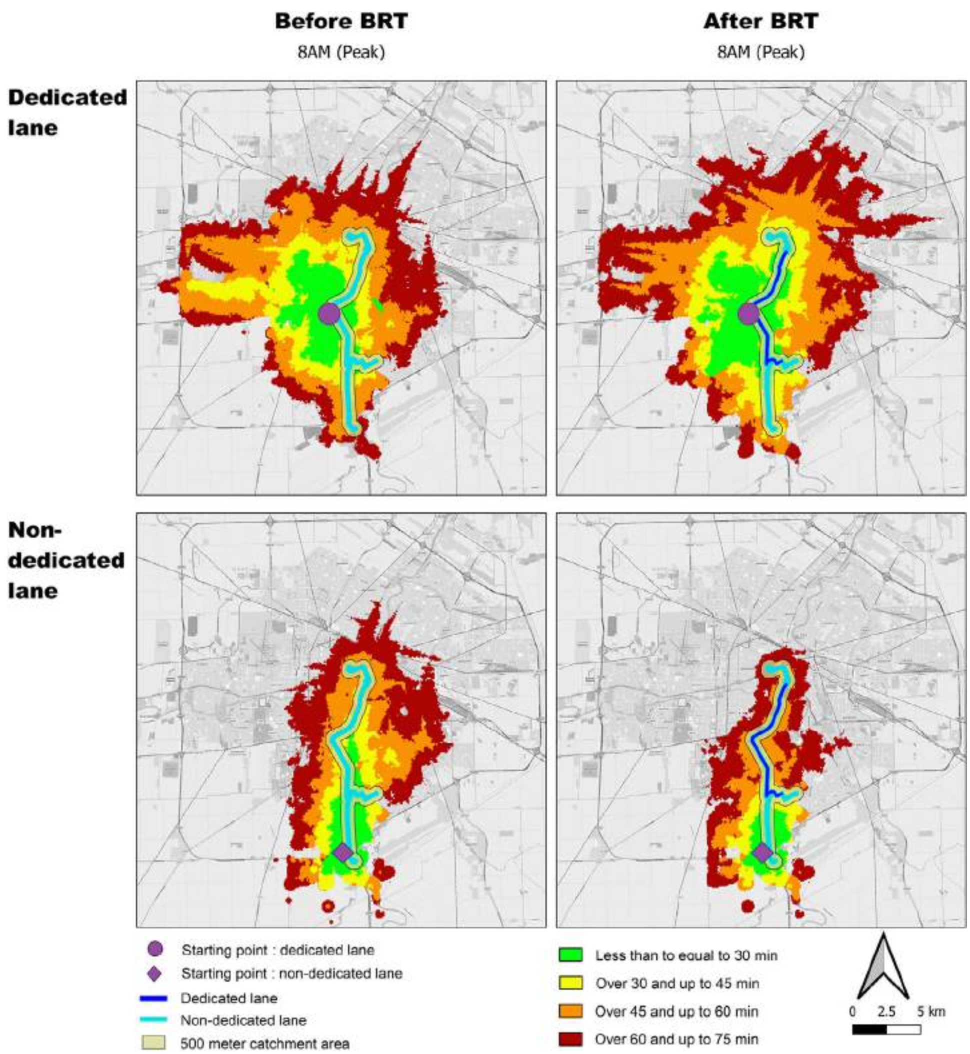

Fig. 3. Space-time accessibility maps at 8 AM (peak time).

counterpart in the non-dedicated lane part presents a smaller accessible area after the BRT construction, especially in Northern Winnipeg. Substantial changes in the transit network, such as the addition, elimination, and relocation of several transit routes and stops, as well as changes in bus schedules, could have contributed to the decline in the area of accessible regions near the non-dedicated lane section.

Fig. 4 shows the isochrone maps at noon, reflecting a similar pattern as the previous Fig. 3. Based on Figures 3 and 4, it is evident that the accessible regions from the starting point located near the dedicated lane section are larger than those in non-dedicated lanes, regardless of both new BRT construction and the time window. The dedicated lane (Southwest Transitway) in the new BRT service provides the greatest enhancement in accessible areas during off-peak hours (12 PM). Meanwhile, the largest accessible area is from the dedicated lane section after the BRT during the morning peak. It can be explained by the higher transit frequency and shorter headways during this peak period as it is a popular time for commuting to work.

5.2. Space-time constrained cumulative accessibility to essential services

In this section, we present cumulative accessibility results using bar graphs showing accessibility levels across different parts of the BLUE corridor: 1) entire corridor, 2) dedicated lane section, and 3) non-dedicated lane part Fig. 5. presents the results for the entire corridor, focusing on the 30-minute and 60-minute time budgets. The details on the accessibility percentage changes for all of the essential services within each time window and every time budget (30, 45, 60, 75 minutes) are provided in Table 2.

As can be seen in Fig. 5, the accessibility to most destinations is higher during morning rush hours (7 - 9 AM), which is in line with the previous section. Additionally, regardless of BRT implementation and time budget, the most accessible destinations are health services especially in morning rush hours, whereas the least accessible services are accommodations, especially during early evening rush hours. Such difference could be due to the greater number of health services near the transit line as well as the higher frequency of service during morning rush hours.

A notable finding in Fig. 5 is that in almost all bar charts, we can see a rise in accessibility after the BRT implementation implying the positive impacts of the new BLUE BRT on residents' accessibility. Specifically, the highest increases in accessibility can be seen within the late evening time duration (7 - 9 PM) which can considerably benefit night shift essential workers. In addition, as illustrated in Fig. 5, within 30 minutes time budget, accommodation services see the greatest rise in accessibility, whereas within 60 minutes time budget, grocery services face the most increase.

Despite the overall increase in accessibility after the BRT construction, there have been a marginal drop in local (i.e., 30-minute) access to health and finance services during early evening rush hours (around 0.6%), as well as regional (i.e., 60-minute) accessibility to health services during morning rush hour (about 0.1%). A possible explanation for these minor reductions could be the changes in transit schedules and stop locations combined with the elimination of some feeder routes.

Table 2
The accessibility percentage changes for all of the essential services within each time window and all time budgets (30, 45, 60, 75 minutes).

	Time budget	Departure time	Dedicated lane	Non-dedicated lane	Entire corridor
Health	30 mins	7AM - 9AM	4.70%	-1.30%	0.91%
		11AM - 1PM	8.27%	-1.18%	2.44%
		3:30PM – 5:30PM	2.07%	-2.29%	-0.64%
		7PM – 9PM	8.60%	-0.92%	2.68%
	45 mins	7AM - 9AM	4.88%	-1.95%	0.93%
		11AM - 1PM	7.97%	0.55%	3.68%
		3:30PM – 5:30PM	3.68%	-0.99%	0.99%
		7PM – 9PM	10.22%	1.90%	5.41%
	60 mins	7AM - 9AM	3.94%	-3.60%	-0.11%
		11AM - 1PM	5.73%	-1.82%	1.65%
		3:30PM – 5:30PM	3.41%	-2.70%	0.17%
		7PM – 9PM	8.65%	4.06%	6.21%
	75 mins	7AM - 9AM	1.43%	-3.23%	-1.02%
		11AM - 1PM	3.56%	-0.90%	1.22%
		3:30PM – 5:30PM	1.46%	-2.14%	-0.41%
		7PM – 9PM	4.12%	5.29%	4.72%
Grocery	30 mins	7AM - 9AM	6.71%	-1.15%	1.27%
		11AM - 1PM	24.64%	-1.60%	2.44%
		3:30PM – 5:30PM	4.98%	-1.11%	0.80%
		7PM – 9PM	16.84%	-1.63%	4.04%
	45 mins	7AM - 9AM	7.15%	-2.37%	1.28%
		11AM - 1PM	15.88%	-0.68%	3.67%
		3:30PM – 5:30PM	4.36%	-2.25%	0.31%
		7PM – 9PM	15.48%	1.04%	6.62%
	60 mins	7AM - 9AM	7.29%	-2.88%	1.69%
		11AM - 1PM	8.47%	-0.56%	4.04%
		3:30PM – 5:30PM	5.34%	-2.03%	1.33%
		7PM – 9PM	13.41%	4.16%	8.33%
	75 mins	7AM - 9AM	3.62%	-3.10%	0.08%
		11AM - 1PM	2.70%	0.08%	3.14%
		3:30PM – 5:30PM	2.57%	-2.43%	0.29%
		7PM – 9PM	6.94%	5.47%	6.18%
Finance	30 mins	7AM - 9AM	4.92%	-1.80%	0.65%
		11AM - 1PM	18.16%	-4.76%	2.74%
		3:30PM – 5:30PM	2.25%	-2.40%	-0.67%
		7PM – 9PM	13.17%	-0.92%	4.23%
	45 mins	7AM - 9AM	5.24%	-2.98%	0.45%
		11AM - 1PM	10.36%	-0.52%	3.49%
		3:30PM – 5:30PM	2.77%	-1.96%	0.03%
		7PM – 9PM	13.39%	1.44%	6.40%
	60 mins	7AM - 9AM	5.95%	-3.33%	0.91%
		11AM - 1PM	5.40%	-1.65%	2.49%
		3:30PM – 5:30PM	4.01%	-3.16%	0.17%
		7PM – 9PM	10.82%	5.00%	7.70%
	75 mins	7AM - 9AM	2.46%	-2.83%	-0.32%
		11AM - 1PM	1.69%	-0.64%	1.79%
		3:30PM – 5:30PM	2.04%	-2.09%	-0.11%
		7PM – 9PM	5.31%	5.78%	5.55%
Accomodation	30 mins	7AM - 9AM	8.86%	-2.18%	1.76%
		11AM - 1PM	13.97%	-1.98%	3.87%
		3:30PM – 5:30PM	10.22%	-1.01%	3.06%
		7PM – 9PM	17.07%	-1.05%	5.48%
	45 mins	7AM - 9AM	8.23%	-2.53%	1.88%
		11AM - 1PM	9.92%	-0.24%	3.94%
		3:30PM – 5:30PM	7.10%	-0.49%	2.68%
		7PM – 9PM	13.53%	2.14%	6.82%
	60 mins	7AM - 9AM	6.46%	-2.91%	1.60%
		11AM - 1PM	7.06%	-1.58%	2.45%
		3:30PM – 5:30PM	4.76%	-2.12%	1.48%
		7PM – 9PM	10.92%	4.34%	7.40%
	75 mins	7AM - 9AM	3.10%	-9.15%	-1.32%
		11AM - 1PM	5.50%	-1.56%	3.12%
		3:30PM – 5:30PM	3.32%	-5.38%	0.48%
		7PM – 9PM	4.58%	-5.96%	1.90%

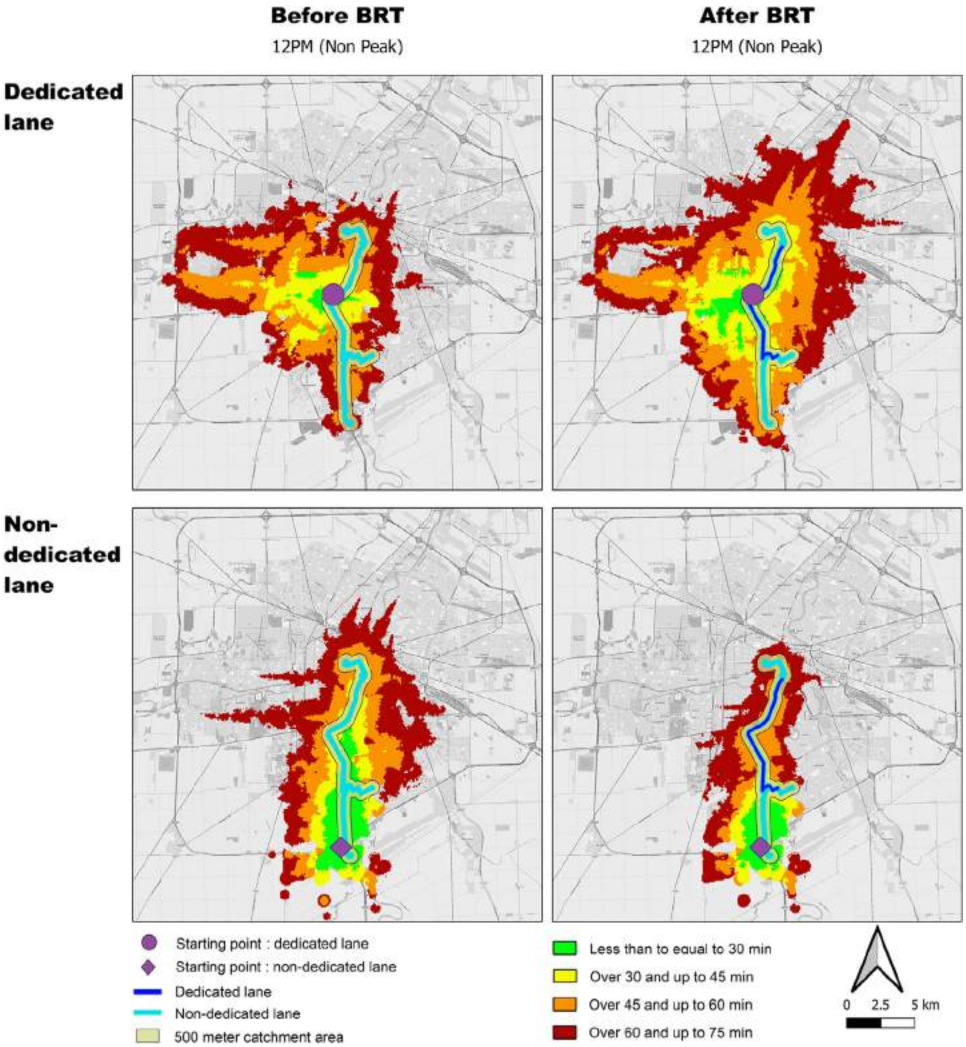

Fig. 4. Space-time accessibility maps at 12 PM (off-peak time).

Figures 6 and 7 visualize the accessibility analysis results for dedicated vs. non-dedicated lane sections with the 30-minute and 60-minute time budgets, respectively. In line with the previous section (Figures 3 and 4), the graphs of both time limits reveal a general increase in accessibility in the dedicated lane part but a drop in the non-dedicated lane sections, except for the 60 minutes time budget during the late evening hours, when there is a climb in accessibility in both dedicated and non-dedicated lane parts. These decreases can be related to adjusting the service schedules by decreasing some of the feeder routes frequency during the COVID-19 pandemic. However, the percentages of the rises in accessibility in the dedicated lane section are higher than the associated absolute percentages of decreases in the non-dedicated lane section.

While there is a rise in accessibility in the area near the dedicated lane during all time windows and across both time budgets, the highest increase is observed for accommodation services. In addition, the average percentage increase is higher within the 30-minute time budget (9.8%) than in 60 minutes (7.6%). Further, the results indicate that in both time budgets, the percentage increase in accessibility in the area near the dedicated lane is larger during mid-day and late evening off-peak hours, especially where it hits the highest percentage increase of approximately 25% for grocery and 18% for finance services within 30 minutes time budget during mid-day hours.

One thing to note is that the accessibility level of block centroids located near the non-dedicated lane is generally higher than those near the dedicated lane, regardless of the BRT implementation, departure time, and travel time budget. Further, the accessibility to health services is the highest while that of accommodations is the lowest. One possible explanation is the uneven spatial distribution of the essential services and their disproportionate concentrations near the non-dedicated lane section as shown in Fig. 2.

Overall, the findings are consistent with those reported in the previous section (Figures 3 and 4). The results of this study indicate that the implementation of the BLUE BRT along Southwest Transitway and other changes made to the transit network have considerably benefitted accessibility, particularly for trip origins within the 500-meter catchment area of the dedicated lane during the mid-day and late evening non-peak hours (11 AM - 1 PM and 7 - 9 PM).

5.3. Geographic patterns of accessibility benefits

Figures 8 and 9 visually demonstrate the average accessibility benefits across all time budgets for each dissemination block in the morning peak (7 - 9 AM) and mid-day off-peak (11 AM - 1 PM) period, respectively. Green points represent the centroids of the dissemination blocks where the average accessibility has increased while the red points demonstrate those centroids witnessing a decline in accessibility. Both Figures 8 and 9 reveal trends similar to those presented in the previous sections; the BLUE BRT construction and other changes made to the previous transit network, have substantially improved the accessibility of dissemination blocks within a 500-meter catchment area of the dedicated lane section. In contrast, the accessibility of block centroids in the vicinity of the non-dedicated lane parts, which are located in the north and south parts of the BRT corridor, has generally declined. Specifically, the number of red points along the non-dedicated lane sections is smaller during the 11 AM - 1 PM time window (Fig. 9) compared to the

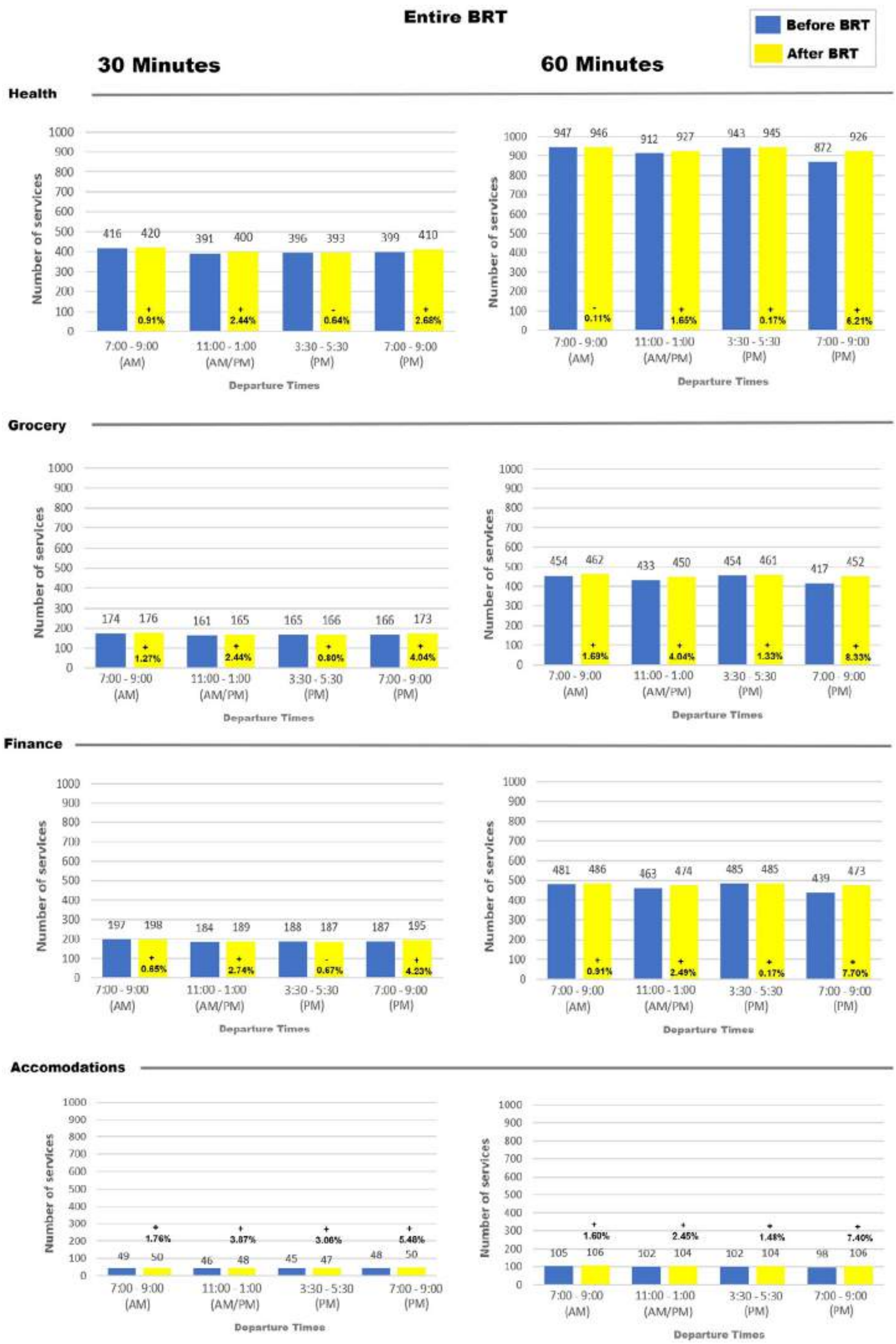

Fig. 5. Cumulative accessibility analysis for the entire corridor.

corresponding number during the morning rush hours (Fig. 8). This indicates that the majority of dissemination blocks near the non-dedicated lanes have seen a reduction in accessibility during morning peak hours. In the case of dissemination blocks near the dedicated lane, the number of darker green points is larger during the mid-day time window, indicating that the higher accessibility benefits are observed during this period.

6. Conclusion and discussion

In this study, we dealt with Winnipeggers' controversial remarks about the untimely release of the new BRT service by evaluating its impacts on accessibility during the COVID-19 pandemic. To this end, we investigated the accessibility benefits of Winnipeg's new BLUE BRT service and Southwest Transitway on four essential services, namely 1) health, 2) accommodation, 3) finance, and 4) grocery. To account for changes in public transit schedule and frequency, we considered four different time windows (morning peak, mid-day off-peak, early evening peak, and late evening off-peak hours) of a day as our departure times. Using Winnipeg's GTFS data, we calculated the multimodal space-time constrained cumulative access measures from the centroids of dissemination blocks located within a 500-meter catchment area of the BLUE BRT corridor before and after its implementation. This helped us to focus on presenting a fine-grained analysis of accessibility at the local level of the BRT corridor. Additionally, we explored the impacts of lane reservation on accessibility improvements by comparing changes in ac-

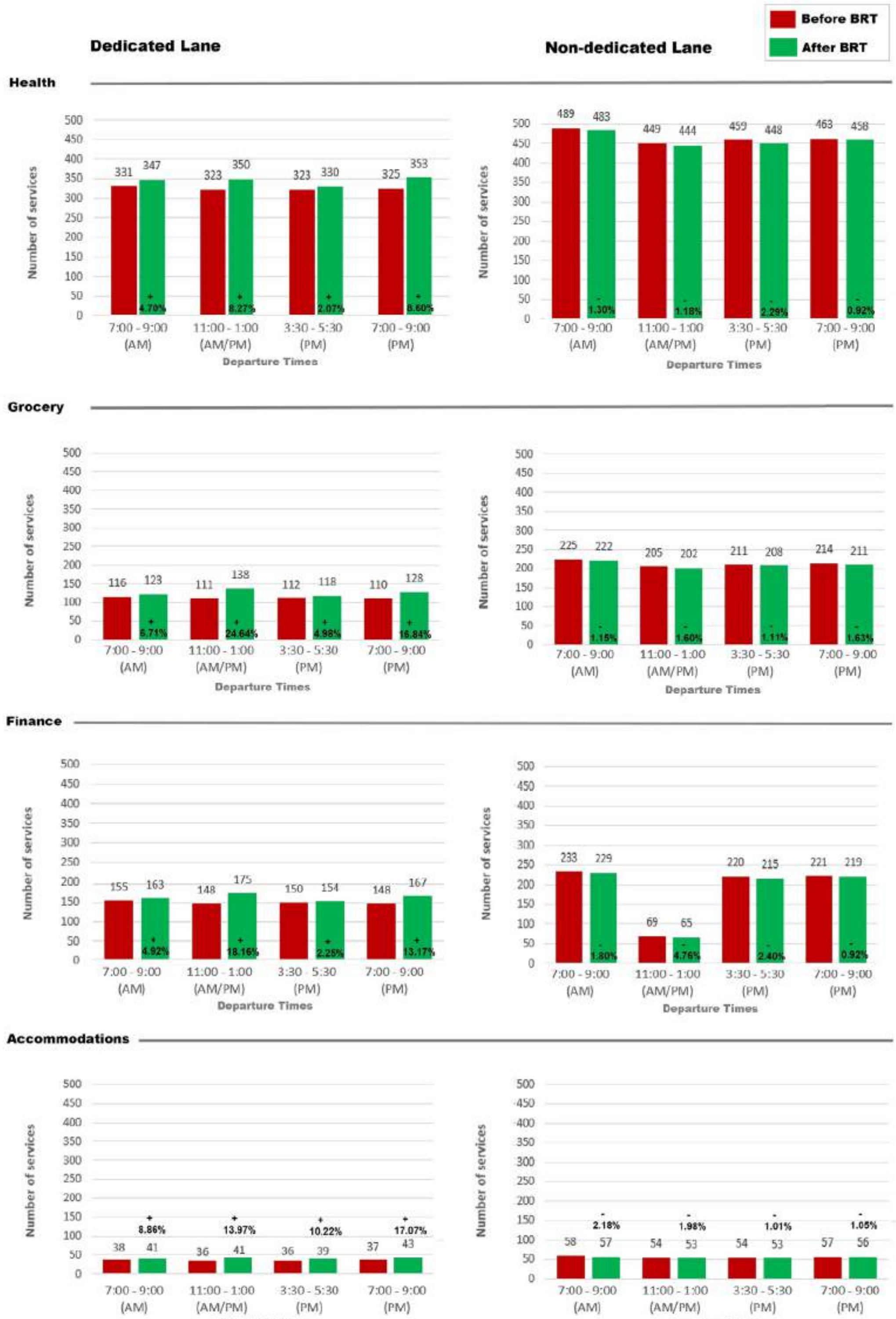

Fig. 6. Cumulative accessibility analysis for the dedicated vs. non-dedicated lane sections (30-minute time budget).

cessibility across different types of segments along the BLUE corridor: sections with- vs. without dedicated lanes.

The results of the accessibility assessment after the new BRT introduction revealed that while there was a growth in the area of accessible regions near the dedicated lane section, the counterpart near the non-dedicated lane part saw a decline. Similarly, the origin located within the dedicated lane section saw a rise in accessibility, whereas there was a marginal decrease for the origin near the non-dedicated lane section, indicating the significant impact of lane reservation on accessibility improvement. However, findings confirm that the BLUE BRT line resulted in an overall positive impact on accessibility to essential services, especially for trip origins near the dedicated lane during the mid-day and late evening off-peak hours (11 AM - 1 PM, 7 - 9 PM) within the 30-minute time budget. This accessibility improvement during late evening hours is imperative for low-income essential workers who have to do night shift work.

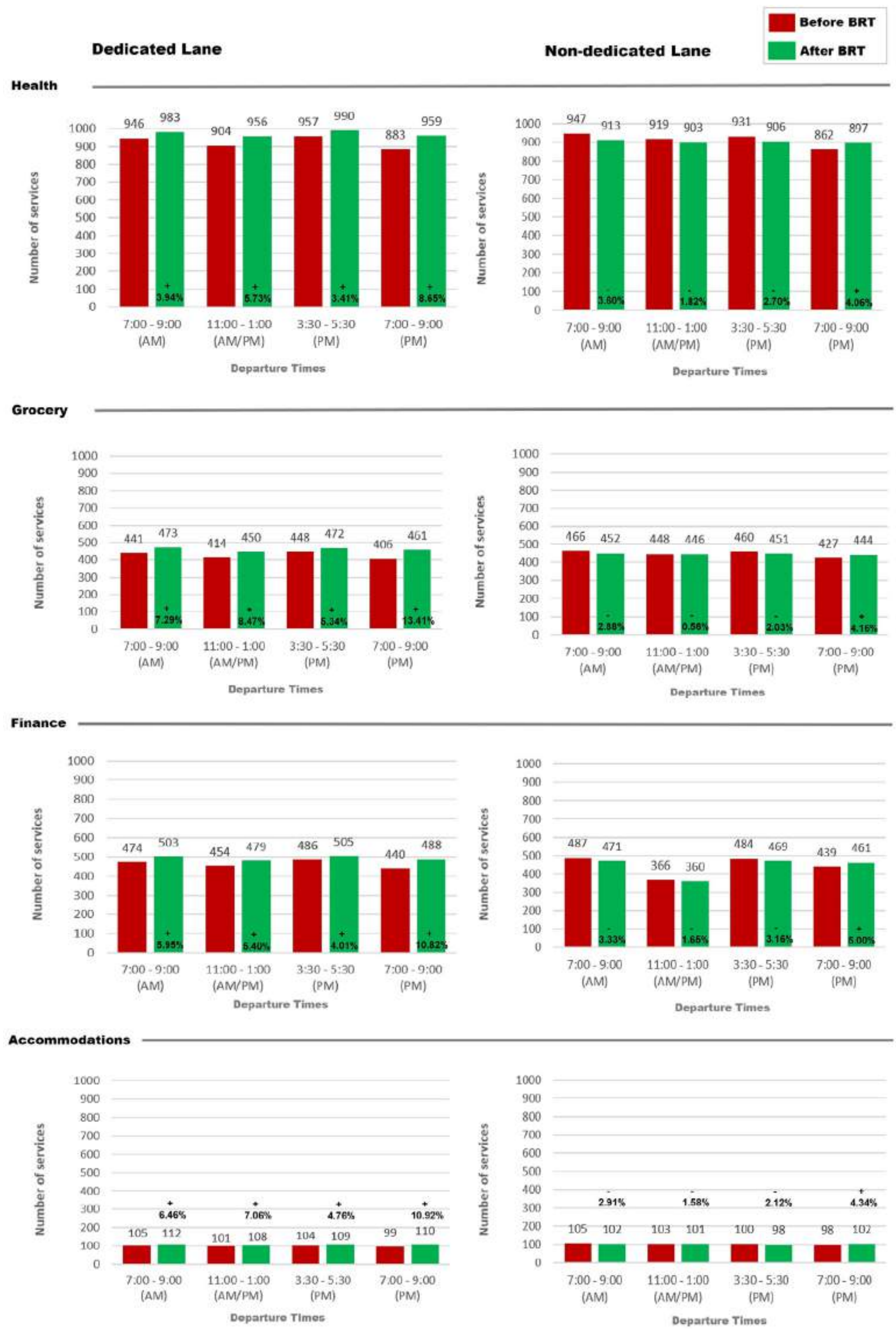

Fig. 7. Cumulative accessibility analysis for the dedicated vs. non-dedicated lane sections (60-minute time budget).

This research offers implications to transport planners and policymakers for enhancing accessibility to essential services. To our knowledge, this is the first study examining the accessibility benefits of the new BRT service that was introduced during the pandemic. Considering the unintended outcome of the BLUE implementation on the accessibility of origins near the non-dedicated lane sections, our research further demonstrates an opportunity for improving service quality at these areas by extending the dedicated lane in the new BRT transitway. This will help the residents of these areas to have better accessibility to a bigger number of essential services near the northern end of the corridor. In addition, the results of this research suggest that transport planners consider taking alternative steps such as increasing service frequency or constructing new feeder routes near the non-dedicated lane section to increase accessibility for origins within this section.

This study has some limitations that should be addressed in future research. First, we only examined the accessibility to four essential ser-

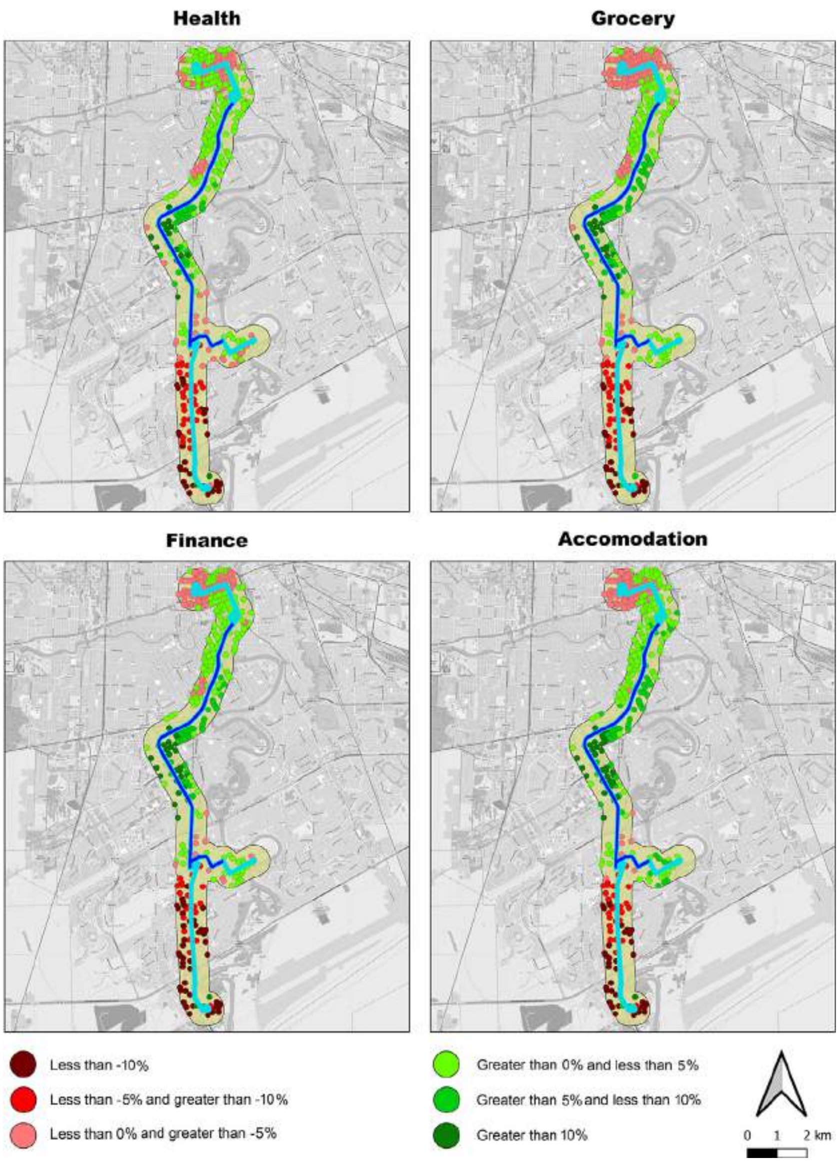

Fig. 8. Geospatial representation of changes in accessibility to each essential service during the morning peak (7 – 9 AM).

vices from origins within a 500-meter catchment area of the BLUE corridor. Future studies can include a wider list of essential services and experiment with different catchment area settings. A possible option is gradually increasing the size of the catchment area to capture the distance decay effects on the new BRT's accessibility benefits. Also, to conduct a more comprehensive assessment and to demonstrate accessibility variations across different days of week and times of a day, future studies should consider measuring accessibility on weekends or late night times. Uncertainties in travel times should be taken into account in future research as well (Chen et al., 2013, 2019). The current study used static GTFS data and assumed all public transit services operate perfectly on time, which is not the case in the real world. In the face of travel time uncertainty, people can also take heterogenous risk-management strategies such as choosing routes not only based on travel time but also considering reliability (Lee and Miller, 2020). Using real-time GTFS data or Automatic Vehicle Location (AVL) data reflecting delays and addressing travelers' behaviours under travel time uncertainty would facilitate a more robust evaluation of the impacts of new public transit services on people's accessibility in space and time (Zhang et al., 2018; Liu and Miller, 2020). Regarding the methodology, we used simple isochrones (can be interpreted as potential path areas (PPAs) in time geography (Miller, 2005) to represent people's potential mobility areas via public transit and walking within a limited time budget and evaluate the new BRT's accessibility benefits. Future studies can employ advanced time geographic measures such as potential multimodal network areas defined within a multimodal network (including a wide range of first/last-mile options) rather than a planar space or a network corresponding to a single transport mode (e.g., automobile) for a more realistic assessment of the new BRT's accessibility impacts. Lastly, due to the lack of the exact residential location information, we considered the centroids of dissemination blocks as a proxy, which could lead to an overestimation or underestimation of accessibility measures.

A viable next step of this research is to assess the impacts of transit service-cut on accessibility to essential services and ridership during the pandemic. In addition, unlike this study that examined the potential mobility (i.e., accessibility) benefits of the new BRT, future studies could attempt to explore the impacts of the BRT on realized mobility patterns (e.g., travel behaviours, transit ridership) within urban areas. In terms of accessibility equity, which is the primary concern among transport planners, future research can examine the difference between community-level vs. individual-level accessibility within a dissemination block or neighbourhood before and after the system change. This can be calculated using an average space-time prism that summarizes individuals' accessibility experiences within the selected area (Lee and

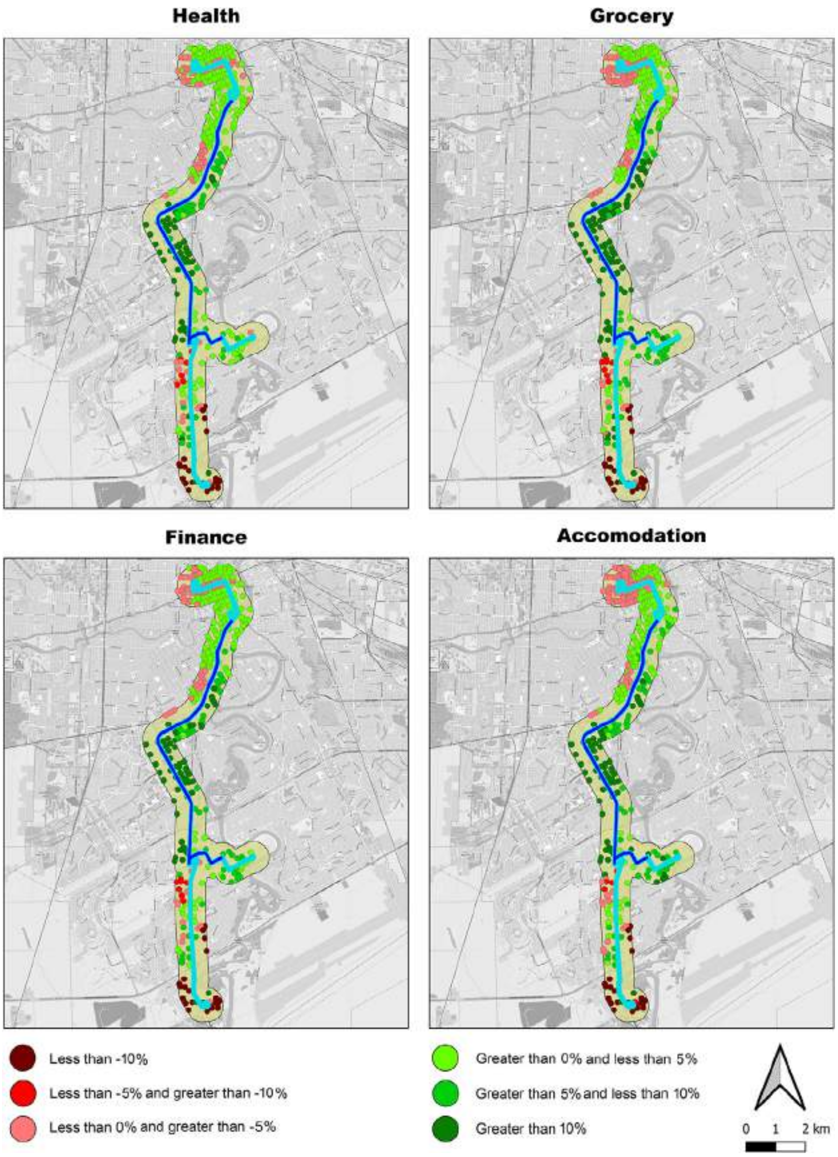

Fig. 9. Geospatial representation of changes in accessibility to each essential service during the mid-day off-peak (11 AM – 1 PM).

Miller, 2019). Furthermore, using socio-economic data and the Palma ratio, which is a measure of inequity in transit-based accessibility, future studies can assess the impact of new BRT service on the equity in access to essential services across space, income, race, and occupation (Liu, Kwan and Kan, 2021). Lastly, future studies can employ ridership and on-time performance data to evaluate the effectiveness of the new BRT service after the pandemic.

Declaration of Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Evaluation framework for an efficient commuting carpool program

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ABSTRACT

Hundreds of cities have already pledged to get to "net zero" by 2050. MaaS (Mobility as a Service) is a one of promising measures but commuting carpool program seems to be effective for concentrated commuting to factories in suburban areas where public transportation is insufficient. The commuting carpool is easy to understand as a service, but there are considered many parameters for designing it. Especially companies in Japan have a big role to implement its service because collaborations with public and private sectors are not sufficient viewpoint of carpooling infrastructures and financial supports. In this study, we propose an evaluation framework for companies with two phases: Basic design to make a decision for implementation through the feasibility studies, and Detailed design and Improvement to consider detailed implementation.

We focus on practical evaluation framework for Basic design and conduct a case study on commuting to a newly constructed factory. We apply it to extract parameters which are necessary for the feasibility study. As for the effect of the introduction of the program, its service is able to reduce the number of vehicles by 30-66% and CO2 emissions by 373-800 tons per year.

1. Introduction

At the 26th UN Climate Change conference (COP26) in 2021, governments will outline steps they each need to take to limit global warming. Hundreds of cities have already pledged to get to "net zero" – removing as much CO2 as they produce – by 2050. NET ZERO TRACKER (2021) describes 136 countries declare a net zero target as of end of 2021.According to the International Energy Agency (2021), if Carbon Neutrality (CN) is achieved in 2070, the contribution to CO2 reduction from improved energy efficiency is expected to be about 15%. Therefore we are expected to take several measures as transport sectors' contributions. The effect of traffic congestion on commuting time has been a serious issue for many years. Many countries have proposed and implemented innovative schemes to solve this problem. In order to achieve energy efficiency in the transportation sector, it is expected to carry as many people as possible when traveling. MaaS(Mobility as a Service) seems to be a one of promising measures for CN. MaaS alliance (2022) describes "MaaS integrates various forms of transport services into a single mobility service accessible on demand. MaaS aims to provide an alternative to using the private car that may be as convenient, more sustainable, help reduce congestion and constraints in transport capacity and be even cheaper". Several MaaS apps like Whim and Moovit have already offered added value by using a single application to provide access to mobility with a single payment channel instead of multiple ticketing and payment operations based on public transportations.

Recently, the mobility budget as a kind of MaaS has included not only public transportation but also car leasing program. In Europe, the mobility budget is a monthly stipend for employees to cover their travel costs and a promising new tool in remuneration and transport policy, especially because of its potential to decrease the company car fleet and lower car use Zijlstra et al.(2019)explained that the objective of the mobility budget is to shift employee preference to other modes of transport or make them combine other models of transport with an inexpensive car. If implemented appropriately, the mobility budget would lead to a reduction in the number of cars, which would lead to an increase in multimodal transport. ReachNow, which was launched by the subsidiary of German car manufactures, proposes Mobility Budget as a service for enterprises and describes, "Whether you are commuting to work or getting around in your free time, there is now a mobility service for every requirement. Instead of a company car, all employees have access to an entire car-sharing fleet. Public transport and rental bicycles complete the "fleet" of a modern company."

In urban areas with extensive public transportation systems, the new option of mobility as a service (MaaS)/mobility budget can support the shift from overuse of private cars and realize the reduction of road con-

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gestion and commuting time. However, in areas where public transportation is not extensive, there are insufficient mobility service options in comparison to urban areas. Therefore, commuting in suburbs and rural areas continues to be highly dependent on private vehicles.

The novel Coronavirus disease of 2019 (COVID-19) pandemic has led to an increase in telecommuting and staggered work hours to avoid congestion Van Wee et al.(2021.) hypothesize that commuting levels of large parts of the population, especially those with office work, and business travel will decrease due to COVID-19.As one of the reasons, they point out that many people might have become more experienced for onsite activities such as e-working. However, it is difficult to implement these measures in production plants located in the suburbs because these plants work on a fixed schedule that renders the working hours inflexible and it is impossible for factory employees to implement telecommuting with the current technology. We believe that implementing a measure for preventing significant traffic jam in commuting time to factories in an area, where there is less public transportation, enables us to reduce amount of CO2 as a major contribution in even COVID-19.

In this study, we focus on designing a carpool program to alleviate road congestion caused by many private cars. There are several types of useful carpooling app like Waze and Scoop but if we depend on commuters' voluntary participation, we won't be able to achieve reduction target for CN. In order to research practically, we focus on carpooling program for commuting to factories in suburbs. As a special feature, companies in Japan always offer all commuting fee for all transportation modes included owner's car. There are few merits for voluntarily participating its program to commuters by own car. Especially companies in Japan have a big role in order to achieve CO2 reduction target for CN. Therefore the evaluation framework is essential for companies considering implementing it voluntarily.

When a company is considering a commuting carpool for the first time, it is difficult to make a decision for implementing it. Because carpooling is easy to understand as a service, but there are many parameters that companies have to consider for designing it. On the viewpoint of service, we need to clarify how large scale we should prepare for its service in order to achieve the target number of car and CO2 reduction. On the viewpoint of users' psychological conditions, we need to consider individual differences like relationship with users.

In this study, in order to reduce the complexity, we propose an evaluation framework with two phases: "Basic design" to make a decision for implementation, and "Detailed design and Improvement" to consider detailed implementation and then proceed with post-operation improvement. Basic design is the phase that focuses on the feasibility study of whether or not to implement the service. Detailed design and improvement is the phase for detailed design with many specific parameter values for implementation and for improvement after operation. In addition, the proposed framework is characterized by its orientation toward a practical framework that can be used not only for planning services but also for implementing improvements after operation. Furthermore, we conduct a case study using the proposed framework for Basic Design to verify whether companies can extract the information they need before implementing a carpool scheme.

2. Related work

Carpool services have a long history in the US. Chan and Shaheen(2012) described it as technology-enabled ridesharing, starting in World War II and continuing as Phase 5 since 2004. Recent services are smartphone-based and are characterized by matching technologies. However, carpool services have not garnered the interest expected of them Shaheen et al (2018). describe carpooling is the second most common travel mode to work in the united states after driving alone. However, total percentages have declined in recent decades. More policy support is needed to reverse this trend. They also describe providing tools that make it easier for employees to find a match as one of support by employers. In North America and Europe, in order to promote the carpool program, public and private sectors are working together to provide carpooling infrastructure such as dedicated lanes and stops for carpool. Ministry of Land, Infrastructure, Transport and Tourism (MILT) Japan (2019) promotes eco-commuting, the practice of switching from private cars to public transportation and other eco-friendly means of commuting. Companies promoting it can get public certification and use it as a brand asset. MILT expects that it encourages local governments and companies to voluntarily implement measures like carpool. However, the current situation in Japan is that collaboration with public and private sectors is not sufficient viewpoint of carpooling infrastructure and financial support. Complicating matters is the fact that in Japan, carpooling is not allowed for earning money, but only to share the costs associated with it, and additionally as mentioned in Section 1, Japanese companies usually offer commuting costs to workers.

Therefore, companies have a major role to play in promoting commuting carpools in Japan.

To make carpooling a popular service like other mobility services, it is necessary to solve diverse technical and psychological issues. Various studies have been conducted to address these issues. In terms of technology, there have been many studies on agent-based simulations. In particular, researchers (Galland et al. 2013; Hussain et al. 2015, 2017) have studied interactions taking into account between agents in recent years.

Mourad et al.(2019)performed a review on researched models and algorithms for the optimization of shared mobility services. In carpooling program studies, there are three objective functions: minimum travel distance, travel time, and maximum number of participants, and four constraints: routing constraints, time, capacity, and synchronization constraints. Many studies (Viegas and Manuel , 2008; Agatz et al. 2011;Knapen et al. 2012) have been conducted on optimization.

Olsson et al. (2019) analyzed carpooling studies conducted worldwide from 2014 to 2018, and concluded that psychological factors are becoming important. One of the key issues is the different level of tolerance for allowing others to ride in a space that is usually reserved to one's self during commuting Bulteau et al. (2021). found that one of finding is the importance of carpooling with a colleague, exhibiting the key role of trust. Women are more willing to carpool as a driver when there is this psychological incentive in Paris region. In a study in Germany, König et al.(2018) found that the results underline the importance of the attribute walking distance to pick-up point for the elderly. Xia et al. (2019) considered the matching model with both social obstruction (lack of trust) and route networks.

Thus, there have been various studies on commuting carpools. However, Thomas et al. (2012) describes commuting research tends to focus on individual commuters and their place of residence, rather than on workplaces and company-induced measures. Additionally, to the best of our knowledge, there is no practical evaluation framework that can clarify the conditions necessary to achieve the goal from the viewpoint of an implementing company.

3. Evaluation framework

3.1. Overview of evaluation framework

Table 1 shows overview of evaluation framework. In Basic design, a feasibility study is conducted. The company wants to identify the basic numbers needed to the service scale and operation toward the target goals that it has. There are five parameters that should be clarified in the basic design. The first is to determine the number of employees that need to show interest in the program and become participants. Second, the number of seats on a vehicle for a carpool needs to be set. It is easy to understand that if the number of participants is large, the amount of vehicle reduction by this program will be large. However, if the number of seats exceeds the expectation of the participants, they would lose interest in the program, and as a result drive their own personal cars. The

Table 1
Overview of evaluation framework

	Basic design	Detailed design and Improvement
Overview	Ø Feasibility study for making decision whether a company implements its service	Ø Detailed design considering concrete value Ø Considering improvement measures Ø Taking their measures for improvement
What companies want to clarify	Ø How large scale a company should prepare for its service Ø What basic design is for its service operation	Ø Practical several parameters for service implementation and improvement
Considered parameters in design	Ø How many participants are needed to gather Ø How many seats in a car should be set Ø How ratio carpool-driver should be set Ø What acceptable time should be set Ø How large effects are ideally expected	Ø Concrete number for target achievement Ø Geospatial features Ø Individual users' features

third is to set an appropriate ratio of carpool-driver (CD) and carpool-passenger (CP). If all participants wanted to have a CD, there would be no CPs. As a result, they will not contribute to the goal of vehicle reduction, even though they are participating in the program. The forth is to set acceptable time by user that is difference between the desired time to destination directly and changing time for detour. Goff et al. (2022) finds that current solo drivers are more likely to switch to carpooling as a driver rather than as a passenger in Lyon's urban area. Thus, we have to consider CD/CP ratio to achieve better results. Finally, a company needs to determine the number of vehicles that can ideally be reduced by implementing this program. By establishing the gap between the ideal and estimated amount of vehicle reduction, it would be possible to determine areas of improvement before launching the program.

In Detailed design and Improvement, the company conducts service design considering concrete demands, service features and users' psychological conditions. After launching its service based on detailed design, it considers improvement measures by understanding the gap between ideal values calculated in Basic design and observed data and then takes their measures for its service improvement. In order to implement and improve the service, it is necessary to clarify the parameters, and it is desirable to examine them from three major perspectives: concrete number for target achievement, geospatial features, and individual users' features. For the concrete number for target, we will need to verify the concrete number for target based on the five parameters (participants, seats, carpool-driver ratio, acceptable time and effect size) considered in the basic design. For geospatial features, we need to set up pick-up/drop-off points based on concrete demand and actual configurability based on the specific addresses of individual participants. For individual users' features, it depends on the extent to which each service should be supported, but deeper consideration is needed. For example, if we want to match only the same sex to avoid danger with the opposite sex, we need to verify that the relationship with users is incorporated into the matching algorithm. If the CP is not ensuring round trip per day, it will be difficult to start using it, and it will be necessary to verify that the actual use is low. Also, during improvement, if we want to increase the use of the system, we need to verify the effectiveness of giving incentives such as providing priority parking to participants.

In this paper, we focus on evaluation framework for basic design.

3.2. Overview of evaluation framework for basic design

The proposed framework for basic design has two major functions: the first function is to perform an evaluation without considering spatial–temporal matching, which allows us to calculate the ideal vehicle reduction rate and other factors, and reduce the number of simulation cases. The second function is to simulate the carpool scheme taking into account the spatiotemporal matching techniques and other characteristics of each service provided. It is possible to determine the gap between the ideal value and the value achieved in the simulation. This gap enables us to determine the measures that should be taken to improve our program.

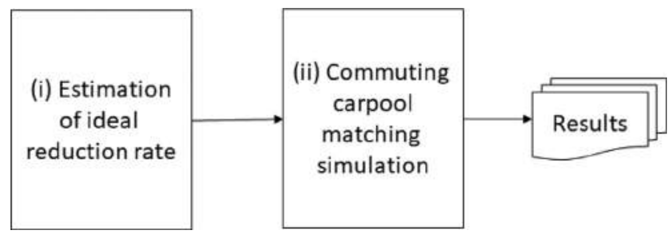


Fig. 1. Evaluation framework

First, we set a target value, such as the number of commuter vehicles that a company should reduce. Second, to achieve that target value, we estimate the ideal number of employees a company should motivate to participate. Finally, we conducted a simulation to match the participant drivers with the participant passengers based on geographic and time constraints in the carpool and estimate the effect.

Fig. 1 illustrates the proposed evaluation framework for basic design. In (i) estimation of the ideal reduction rate, we first determine the number of employees who demand to use their own cars for commuting (N_d). To achieve the target vehicle reduction rate (R_t), we estimate the ideal vehicle reduction rate (R_i) using the number of participants (N_p), the CD rate (r_{cd}), and the number of carpool seats (N_s), which indicates the maximum number of carpool seats per vehicle. R_i is defined as the ideal vehicle reduction rate; this rate is ideal or the maximum rate possible because it is estimated without considering constraints such as spatiotemporal matching and user preferences. By estimating R_i without considering spatiotemporal matching and other factors, we can determine the number of participants we need to encourage and the range of N_s , r_{cd} we need to set in order to achieve R_t. In addition, determining the range of parameters enables the reduction of the simulation case number in (ii) commuting carpool matching simulation.

We conduct (ii) commuting carpool matching simulation using the range of parameters set to estimate the ideal reduction rate. Vehicle reduction rate (R_r) calculated by the matching simulation is lower than R_i because it considers spatiotemporal matching. Based on the results of the various simulations, we can determine the number of participants we need to plan for, which areas we need to increase the number of participants in, and so on. It is also possible to estimate the amount of CO_2 reduction, SOV reduction, and gasoline consumption reduction using this program.

Section 3.3 introduces the method to estimate the ideal reduction rate Section 3.4. introduces the commuting carpool matching simulation adopted in this study. As described in Section 2, various studies have been conducted on efficient matching methods. In this study, we utilize a suitable simulator for each commuting carpool service in the commuting carpool matching simulation function.

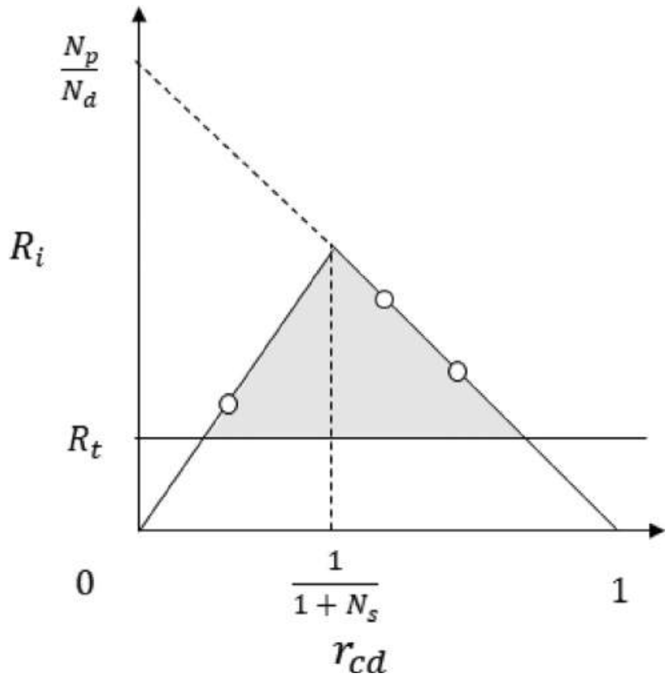


Fig. 2. Relationship between equation (1) and (2) and R_t

3.3. Estimation of ideal reduction rate

In this section, we estimate R_i without considering spatiotemporal matching, user preferences, and other constraints. To reduce the number of commuter vehicles, it is desirable to have a large number of participants. However, if the number of participants is large and they are all CDs, there is no matching and no reduction in the number of vehicles. Therefore, it is necessary to set an appropriate balance between CDs and CPs and match them efficiently. Additionally, N_s is an important value to achieve vehicle reduction because the number of reductions depends on it Equations (1). and (2) show the relationship between R_i and r_{cd} Fig. 2. also shows the relationship between Equations (1) and (2) and R_t. We estimate R_i cases in the gray area; the three surrounding lines represent simulation cases for commuting carpool-matching simulations. The dots in Fig. 2 are examples of the simulation cases.

$$R_i = \frac{N_p N_s}{N_d} r_{cd}, \qquad r_{cd} \le \frac{1}{1+N_s} \tag{1}$$

$$R_i = \frac{N_p}{N_d}(1 - r_{cd}), \qquad r_{cd} \ge \frac{1}{1+N_s} \tag{2}$$

3.4. Commuting carpool matching simulation

Using estimated simulation cases, we conduct a commuting carpool matching simulation considering spatiotemporal matching, user preferences, and other constraints, and extract the cases $R_r \ge R_t$ as candidate measures.

In this study, we assume that all employees commute to work in their personal cars. This program is a carpool-matching service for CDs and CPs. CDs are participants who declare that they are willing to cooperate in letting other commuters ride in their private cars. CPs are participants who declare that they are willing to ride with other employees in their private cars to work. This carpool-matching service matches CDs and CPs by considering the ODs, time, and desired meeting points of the CDs and CPs. The meeting points are the places where CDs can pick up CPs and drop them off. With a large number of cars moving around, it would not make sense to cause further traffic congestion by allowing pick-up and drop-off on any street for this program. Therefore, the service predefines meeting points in advance. Assuming practical usage, participants also expect the service to match people with high ride evaluation ratings, the number of passengers considering the COVID-19 situation, and other CD and CP psychological wishes. In this study, we first simulated a program considering only spatiotemporal matching. Because the objective is to reduce the number of commuter vehicles, the service accepts and processes reservation requests in batches (e.g., closing reservation the night before). For efficient matching, we use the time-window method, which many existing studies have adopted, and set a desired time difference which is acceptable to each CD and CP (T_{dif}) . T_{dif} indicates the acceptable time for each CD and CP beyond the minimum time to reach to their destination.

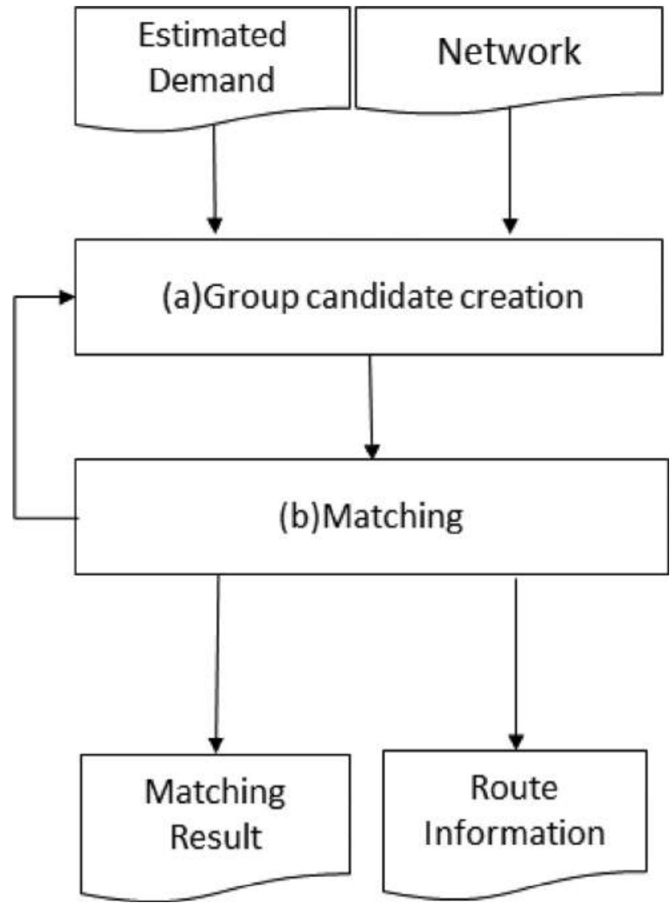


Fig. 3. Overview of commuting carpool matching simulation

Fig. 3 shows the overview of the commuting carpool matching simulation in this study.

As demand information, the desired start/end time, T_{dif}, the home, work place, and desired start/end time of each CD and CP are prepared. In addition, CDs register points where they can drop in, and CPs register places where they want to be picked-up/dropped-off within predefined meeting points. As this program targets suburban factories, more than several thousand people will participate in this program. Thus, the simulation must finish executing such huge cases in a realistic time. We adopted a method of dividing the participants into several groups and proceeding with the matching calculation. If several CDs and CPs are not successfully matched, the adopted matching simulation method regroups only the unmatched participants and matches them repeatedly. Subsequently, unmatched CDs and CPs commute by their personal vehicle. We prepared several patterns of estimated demand and analyzed and evaluated the simulation results based on various indices.

Fig. 4 shows an overview of group candidate creation, which divides participants into several groups. First, the (a-1) grouping function forms

Table 2
Constant value overview of group candidate creation

Symbol	Description
K	Total number of CD
$Capa_j$	Number of seat in CD's car which operates space-time route j
W_{ij}^x	Penalty for deviation from CPi's desired time when space-time route$j$ is operated
W_j^y	Penalty for deviation from CD's minimum commute time when space-time route$j$ is operated
W_i^z	Penalty when CPi does not use any space-time routes
$m_{tj} \in \{0,1\}$	If space-time route j is operated in t, this value is 1. $(t \in U, j \in T_i)$
$x_{ij} \in \{0,1\}$	If space-time route j is used by CPi, this value is 1. $(i \in S, j \in T_i)$
$y_j \in \{0,1\}$	If space-time route j is operated, this value is 1. $(j \in T)$
$0 \le z_i \le 1$	If any space-time routes are not used by CPi, this value is 1.

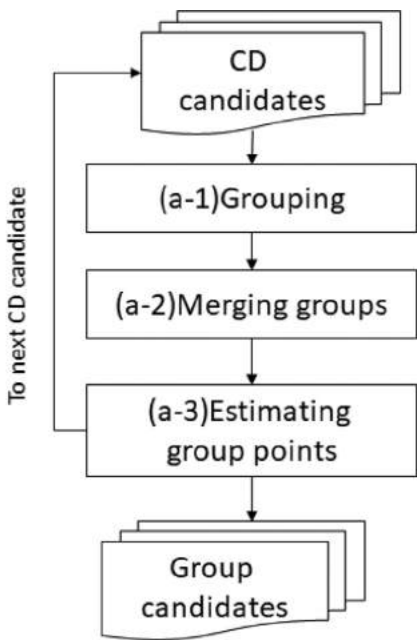


Fig. 4. Overview of group candidate creation

a group by matching the location where a CD can stop and the CPs want to be picked-up/dropped-off. This confirms that a CD can take a detour to carpool with CPs one by one within the CD's T_{dif} and then registers the CP as a group member. As a result, one CD belongs to one group, and one CP can belong to several groups. Second, the (a-2) merging groups function makes groups having common CPs, who belong to two or more groups, to combine them. The reason for merging the groups separated once is that it is more efficient to process them when they are a large group. We select a method that balances estimation time and optimization. Third, the (a-3) estimating group point function estimates give priority to processing. Group points show the number of groups in which all CPs belong. Subsequently, it continues to execute grouping for the next CD candidate as long as there are CD candidates available. As a result, each group candidate would have had one or several CDs.

(b) The matching function creates a route diagram in order of decreasing group points for each group candidate formed. A group with high group points has the possibility of efficient matching because several CDs and CPs have the same meeting points in a group. Therefore, the method begins with matching from a group with less group points, which has a low possibility of efficient matching.

It uses the spatiotemporal routes and start times taken by each CD on their commute to work to match the CDs and CPs included in a group. Our method to determine the specific matching uses linear programming, as shown in equations (3)–(7) Table 2. shows the constant value and the decision variable. Equation (3) aims to minimize three penalties. The first is a penalty for deviation from a CP$_i$'s desired time when the space–time route$_j$ is operated. The second is a penalty for deviation from a CD's minimum commute time when the space–time route$_j$ is operated. The third is a penalty if CP_i does not use any space–time routes by unmatching. We set the third penalty's weight factor to be much larger than the other two. With the aforementioned penalty settings, the first priority is to maximize the number of matches for CPs; the next priority is to satisfy the wishes of CDs and CPs as much as possible. As described in Section 1, companies in Japan always offer all commuting fee for all transportation modes included own car. Because of it, we think travel costs are not dominant for choice of carpooling. In this study, thus, we don't consider travel costs.

Table 3
Simulation conditions by each parameter

Parameter	Conditions
N_d	2500
N_p	1000, 1500, 2000, 2500
N_s	1, 2, 3
r_{cd}	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9

$$\text{minimize\&\&} \sum_{i \in S} \sum_{j \in T_i} W_{ij}^x x_{ij} + \sum_{j \in T} W_j^y y_j + \sum_{i \in S} W_i^z z_i \quad (3)$$

$$\text{subject to} \sum_{j \in T_i} x_{ij} + z_i = 1 \ (\forall i) \quad (4)$$

$$\sum_{i \in S} x_{ij} \le Capa_j \times y_j \ (\forall j) \quad (5)$$

$$\sum_{j \in T} \left(m_{tj} \times y_j\right) \le K \ (\forall t) \quad (6)$$

$$\sum_{j \in T_k} y_j \le 1 \ (\forall k) \quad (7)$$

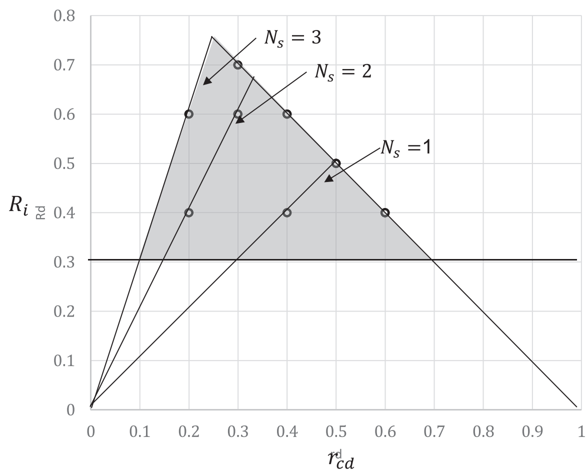
4. Case study

Using the proposed evaluation framework, we conducted a case study on a newly constructed factory. In this case study, it was assumed that the goal is to reduce the number of commuter vehicles by 30% of the total number. We aimed to identify the necessary conditions. As the newly constructed plant will employ approximately 2,500 people, assuming that all employees commute by private car, the program should reduce the number of commuting vehicles by approximately 750.

T_{dif}, which is the desired time difference acceptable to each CD and CP, was set to 10, 20, and 30 min. T_{dif} is assumed to have the same value for all participants in each simulation case. We verify whether we provide the information that a company wants to know before introducing this program.

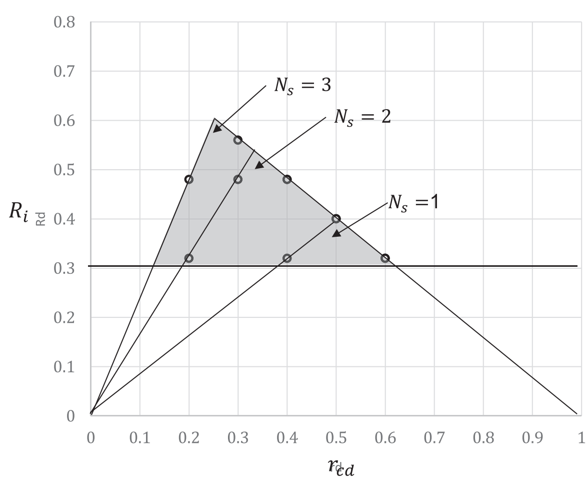
4.1. Estimation of ideal reduction rate

To estimate the ideal reduction rate, Table 3 lists the choices for each parameter. A total of 108 cases were used as combinations. We



Np = 2500		r_{cd}								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
R_i	$N_s = 3$	0.3	0.6	0.7	0.6	0.5	0.4	0.3	0.2	0.1
	$N_s = 2$	0.2	0.4	0.6	0.6	0.5	0.4	0.3	0.2	0.1
	$N_s = 1$	0.1	0.2	0.3	0.4	0.5	0.4	0.3	0.2	0.1

Fig. 5. Estimation of $\boldsymbol{R_i}$ ($\boldsymbol{N_p}$ = 2500)



Np = 2000		r_{cd}								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
R_i	$N_s = 3$	0.24	0.48	0.56	0.48	0.4	0.32	0.24	0.16	0.08
	$N_s = 2$	0.16	0.32	0.48	0.48	0.4	0.32	0.24	0.16	0.08
	$N_s = 1$	0.08	0.16	0.24	0.32	0.4	0.32	0.24	0.16	0.08

Fig. 6. Estimation of $\boldsymbol{R_i}$ ($\boldsymbol{N_p}$ = 2000)

extract the cases that are in the region bounded by equations (1) and (2) and $R_i > 0.3$. It is clear that R_r, as the space–time simulation result, is smaller than R_i in the target case. Therefore, $R_i = 0.3$ is excluded from the simulation. For $N_p = 2500$, Fig. 5 shows the estimation results of R_i for different values of N_s and r_{cd}. As shown in Equation (1), the slope changes depending on the value of N_s. The gray area shows the cases where R_i is estimated using equations (1) , (2); $R_i > 0.3$. The simulation results showed that 13 cases were the next matching simulation cases. The same estimation was performed for N_p= 2000, 1500, and 1000. For $N_p = 2000$, Fig. 6 shows that 13 cases were extracted. For $N_p = 1500$, Fig. 7 shows that 5 cases were extracted, and for $N_p = 1000$, Fig. 8 shows no case exceeded R >0.3. Finally, a total of 31 cases were extracted

4.2. Simulation setting

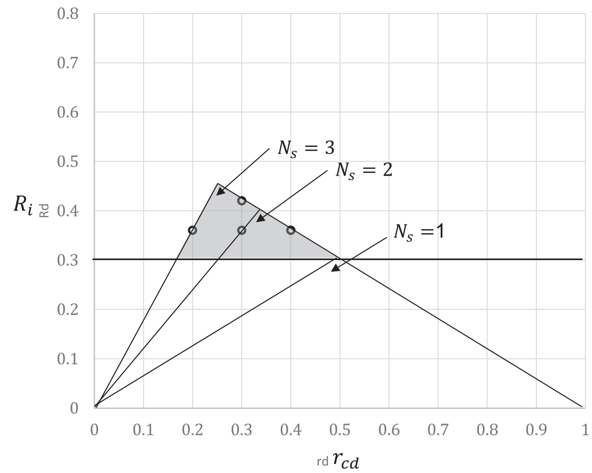
We conducted a matching simulation for 93 cases considering T_{dif}= 10, 20, and 30, respectively, at N_p= 2500, 2000, and 1500. Unless extracting considering R_i, we would have 324 simulation cases for N_p= 2500, 2000, 1500, and 1000. Therefore, we confirmed a 70% simulation case reduction by our proposed method. CD and CP demand is generated from meeting points, and the CDs commute to five parking lots at the new factory in the morning. The new factory is located an hour's drive away from each worker's home. If workers commutes only by public transportations, they will spend a considerable amount of time Fig. 9. shows the simulation network and the amount of generation demand.

4.3. Simulation result

Based on the estimated ideal reduction rate, we analyze the simulation results from the viewpoint of driver rate, seat number for carpooling, and the desired time difference for each CD and CP.

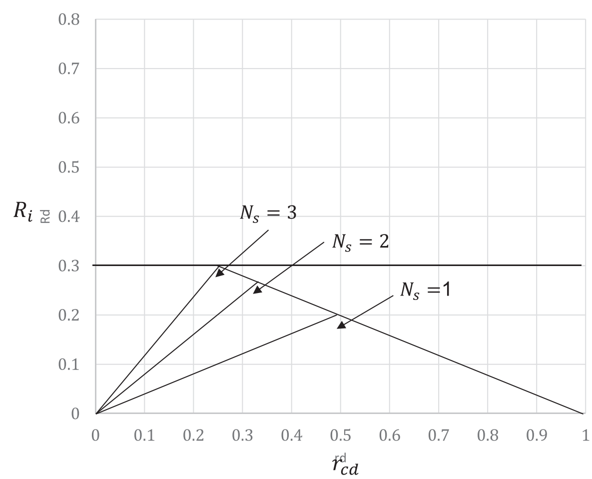
Fig. 10 shows the results for 1,500 participants. Setting $r_{cd} = 0.2$, R_r does not exceed 0.3. 9 cases of $r_{cd} = 0.3,\ 0.4$ are found to exceed all cases of T_{dif}=10, which did not exceed the target value at $r_{cd} = 0.3$, 0.4. We found that $r_{cd} = 0.3,\ 0.4$ and $T_{dif} = 20$ and 30 are desirable. The maximum value of R_r value was 0.38.

Fig. 11 shows the results for the case of the 2000 participants. 34 cases with $r_d = 0.2,\ 0.3,\ 0.4,\ 0.5,\ 0.6$ exceeded the target value. In the case of $N_s = 1$, some of the values exceed the target value at $r_d = 0.4,\ 0.6$; however, we know that we should aim for $r_{cd} = 0.5$ because it is just below the target value. In the case of $N_s = 2$, the target value may not be exceeded at $r_{cd} = 0.2$; hence, we should aim for $r_{cd} = 0.3$. If there are 2000 participants, $r_{cd} = 0.3, 0.4, 0.5$ are desirable. Although it does not depend on T_{dif}, for $N_s = 1, 2$, we found that it is necessary to encourage the user to change from CD to CP or from CP to CD partially



Np = 1500		r_{cd}								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
R_i	$N_s = 3$	0.18	0.36	0.42	0.36	0.3	0.24	0.18	0.12	0.06
	$N_s = 2$	0.12	0.24	0.36	0.36	0.3	0.24	0.18	0.12	0.06
	$N_s = 1$	0.06	0.12	0.18	0.24	0.3	0.24	0.18	0.12	0.06

Fig. 7. Estimation of $\boldsymbol{R_i}$ ($\boldsymbol{N_p} = 1500$)



Np = 1000		r_{cd}								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
R_i	$N_s = 3$	0.12	0.24	0.28	0.24	0.2	0.16	0.12	0.08	0.06
	$N_s = 2$	0.08	0.16	0.24	0.24	0.2	0.16	0.12	0.08	0.04
	$N_s = 1$	0.04	0.08	0.12	0.16	0.2	0.16	0.12	0.08	0.04

Fig. 8. Estimation of $\boldsymbol{R_i}$ ($\boldsymbol{N_p} = 1000$)

for $r_{cd} = 0.2, 0.4, 0.6$ in order to achieve the goal. The maximum value of R_r is 0.52.

Fig. 12 shows the results for the case of 2500 participants. $r_{cd} = 0.2, 0.3, 0.4, 0.5, 0.6$ exceed the target value in all 39 cases. The maximum value of R_r is 0.66. In this case study, we find that T_{dif} has only a partial impact because there was no significant R_r difference due to T_{dif}.

Using the proposed evaluation framework, we determine whether a company can acquire the content that it wants to know in advance for service implementation.

In this case study, we set the method to extract parameters based on simulation results shown in Fig 13.

To achieve the target reduction rate, we find that we have to motivate at least 1,500 participants: $N_p = 1500,\ 2000\ and\ 2500$. The maximum number of seats for the carpool should be at least two for all N_p: $N_s \geq 2$ Table 4. shows the results of the cases that exceeded $R_r > 0.3$ by r_{cd}. We find 94% in $r_{cd} = 0.3$. as highest case rate:$r_{cd} = 0.3$.

Finally, we find that all extractedcases exceeded $R_r > 0.3$ by T_{dif}.: $T_{dif} = 10,\ 20\ and\ 30$.

Fig. 14 shows R_r, SOV rate, fuel consumption reduction and CO2 emissions reduction for extraction parameters cases: total 17cases. We find that we can expect the R_r to be 31-38% at $N_p = 1500$, and 51-66% if the number of participants can be increased to $N_p = 2500$.

We estimate that this program can reduce the maximum SOV rate by approximately 90% in $N_p = 2500$.

Table 4
r_{cd} Highest case rate with R_r >0.3

	r_{cd}				
N_p	0.2	0.3	0.4	0.5	0.6
1500	0/3	5/6	4/6	-	-
2000	3/6	6/6	6/6	6/6	6/6
2500	6/6	6/6	6/6	6/6	6/6
Total	9/15	17/18	16/18	-	-
	60%	94%	89%	-	-

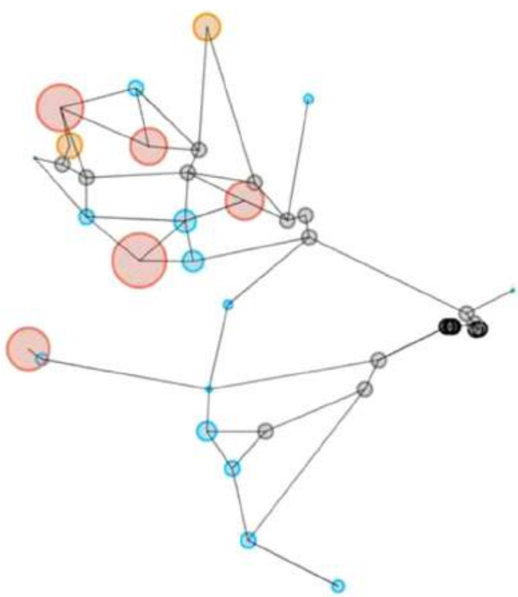
The cost reduction is calculated by dividing the reduction in the total distance traveled by the average fuel consumption (21.9 km/l: JC08 mode) and adding the result with the average gasoline price (144 yen/l). The CO2 emissions reduction is calculated by using CO2 Emissions from gasoline (2.322kg-CO2/l: Ministry of the Environment of Japan).

Additionally, it is found that we can expect a cost reduction of up to 50 million yen/year and CO2 emission reduction of up to 800 ton/year through reduced fuel consumption in $N_p = 2500$.

Table 5 shows extracted parameter results and expected service effects. We conduct feasibility studies using the extracted results. We perform a sensitivity analysis of the extracted parameters, assuming that N_p=1500 is feasible given the current situation of the company. If N_s=3 is expected, Fig. 10 shows that $0.25 \leq r_{cd} < 0.4$ is desirable. The simulation results show that there is no case where R_r>0.3 for $r_{cd} = 0.2$, and

Table 5
Extracted parameter results and expected service effects

	Extracted parameters			Expected service effects			
	N_s	r_{cd}	T_{dif}	R_r (%)	SOV rate (%)	Fuel reduction costs per year (million yen)	CO2 Emissions reduction per year (ton)
1500	2	0.3	10,	31-38	47-54	23-28	373-453
2000	or		20,	39-51	29-39	29-38	468-620
2500	3		30	51-66	9-21	38-50	612-800



Type	Color	Meaning
Meeting points	Red	More than 8% of total demand
	Orange	5-8% of total demand
	Blue	Less than 5% of total demand
Others	Black	Destination: factory parking lot
	Gray	Intersection

Fig. 9. Simulation network and amount of input demand

the value at which R_i reaches max is r_{cd}=0.25. If N_s=2 is expected, then $0.3 \le r_{cd} < 0.4$ is desirable. If we are pessimistic, we can find that it is desirable to set $0.3 \le r_{cd} < 0.4$ as the target with N_s=2. The results of this feasible studies can help companies make a decision on whether to implement. If the company decided to implement the system, it can examine the detailed design based on the results of the feasible studies, and since it can see the target values, it can understand the gaps in the improvement phase.

5. Conclusion

Hundreds of cities have already pledged to get to "net zero" – removing as much CO2 as they produce – by 2050.We are expected to take several measures as transport sectors' contributions. MaaS is a one of promising measures for CN but carpooling programs seems to be effective for concentrated commuting to factories in suburban areas where public transportation is insufficient. Focusing on the carpooling program for commuting to the factory, we proposed a practical framework that companies can use. Carpooling is easy to understand as a service, but there are many parameters that companies have to consider for designing it. In this study, in order to reduce the complexity, we propose an evaluation framework with two phases: "Basic design" to make a decision for implementation, and "Detailed design and Improvement" to consider detailed implementation and then proceed with post-operation improvement. Basic design is the phase that focuses on the feasibility study of whether or not to implement the service. Detailed design and improvement is the phase for detailed design with many specific parameter values for implementation and for improvement after operation.

In this paper, we focus on evaluation framework for basic design and conduct a case study on commuting to a newly constructed factory. We applied the evaluation method to extract N_p, N_s, r_{cd}, and T_{dif}, which are necessary for basic design.

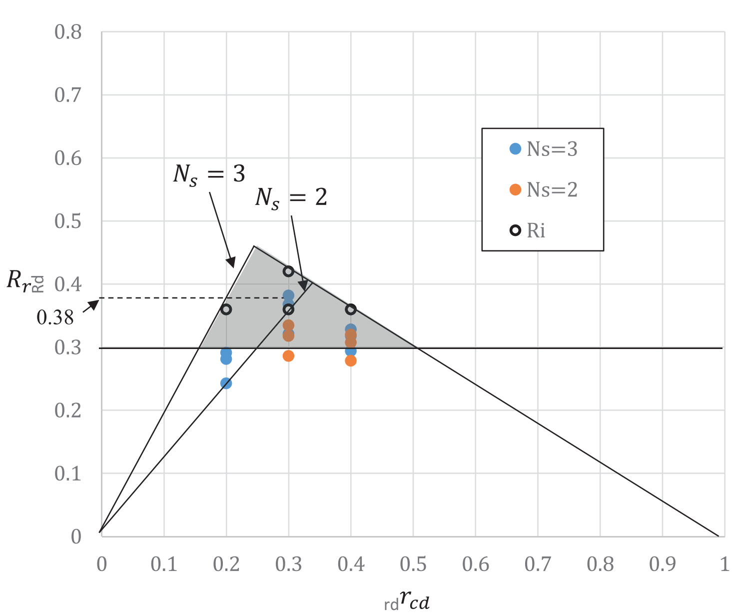


Fig. 10. Simulation results (N_p = 1500)

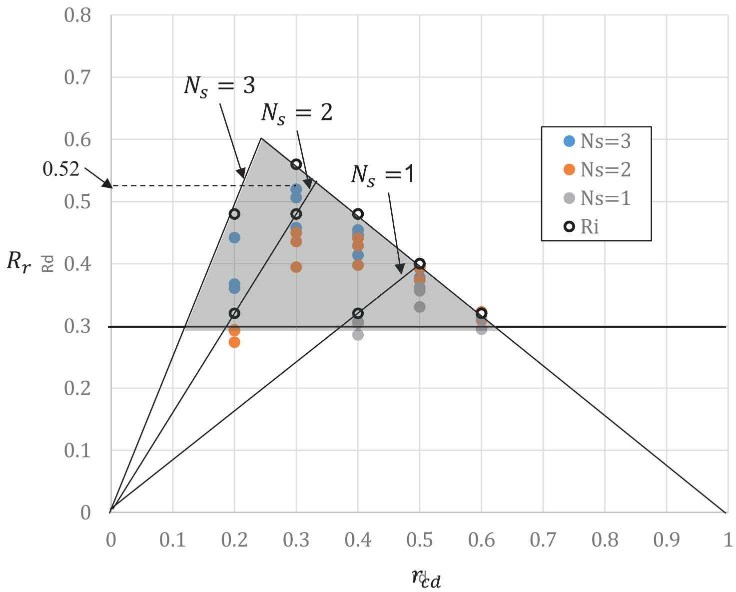


Fig. 11. Simulation results (N_p = 2000)

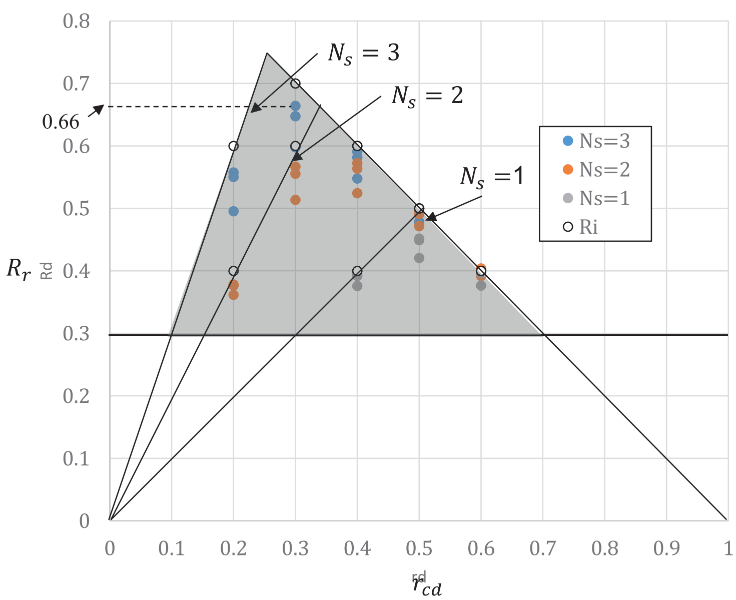


Fig. 12. Simulation results (N_p = 2500)

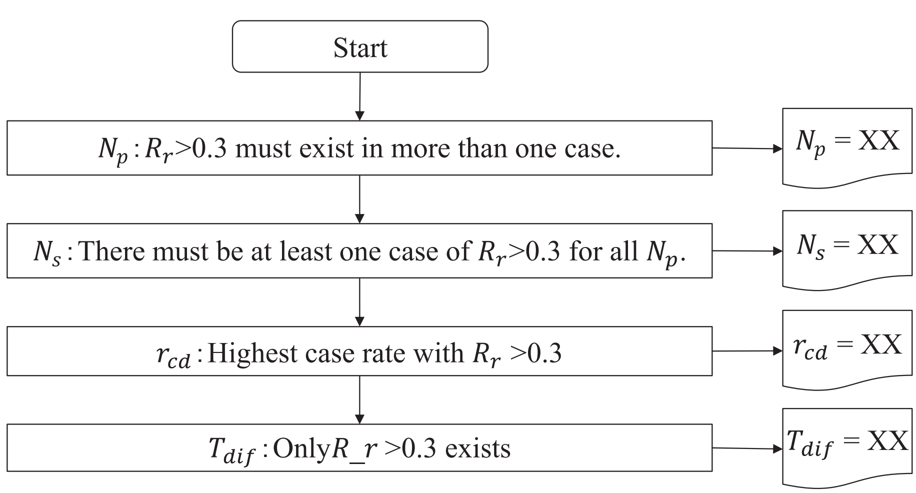


Fig. 13. Extraction parameters based on simulation results

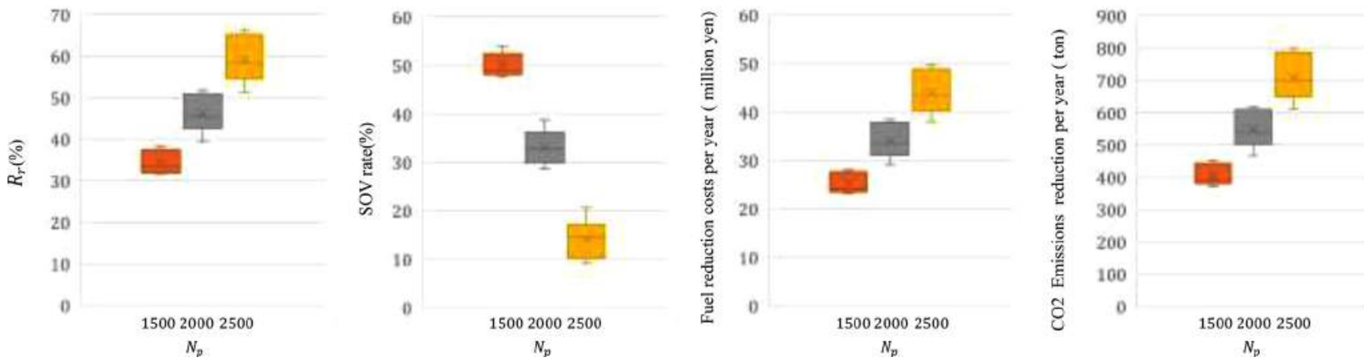


Fig. 14. Result of extraction parameters cases: 17 cases

As for the effect of the introduction of the system, it was found that the number of vehicles could be reduced by 30-66% and CO2 emissions can be reduced by 373-800 tons, depending on the N_p. If the company decided to implement the system, it could examine the detailed design based on the results of the feasible studies. Since it can see the target values, it can understand the gaps in the improvement phase.

Our future work is to execute detailed design and improvement ad a feasibility study. The perspective is that a reduction in the use of vehicles during commuting will result in a reduction in traffic congestion and traffic time, resulting in increase in user satisfaction. Adding traffic simulation to our proposed framework enables us to calculate the target vehicle reduction rate(R_t) needed to reduce the total travel time and improve user satisfaction in situations where there are other transportation modes. When R_t cannot be achieved, we can reconsider the introduction of other means of transportation (e.g., commuter buses), and again search for conditions achieving each service' R_t by traffic simulation based on carpool and additional transportation modes. Subsequently, we would re-estimate R_i of the carpool program and re-simulate considering spatiotemporal matching.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Examining the who, what, and how of risky driving related crashes in residential areas

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ABSTRACT

This study contributes to efforts towards creating livable communities, by identifying and proposing countermeasures for factors that are associated with residential area crashes. Three risky driving pre-crash actions: driving under the influence of alcohol or drug, aggressive driving, and speeding were considered. The study used residential area crash data from Alabama, USA and developed a latent class multinomial logit model to identify factors associated with the pre-crash actions. The results showed that male drivers had 0.44% and 2.09% higher chances to be at fault in driving under the influence of alcohol or drug and aggressive driving crashes, respectively, while female drivers were found to have a 1.82% higher likelihood to be at fault in speeding-related crashes but less likely to be at fault in aggressive driving or driving under the influence of alcohol or drug-related crashes in residential areas. Speeding and driving under the influence of were found to be the leading contributing factors in rural area residential crashes whereas aggressive driving was more pronounced in urban areas. These findings provide a basis for the implementation of appropriate crash countermeasures to reduce residential area crashes, as part of efforts geared towards promoting community safety and livability across the state.

Introduction

The United Nations Sustainable Development Goal (SDG) 11, as part of the 2030 Agenda for Sustainable Development, calls on member states to strive to "make cities and human settlements inclusive, safe, resilient, and sustainable". The Agenda further identifies transport as a defining characteristic of cities and human settlements and recognizes sustainable transport as an integral and necessary component of achieving SDG 11. Indeed, a critical component of a livable community is the provision of safe mobility for everyone who lives in that community and this is at the core of achieving SDG 11. To achieve this goal, much effort has been put into developing smart cities, but little attention has been paid to traffic safety concerns in residential areas which are the source and destination of most travel activities (Sharpe et al., 1958; Cervero, 1996; Calvo et al., 2019). While the transport networks in communities ensure mobility needs are met, they can also be a major source of traffic and pedestrian safety concerns. Residential area road safety concerns have particularly been crucial during the lockdown in response to the Covid-19 pandemic where many people took to their neighborhood streets to walk, jog, and exercise. Although transport systems in safer communities are planned and designed to equitably serve the mobility needs of residents and provide the opportunity for people, especially children to engage in outdoor activities without risks attributable to motor vehicle traffic, community livability and sustainability can be threatened by the activities of risky drivers. This study contributes to efforts towards creating livable communities, by identifying and proposing countermeasures for factors that are associated with risky driving behaviors that contribute to residential area crashes.

Residential roads are typically designed with lower speed limits and roadway features that allow for safe movement and interaction between vehicles and non-motorists. Nonetheless, drivers often utilize residential roads and streets as part of an overall strategy to reduce perceived travel time and avoid congested conditions (Wu et al., 2009; Ben-Elia and Ettema, 2011; Dinh and Kubota, 2013; de Baets et al., 2014; Svenson and Eriksson, 2017; Ringhand and Vollrath, 2019). Despite a variety of measures adopted to ensure traffic safety in residential areas, annually, many road users sustain varying degrees of injury in residential area crashes. These crashes also contribute significantly to non-vehicular property damage in communities. To be able to improve road safety in general, several studies have previously been carried out to understand the factors that are associated with the occurrence and severity of crash outcomes. For instance, studies have found factors such as rider age and gender, rider condition at the time of the crash, environmental and roadway conditions, and motorcycle features to be significant contributing factors to motorcycle crashes (Quddus et al., 2002; Haque et al., 2010; Waseem et al., 2019; Lam et al., 2019; Thompson et al., 2020). Simi-

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larly, motor-vehicle crash factors such as driver age and gender, pre-crash actions and decisions, weather and lighting conditions, manner of a collision, location of a crash, vehicle type, and roadway geometry have previously been studied (e.g., Abdel-Aty, 2003; Kweon and Kockelman, 2010; Briggs et al., 2008; Kim et al., 2013; Shaheed and Gkritza, 2014; Adanu and Jones, 2017; Lidbe et al., 2020).

Behavioral factors and human errors have been identified as a leading cause of traffic crashes, with some road user groups being more prone to engaging in risky behaviors (Tillmann and Hobbs, 1949; Treat et al., 1977; Elander et al., 1993; Hendricks et al., 2001; Adanu et al., 2017, 2019). Risky driving behaviors such as speeding, aggressive driving, driving under the influence (DUI) of alcohol or drug, failure to use safety equipment, driving with an invalid license, have extensively been studied and found to be influenced by both individual and sub-regional factors such as policies, socioeconomic, and rigor of traffic law enforcement (Adanu et al., 2019). These risky behaviors increase the likelihood of crashes and increase crash injury severity. This paper investigates the factors that are associated with some risky driver behavior-related crashes in residential areas. The study used crash data from the state of Alabama and developed a latent class multinomial logit model (LC-MNL) to identify significant crash factors that may be targeted in a prioritized strategy to improving traffic safety in residential areas. The findings from the study are expected to assist city administrators in promoting community safety and livability across the state.

Data description

Data for the study was obtained from the Critical Analysis Reporting Environment (CARE) system developed by the Center for Advanced Public Safety at the University of Alabama. The CARE database was queried to select crashes that happened in residential areas in Alabama between 2018 and 2019. The data were error-checked and observations with missing or ambiguous values were omitted from the original dataset before performing the model estimation. This yielded a total of 7,431 observed crashes. Only two years of crash data was used for the study to minimize the potential for biased inferences from the data due to temporal instability of crash factors (Behnood and Mannering, 2015). To understand driver behavioral factors that contribute to crashes in residential areas, three pre-crash actions (DUI, aggressive driving, and speeding) that were reported as the primary contributing circumstances were considered. Aggressive driving generally consists of several items. While some of these items such as horn-honking and yelling at others may not directly lead to crashes, others such as red light running may lead to crashes. The crash reporting form used for the CARE crash database captures various forms of aggressive driving behaviors, either collectively or as individual items. For instance, due to the sensitivity and prevalence in this region, red light running is captured as an individual item in the crash report. Similarly, failure to yield, which may be described as an aggressive behavior, is also recorded as an individual item. Further, an additional item designated as “aggressive driving” – defined as reckless driving is also reported. For the purpose of this study, therefore, all the various forms of driver aggression (i.e., failure to yield, reckless driving, red light running, following too close, improper lane change) which contributed to crash occurrence were grouped together as “aggressive driving”. Distracted and drowsy driving were not included because they accounted for less than 2% of the total residential area crashes. More than 40 variables were considered in the latent class analysis. The distribution of the crashes by injury outcome reveals that about 30% of the residential area crashes during the study period resulted in an injury outcome. With respect to driver behavior, DUI accounted for 34.8% of the crashes while aggressive driving and speeding were responsible for 23.8% and 41.5%, respectively. Figs. 1-3 present the distribution of based on the location, injury outcome, and gender of the at-fault driver.

Land-use patterns and travel behavior differ between rural and urban areas (Pateman, 2011). Whereas homes in rural areas are often sparse, urban areas are characterized by more dense development. These influence the traffic mix and driving behaviors. Fig. 1 reveals that DUI accounted for a similar proportion of crashes in rural and urban residential areas while aggressive driving accounted for a higher proportion of crashes in urban areas. Speeding in rural residential areas represented a higher proportion of crashes than in urban areas. Fig. 2, however, shows that DUI accounted for a higher proportion of serious injury (fatal and incapacitating injuries) whether in rural or urban residential areas. Fig. 3 revealed that male drivers were involved in a higher proportion of DUI and aggressive driving crashes while female drivers were responsible for a higher number of speeding crashes. In approximately 10% of the crashes, the gender of the driver is unknown. This probably constitutes hit-and-run crashes in the residential areas. These statistics highlight the need for studying these residential crashes as part of efforts towards improving public safety and overall community livability.

Table 1 shows the summary statistics of the variables that were found to be significant in the LC-MNL model. These variables relate to the at-fault driver. The summary statistics reveal that rear-end collisions made up 16.6% of the crashes while sideswipe and side-impact accounted for 7% and 7.9%, respectively. Younger drivers were responsible for 32.8% of the crashes while adult drivers accounted for 36.7%. Older drivers on the other hand were involved in only 2.7% of the crashes. About 34.6% of the crashes occurred on weekends and 16.8% occurred between midnight and 6AM, while 35.1% and 31.8% occurred between 6PM and midnight and noon and 6PM, respectively. At-fault drivers who did not have a valid license contributed to 34.9% of the crashes while those that did not use seatbelt were involved in 10.5% of the crashes. More than half (54.9%) of the crashes happened at intersections.

Method

Road crashes are complex events that often involve a variety of factors; many of which may be unknown and recorded by the reporting police officer. Indeed, it is impossible to include all probable crash factors in the standard crash report form. The absence of detailed information can affect the accuracy of results from traditional statistical analyses, hence limiting the accuracy of decisions made from such crash models. Various statistical methods can be used to overcome this inherent problem, typically referred to as unobserved heterogeneity, in crash data and analysis (Mannering et al., 2016). For instance, random parameters (mixed logit) models (Milton et al., 2008; Morgan and Mannering, 2011; Anastasopoulos and Mannering, 2011; Kim et al., 2013) and latent class (finite mixture) models (Yasmin et al., 2014; Shaheed and Gkritza, 2014; Lidbe et al., 2020) have been used extensively to capture unobserved heterogeneity in data analysis by allowing parameters to differ across crash observations (Morgan and Mannering, 2011; Behnood and Mannering, 2015; Mannering et al., 2016). Methodologically, the random parameters approach uses continuous mixing distributions to capture heterogeneity by allowing the analyst to specify the functional form of the mixing distribution (for example, normal, lognormal, uniform, triangular, etc.), whereas the latent class approach identifies unobserved classes by replacing the continuous distribution assumption of random parameter model with a discrete distribution in which unobserved heterogeneity is captured by the membership of distinct classes (Greene and Hensher, 2003; Mannering and Bhat, 2014). This study used LC-MNL because it has previously been shown to perform better than random parameters logit (Greene and Hensher, 2003; Shen, 2009; Wen et al., 2012; Adanu and Jones, 2017).

For this study, the LC-MNL model allows the risky behavior to have C different classes so that each of the classes will have their own parameters with the probability given by (Behnood et al., 2014):

$$P_n(c) = \frac{exp\left(\alpha_c Z_n\right)}{\sum_{\forall C} exp\left(\alpha_c Z_n\right)} \quad (1)$$

where Z_n represents a vector that shows the probabilities of c for crash n, C is the possible classes c, and α_c represents the estimable pa-

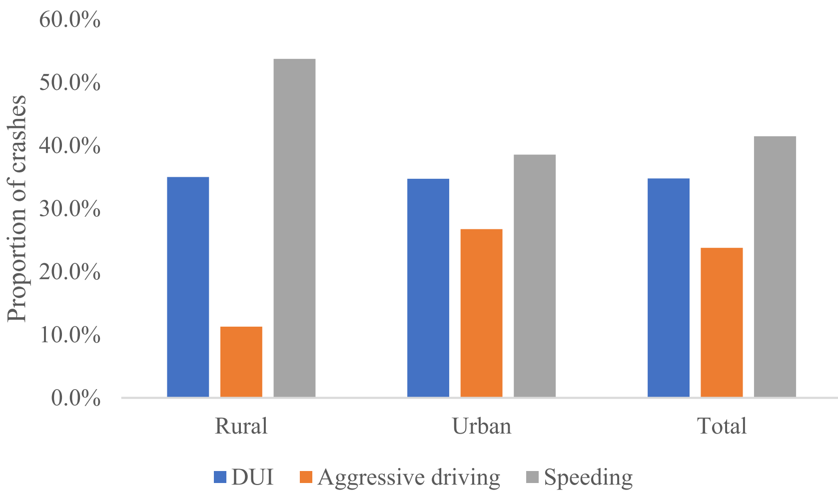

Fig. 1. Distribution of primary contributing circumstances and location of the crashes.

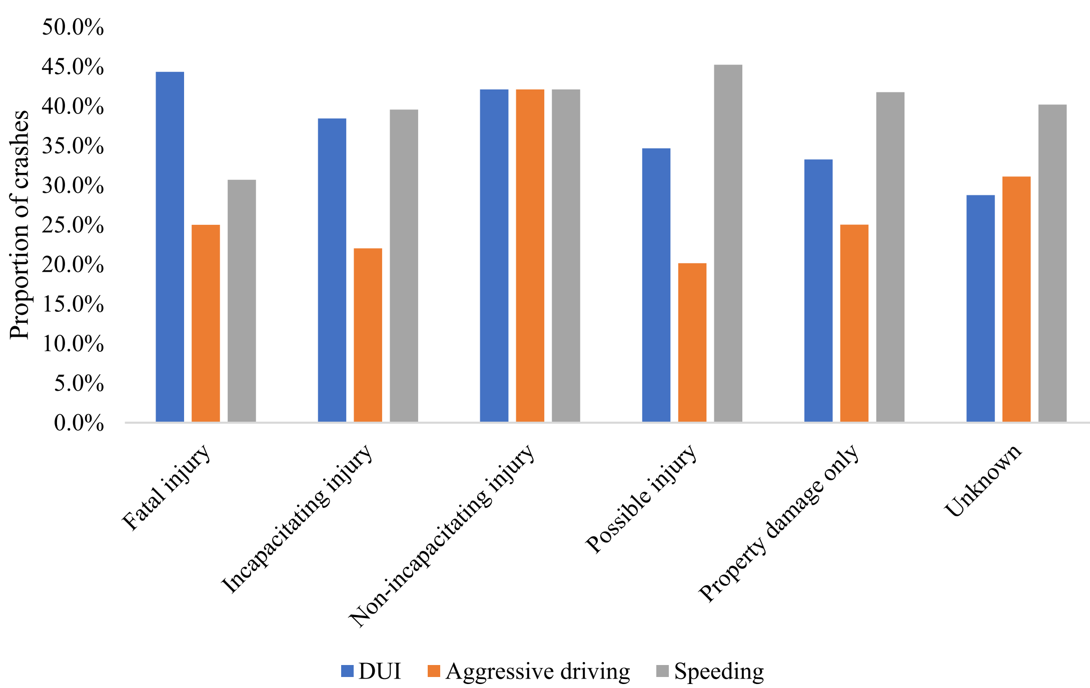

Fig. 2. Distribution of primary contributing circumstances and crash injury severity.

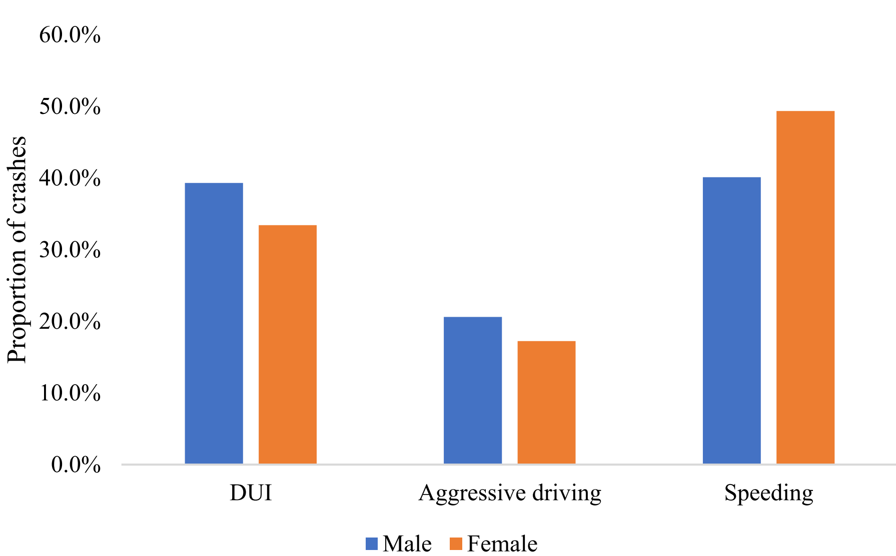

Fig. 3. Distribution of primary contributing circumstances by at-fault driver gender.

Table 1
Summary statistics of variables included in the LC-MNL model.

Variable	Description	Number of observations	Percentage
Rear-end crash	Crash type is rear-end collision	1234	16.6
Side-impact crash	Crash type is side-impact	587	7.9
Sideswipe	Crash type is sideswipe	520	7.0
Single-vehicle	Only one vehicle involved in crash	3820	51.4
Non-motorist	Collision with a non-motorist	59	0.8
Sport Utility Vehicle	Vehicle type is Sport Utility Vehicle	1442	19.4
CMV	Vehicle type is commercial motor vehicle	111	1.5
Rural area	Location of crash is rural area	1427	19.2
Intersection	Crash occurred at an intersection	4080	54.9
Early hours	Crash occurred between midnight and 6AM	1248	16.8
Afternoon	Crash occurred between noon and 6PM	2363	31.8
Night	Crash occurred between 6PM and midnight	2608	35.1
Weekend	Crash occurred on weekend	2571	34.6
No seatbelt	Driver did not wear a seatbelt	780	10.5
Invalid license	Driver did not have a valid driving license	2593	34.9
Self employed	Driver is self employed	245	3.3
Unemployed	Driver is unemployed	1204	16.2
Female driver	Driver is female	2073	27.9
Male driver	Driver is male	4644	62.5
Older driver	Driver is more than 60 years	201	2.7
Middle aged driver	Driver age is between 45 and 60	1196	16.1
Adult driver	Driver age is between 25 and 45	2727	36.7
Younger driver	Driver age is less than 25	2437	32.8

rameters (class specific parameters). The unconditional probability that a crash will involve risky behavior i is given by:

$$P_n(i) = \sum_{\forall C} P_n(c) * P_n(i/c) \tag{2}$$

where $P_n(i/c)$ is the probability of crash n to involve risky behavior i in class c. Based on the two equations above, the latent class logit model for class c will be:

$$P_n(i/c) = \frac{exp\left(\beta_{ic} X_{in}\right)}{\sum_{\forall I} exp\left(\beta_{ic} X_{in}\right)} \tag{3}$$

where I represents the possible number of risky driving behavior levels and β_{ic} is a class-specific parameter vector that takes a finite set of values.

Marginal effects are commonly computed from the partial derivative for each observation, to investigate the effect of individual parameters on the crash-severity outcome probabilities. The marginal effect in a LC-MNL model for binary variables is computed for each class as the difference in the estimated probabilities with the indicator changing from zero to one while keeping all the other variables at their means. Greene (2007) has shown that the direct and cross-marginal effects can be computed respectively as follows:

$$\frac{\partial P_{ni}}{\partial x_{nik}} = \beta_{ik} P_{ni}\left(1 - P_{ni}\right) \tag{4}$$

$$\frac{\partial P_{nq}}{\partial x_{nik}} = -\beta_{ik} P_{ni} P_{nq} \tag{5}$$

The direct marginal effect indicates the effect of a unit change in x_{nik} on the probability, P_{ni}, for crash n to be caused by risky behavior i. The cross-marginal effect shows the impact of a unit change in variable k of alternative i ($i \neq q$) on the probability P_{nq} for crash n to result from risky behavior q. The final marginal effect of an explanatory variable is the sum of the marginal effects for each class weighted by their posterior latent class probabilities (Greene, 2007; Xie et al., 2012).

Model estimation results

The latent class multinomial logit model was estimated using NLOGIT 6 software. Two distinct classes with homogeneous attributes were found significant; Latent Class 1 with probability 0.67 and Latent Class 2 with probability 0.33. Estimation results with more than two latent classes did not statistically improve the models in terms of data fit. The class-specific probabilities are a set of fixed constants (Eq. 2) since segmentation based on crash-specific characteristics did not produce a superior model. Table 2 presents the LC-MNL estimation results. A total of 23 variables were found to be statistically significant, mostly at 95% confidence level, and the McFadden Pseudo ρ^2 was 0.13. The model estimation results for each class show that each variable has two sets of parameters associated with it. However, it can be observed that some of the parameters have the same sign between the two latent classes (e.g., side-impact crash, middle-age driver, self-employed driver, Sport Utility Vehicle), while others have opposite signs (e.g., rural area, weekend, older driver) or are not significant in both classes (e.g., commercial motor vehicle, no seatbelt). This indicates that there is heterogeneity between the two classes. For this reason, it would be inaccurate to base the interpretation of the model on the magnitude and sign of the parameters. Rather, model interpretation is more appropriately based on examining the marginal effects.

Table 3 shows the direct and cross marginal effects for the explanatory variables. The marginal effects are very small, so they were multiplied by 100, expressing them as percentage point differences. The marginal effects show that the probability that an aggressive driving crash was a rear-end collision is higher by 0.16% while the probability that speeding led to rear-end collision is 1.54% higher. This indicates that rear-end collisions were less likely to be caused by intoxicated drivers. Similarly, the results show that side-impact and sideswipe crashes were more likely to be caused by aggressive drivers and those drivers that speed through residential areas. Single-vehicle crashes that occurred in residential areas were found to have higher chances that they involved speeding.

DUI crashes were found to have a 0.51% higher likelihood of occurrence in rural areas and the probability that speeding was the primary contributor in rural area residential crashes was 0.44% higher, implying that aggressive driving related crashes were less likely to happen in rural areas across the state. However, crashes that occurred at intersections had 14.63% higher likelihood to involve an aggressive driver and less likely to involve speeding or DUI. Residential area crashes involving commercial motor vehicles were more likely to result from DUI and speeding and not aggressive driving. Crashes that were caused by drivers who were driving Sport Utility Vehicles were found to have a higher likelihood of involving speeding or DUI.

Table 2
LC-MNL model estimation results.

Variable	In behavior function of	Latent Class 1 Parameter estimate	t-statistic	Latent Class 2 Parameter estimate	t-statistic
Constant	DUI	1.26	8.04	-2.02	-2.76
Side-impact crash	DUI	-0.04	-0.25	-1.31	-1.87
Sideswipe	DUI	-0.21	-1.13	-1.30	-2.30
No seatbelt	DUI	0.79	5.08	-1.28	-1.33
Invalid license	DUI	0.07	0.83	-2.19	-2.91
Older driver	DUI	-0.74	-2.39	3.06	3.59
Self-employed	DUI	0.37	2.47	1.32	1.57
CMV	DUI	-0.24	-0.59	1.91	2.63
Rural area	DUI	-0.71	-4.96	3.12	4.44
Rear-end crash	DUI	-0.95	-6.80	1.01	1.94
Sport Utility Vehicle	Aggressive driving	-0.53	-2.24	-0.21	-1.10
Middle-aged driver	Aggressive driving	-1.48	-3.78	-1.57	-4.43
Non-motorist	Aggressive driving	-1.60	-1.09	1.49	1.84
Intersection	Aggressive driving	1.45	8.62	0.74	4.46
Early hours	Aggressive driving	-1.13	-3.09	1.64	5.49
Weekend	Aggressive driving	-0.43	-2.09	0.35	2.07
Unemployed	Aggressive driving	-1.27	-2.83	0.95	3.75
Male driver	Aggressive driving	-2.89	-4.15	1.03	2.84
Afternoon	Speeding	1.06	8.58	-1.90	-5.97
Night	Speeding	-0.31	-2.81	-1.19	-5.65
Single vehicle	Speeding	0.50	4.32	1.18	5.91
Female driver	Speeding	0.11	0.90	0.94	2.46
Adult driver	Speeding	-0.27	-2.04	1.74	4.68
Younger driver	Speeding	1.40	11.79	1.28	3.64
Latent class probability		0.67	27.11	0.33	13.59
Model fit statistics					
Number of observations		7,431			
Log likelihood at zero		-8163.79			
Log likelihood at convergence		-7137.26			
McFadden Pseudo-ρ^2		0.13			

Table 3
Estimated marginal effects of the variables included in the LC-MNL model.

Variable	In behavior function of	Effects on probabilities of behavior (%) DUI	Aggressive driving	Speeding
Side-impact crash	DUI	-0.10	0.05	0.05
Sideswipe	DUI	-0.27	0.11	0.16
No seatbelt	DUI	0.86	-0.05	-0.82
Invalid license	DUI	-0.03	0.17	-0.14
Older driver	DUI	0.14	-0.28	0.14
Self-employed	DUI	0.29	-0.09	-0.20
CMV	DUI	0.05	-0.06	0.01
Rural area	DUI	0.51	-0.95	0.44
Rear-end crash	DUI	-1.70	0.16	1.54
Sport Utility Vehicle	Aggressive driving	0.23	-0.56	0.34
Middle aged driver	Aggressive driving	0.61	-1.66	1.05
Non-motorist	Aggressive driving	0.02	-0.01	-0.01
Intersection	Aggressive driving	-7.14	14.63	-7.49
Early hours	Aggressive driving	0.21	0.95	-1.16
Weekend	Aggressive driving	0.20	0.14	-0.33
Unemployed	Aggressive driving	0.06	0.46	-0.52
Male driver	Aggressive driving	0.44	2.09	-2.53
Afternoon	Speeding	-3.20	1.81	1.39
Night	Speeding	1.44	2.29	-3.73
Single vehicle	Speeding	-3.53	-3.61	7.14
Female driver	Speeding	-0.56	-1.26	1.82
Adult driver	Speeding	0.71	-3.26	2.55
Younger driver	Speeding	-5.55	-2.96	8.50

It is worth noting that there was a higher probability that drivers not wearing a seatbelt were more likely to be driving intoxicated but less likely to be engaged in aggressive driving or speeding. Also, the marginal effects reveal that aggressive driving crashes were more likely to involve drivers who did not have a valid license. The results further show that speeding and DUI crashes were less likely to be caused by drivers who did not have a valid license.

Further, residential area crashes had 0.14% higher likelihood to involve DUI or speeding when the at-fault driver is older than 60 years. Crashes involving drivers who were between 45 and 60 years had 0.61% and 1.05% higher probability to be caused by DUI and speeding, respectively. The probability that the crash involves DUI or speeding is even higher when the driver is between 25 and 45 years. However, drivers younger than 25 years were found to have 8.5% higher likelihood of getting into speeding-related crashes but 5.6% lower probability of being at fault in DUI-related crashes in residential areas. The results show that unemployed drivers were more likely to be at fault in DUI and aggressive driving crashes while self-employed drivers were found to be more likely to be at fault in DUI but not aggressive driving or speeding-related crashes. Crashes that involved a collision with a non-motorist were observed to have a 0.02% higher likelihood to be caused by DUI and less likely to be caused by speeding or aggressive driving. The results further showed that male drivers had 0.44% and 2.09% higher chances to be at fault in DUI and aggressive driving crashes, respectively, while female drivers were found to have 1.82% higher likelihood to be at fault in speeding-related crashes but less likely to be at fault in aggressive driving or DUI-related crashes in residential areas.

Results reveal that crashes that happened between 6PM and 6AM were more likely to involve DUI or aggressive driving and not speeding. The marginal effects show that the likelihoods of the crashes being DUI and aggressive driving-related are higher between 6PM and midnight than between midnight and 6AM. However, residential area crashes that happened between noon and 6PM were more likely to be caused by aggressive driving and speeding. Lastly, weekend crashes were found to have 0.2% and 0.14% more likelihood to be caused by DUI and aggressive driving, respectively.

Discussion

Safe community projects are often targeted at identifying the factors associated with injury and injury-related deaths and taking preventive measures to promote sustainable community livability (Lindqvist et al., 1998; Spinks et al., 2009). The excessive use and negative consequences of cars in residential areas have prompted concepts such as New Urbanism in the U.S. and Compact City in Europe, with the aim of mitigating the effects of an automobile-dependent culture by reducing travel distances and creating residential areas with high density and diversity that support public transit and non-motorized travel (Friedman et al., 1994; Cervaro, 1996). Proponents for sustainable and livable communities continue to advocate for city forms that promote safer travel options in residential areas. In recent times, there have been campaigns to limit the activities of large SUVs and trucks on our roads and more particularly in residential areas due to their inherent safety concerns (White, 2003; Fenton et al., 2005; Walker et al., 2006; Schmitt, 2017; Sackett, 2018; Laker, 2019). While this push may be based on the crash records of these vehicle types, it is in fact the outcome of risky driving behaviors and driving styles of the drivers that are indirectly associated with the vehicles. For this reason, discouraging vehicles that are perceived to be inherently unsafe without identifying the drivers and other correlates that contribute to the phenomenon may only mean shifting the risk factor to other vehicle types, without addressing the root cause of the problem. Therefore, safer communities may not necessarily be created by the absence of vehicles that are perceived to be unsafe but rather by taking vehicles away from risky drivers.

The National Highway Traffic Safety Administration (NHTSA) identified DUI (drunk and drug-impaired driving), speeding, failure to seat belts, and drowsy and distracted driving as the leading risky behaviors that contribute to crashes. Whereas factors such as distracted driving and DUI primarily contribute to crash occurrence, speeding increases the severity of the crash. The habit of certain road user groups to engage in risky driving behaviors have been linked to many factors such as age (e.g., Chliaoutakis et al., 2000; Adanu et al., 2017), gender (e.g., Miller et al., 1998; Turner and McClure, 2003; Adanu et al., 2018), socioeconomic status (e.g., Liu et al., 1998), personality (e.g., Yu and Williford, 1993; Nicholson et al., 2005), type of vehicle being driven (e.g., Ulfarsson and Mannering, 2004), and even regional culture (e.g., Lund and Rundmo, 2009; Lund and Albrecht et al., 2013; Atchley et al., 2014; Adanu et al., 2017; Adanu et al., 2019). It has also been observed that risky drivers often engage in multiple traffic violations (Briggs et al., 2008; Phillips and Brewer, 2011; Pulido et al., 2011; Stubig et al., 2012). For instance, Bogstrand et al (2015) observed that a higher proportion of alcohol-impaired drivers were less likely to use the seatbelt and more likely to speed. They also found that a large proportion of drivers who engage in drunk or drugged driving are repeat offenders. Consistent with previous studies, findings from this study show that drivers who did not use seatbelt were more likely to drive under the influence of alcohol or drug. Similarly, aggressive drivers were also less likely to have a valid license at the time of the crash. The results of the study further reveal that DUI-related crashes are more likely to happen in rural areas. Further, it was observed that while male drivers were more likely to engage in aggressive driving and driving under influence, female drivers were more likely to be at fault in speed-related crashes in residential areas. Additionally, drivers were found more likely to engage in impaired and aggressive driving during weekends.

These findings reveal that risky drivers engage in driving behaviors in residential areas as they do in non-residential areas. This exposes people in residential areas to the risk of road crash injuries and increases the likelihood of vehicular (e.g., on street-parked vehicles) and non-vehicular property (e.g., fences, mailboxes) damage. Frequent and severe injury crashes in residential areas therefore compromise community livability. To improve traffic safety in residential areas, there is a need to enforce speed limit compliance. Traffic calming measures such as chicanes and lane shifts, medians and refuge islands, mini-roundabouts, speed cushions/tables/humps, and shared streets, may be implemented to reduce driving speeds in residential neighborhoods as this has the potential to significantly reduce the number and severity of crashes involving motor vehicles. Further, with the appropriate speed management measures, cars would drive at speeds that would be safer and more compatible with walking and bicycling. Additionally, traffic enforcement cameras may be installed to check risky driving behaviors, particularly at intersections. Traffic law enforcement efforts may also be intensified in residential areas to reduce the chances of drivers engaging in risky behaviors. Policies may also be enacted to increase punishment for drivers who engage in behaviors, such as DUI, in residential areas. Such policies would need to be backed by a comprehensive road user education and safety campaigns across the state.

Conclusions

This study estimated an LC-MNL model to understand factors that are associated with risky driving-related crashes in residential areas, as part of efforts to create livable communities. The LC-MNL modeling approach was used to account for unobserved heterogeneity in the data. Crash data for 2018-19 in Alabama were obtained from the Critical Analysis Reporting Environment (CARE) system developed by the Center for Advanced Public Safety at the University of Alabama, with a total of 7,431 crashes occurring during that period. Three risky behaviors: DUI, aggressive driving, and speeding were considered in this study. Two distinct classes with homogeneous attributes were identified with specified probabilities, and a total of 23 variables were found to be statistically significant.

The model results revealed a significant positive relationship between DUI and rural areas, failure to use seatbelt, male drivers, weekends, collision with non-motorists, and older drivers, whereas aggressive driving was more associated with intersections, drivers who did not have any valid license, side-impact and rear-end collisions. Speeding-related crashes were found to significant in rural residential areas and among female and younger drivers. The findings from this study are generally consistent with past studies that have examined the relationships between risky driving behaviors and road crashes. Consequently, these findings provide some basis for the implementation of certain crash countermeasures to reduce the occurrence and severity of crashes in residential areas. For instance, it is recommended that traffic calming measures be installed to ensure speed limit compliance in residential areas. Moreover, the planning, design, and operation of the transportation network outside of residential areas should be configured in such a way as to discourage unnecessary levels of traffic where people live. There is the need to back such policies with comprehensive education and safety campaigns across the entire state, to ensure that communities are safe and livable, in fulfilment of SDG 11.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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15-, 10- or 5-minute city? A focus on accessibility to services in Turin, Italy

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ABSTRACT

The concept of the 15-minute city is receiving increasing attention, both in planning practices and in the academic literature, especially now that the pandemic has made evident the need for a minimum set of proximity-based services accessible by active travel. Most issues of this concept can be traced back to more or less past planning ideas such as the garden city, the neighbourhood unit, the superblock etc.; however, further studies are needed, as many theoretical and methodological questions for its implementation remain unresolved. The paper presents a methodology to operationalise the concept of the 15-minute city, in order to show which parts of the city and what percentage of its population can access a location of a given service on foot within three time thresholds (5, 10 and 15 minutes). The methodology is tested on the Italian city of Turin. The results show that, at least in dense European cities such as the case study, the 15-minute threshold cannot always be assumed as the necessarily most appropriate target, since many services can already be reached by foot within this time, or even less, by the majority of the population. Moreover, the levels of accessibility to services are significantly determined by the number and spatial distribution of the locations of these services. Finally, a recovery of the operational research on accessibility measures and indicators that was developed in the field of regional sciences in the second half of the last century and in the last twenty years is recommended to complexify the operationalisation of the 15-minute city concept.

1. Introduction

In recent years, the concept of the 15-minute city (and its variations, such as the 20-minute neighbourhood) has gathered great momentum and has been embraced in a growing number of scholars' and city mayors' agendas (Moreno et al., 2021). Launched in the 2010s, this model was first proposed in the framework of research on walkability as a factor of urban quality of life and accessibility to services (Barton et al., 2012; Talen & Koschinsky, 2013; Van Dyck et al., 2009); but it has gained further traction during the Covid-19 pandemic, when the introduction of stringent health protocols, social distancing, lockdowns and movement restriction revealed the vulnerability of many urban environments (Allam & Jones, 2020). On the one hand, public transport services have been reduced or suspended across the globe, as overcrowded buses, trams and subways were pointed out as a high-risk factor in spreading Covid-19 (Das et al., 2021); on the other hand, the pandemic highlighted the importance of freeing up outdoor public spaces from circulating and parked cars, where to perform some of those activities that turned out to be no longer feasible in restricted closed spaces (Abdelfattah et al., 2022), and prompted recognition of the value of active travel for exercise (Nurse & Dunning, 2020). The convergent pressures from this twofold emergency have made evident the necessity of a minimum set of proximity-based services that should be accessible by walking or cycling, so to allow citizens to meet some of their basic needs at the neighbourhood level without using motorised transport means (Marin-Cots & Palomares-Pastor, 2020).

As a few authors have pointed out, the 15-minute city is not an entirely new idea. On the contrary, it is quite rooted in history, as it re-interprets several ideas from earlier planning practices, such as Howard's Garden city (Gower & Grodach, 2022), the neighbourhood unit by Clarence Perry (Balletto et al., 2021; Kissfazekas, 2022), the Central place theory by Walter Christaller (Pozoukidou & Chatziyiannaki, 2021), the urban vitality approaches of Jane Jacobs (Ferrer-Ortiz et al., 2022), the geography of time by Torsten Hägerstrand (Ferrer-Ortiz et al., 2022), the human-scale urban design by Christopher Alexander and Jan Gehl (Moreno et al., 2021), the pedestrian pocket proposed by Peter Calthorpe around stations in the Transit oriented development approach (Abdelfattah et al., 2022), the principles of New Urbanism and Smart Growth (Calafiore et al., 2022).

At the same time, the 15-minute city concept is at risk of being reduced to a mere political slogan (Duany & Steuteville, 2021), an aspirational idea (Gower & Grodach, 2022), or even a sort of panacea which, quoting one of its main promoters (Moreno et al., 2021), "will lead to an economic boost, while bringing about social cohesion and interaction and help create sustainable ecosystems in cities" (p. 96). As a matter of fact, the adoption of the concept in practice is often limited to merely

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advocating planning principles such as walkability or those 5Ds (density, diversity, design, destination accessibility and distance to transit; Ewing & Cervero, 2010) of the built environment that encourage active mobility (Pozoukidou & Chatziyiannaki, 2021; Stanley et al., 2015). A recent comprehensive review (Gower & Grodach, 2022) has evaluated how the 20-minute neighbourhood concept has been operationalised in planning documents of 33 cities worldwide; the results show that the concept is generally employed with little measurability or benchmarks, as a city branding device which can create a favourable reputation of the city internationally, but does not facilitate plan implementation.

Even in the academic literature, further studies are needed, as many theoretical and methodological questions remain unresolved (Ferrer-Ortiz et al., 2022). In this sense, this paper proposes a methodology to operationalise the 15-minute city concept with reference to walking accessibility to basic services at the city level; this methodology is tested in the Italian city of Turin, in order to assess which share of the population can reach these services on foot in 15, 10 or 5 minutes. In particular, Section 2 introduces the concept of the 15-minute city and highlights some key elements for its implementation. Sections 3 and 4 describe the methodology and its application to the case study. Sections 5 and 6 discuss the obtained results and their implications for the implementation of the 15-minute city approach in dense European cities.

2. The concept of the 15-minute city

The 15-minute city is one of the variations of a more general concept, which refers to a (part of a) city whose residents can access the most essential activities within a given travel time. By coupling the spatial and temporal dimensions, this concept rides on the philosophy of “chrono-urbanism”, which outlines that the quality of urban life is inversely proportional to the amount of time (and money) invested in transportation (Moreno et al., 2021). Assumed this semantic core, the concept has been interpreted and applied differently on a case-by-case basis, with reference to the spatial scale (neighbourhood/city), the travel means (walking, cycling, public transport, car), the set of activities to be accessed and the time threshold.

As regards the scale, both the neighbourhood and the city can be assumed as the spatial area within which the accessibility to main services should be achieved. Even if the two terms (associated with the chosen time threshold: e.g., 20-minute neighbourhood or 20-minute city) are often used as synonyms as they describe similar planning concepts, a semantic difference should not be ignored (Dunning et al., 2021). In the case of the neighbourhood, the focus is on the proximity of urban functions within each neighbourhood, which means providing a wide array of services locally. In this case, the city can be conceived as a system of neighbourhoods which are somehow self-sufficient for a certain set of services (Duany & Steuteville, 2021), and hierarchically dependent on higher-ranking services at the city level (similarly to Christaller’s Central place theory). When the city is directly referred to, it is assumed that the walking or biking shed would not necessarily correspond to a single neighbourhood; the emphasis of planning is not on the proximity of functions within each neighbourhood, but on the proximity to local functions throughout the whole city (Pozoukidou & Chatziyiannaki, 2021).

Concerning the transport mode used for accessing the services, walking is regularly taken into account, as active mobility is at the core of the 15-minute city concept. Many papers propose indicators and indexes of walkability to evaluate pedestrian accessibility to neighbourhood facilities (Caselli et al., 2022; Gaglione et al., 2022; Harrison & Kohler, 2015). Similarly, McNeil (2011) introduces a bike ability index to assess how many services can be reached within 20 minutes in Portland’s neighbourhood by cycling. Authors such as Roberts et al. (2018) and Schoon et al. (2018) recommend considering also public transport when accessibility not only to local services but also to job opportunities is pursued. A comparison between accessibility by different transport means is proposed by Capasso Da Silva et al. (2020), who measure the number of destinations that can be reached from each parcel in Tempe, Arizona, within 20 minutes by walking (along both the all-roads and the sidewalk-only pedestrian networks), by cycling (along both the all-roads and the low-stress biking networks) and by transit.

The classifications of the urban social functions that are supposed to be reached within the set time threshold vary in detail, but generally agree on certain broad categories of services, such as education, healthcare, commerce (food-related in particular) and entertainment (Calafiore et al., 2022). Some authors (see, for example, Thornton et al., 2022) include also the population density (i.e., the number of inhabitants that can be reached in 15 or 20 minutes), as a proxy of the accessibility to opportunities for social face-to-face interaction. Especially regarding low-density cities, sometimes accessibility to public transport stops is also taken into account, as trains, buses etc. are essential to reach job and education opportunities in other neighbourhoods or at a metropolitan level (Khor et al., 2013; Whitzman et al., 2013); other authors (see for example Moreno et al., 2021) suggest to include directly, in the case of European denser cities, also job opportunities among the destinations that have to be reachable in 15 minutes. Much less attention is paid to quantitative issues such as the number and spatial distribution of the locations of services (and jobs), despite the operational research on accessibility measures and indicators that were developed in the field of regional sciences in the second half of the last century offers tools and approaches to planning the 15-minute city concerning these issues.

As far as the time threshold is concerned, 15 and 20 minutes are the most commonly used. In particular, 20 minutes is the threshold generally assumed by American and Australian cities, which present a low density in their suburban areas; on the contrary, 15 minutes seems to be a threshold preferred by European and Asian cities, which are normally denser than Anglo-Saxon ones. However, the time threshold ranges from 5 minutes (proposed by New Urbanism as the right scale for the neighbourhood; Duany & Steuteville, 2021) to 30 minutes (as in the case of Sidney, where the threshold is adopted for metropolitan-level accessibility to strategic centres where jobs and services are concentrated). It is worth emphasising that in most cases, the choice of one or the other time threshold is neither theoretically nor empirically justified, also because – as highlighted by Mackness et al. (2021) – there is currently little underpinning research on how much time people (having different ages, abilities, ethnicities, socio-economic status and so on) allocate (or would like to allocate) to access services and amenities. Moreover, the adopted time threshold is often assumed to be the same for different mobility modes (walking, cycling, public transport etc.), despite their very different speed.

3. Aims and method

3.1. Aims

The paper aims to present a methodology which allows to operationalise the concept of the 15-minute city, showing which parts of the city and which percentage of its population can access a location of a given service within certain time thresholds and using a specific mode of transport. Therefore, this methodology can be useful:

- in the diagnostic phase, to assess how much a certain city can be considered a 15-minute city (or a 10-minute city, a 5-minute city etc., depending on the time threshold adopted) with respect to the actual spatial distribution of the locations of a given service;
- in the planning phase, after verifying which services are less accessible, to identify how to increase the number of their locations or to spatially re-distribute these locations in order to raise the percentage of inhabitants who can access them in a given time threshold.

In this article, the attention will be focused on the diagnostic application of the methodology, which will be tested on the Italian city of Turin. Walking accessibility to services will be assessed for three time

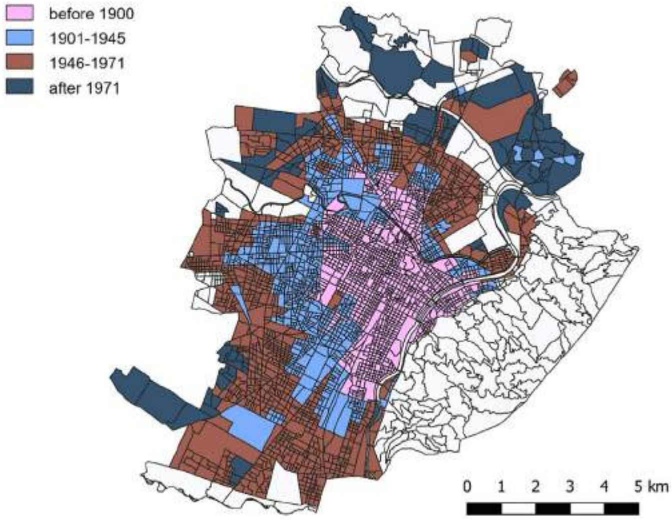

Fig. 1. Building age map of the residential areas in the city of Turin (the white areas are not residential, or data are not available for them).

thresholds, which seem appropriate for dense and walkable cities such as Turin: 5, 10 and 15 minutes.

3.2. Case study

The city of Turin (which is here considered in its administrative limits as a Municipality) is the capital of the Piedmont region, in northwestern Italy, and the core of a functional urban area which includes nearly other 90 municipalities and accommodates over 1,750,000 inhabitants. It is the fourth most populated Italian city: it has about 864,000 inhabitants on 130 square kilometres and a total density of 66 inhabitants per hectare. Turin can be considered an interesting case study for testing the 15-minute city approach for a couple of reasons.

First, the city is highly car-dependent. It has hosted the headquarters and the manufacturing plants of the car company FIAT (which merged with Chrysler into FCA in 2014 and recently with PSA into Stellantis) since its foundation in 1899, and this strongly determined the social identity and the urban rhythm of the city during the 20th century (Vanolo, 2008). The legacy of the dominant role of this automotive company can still be acknowledged in the present mobility patterns: Turin has one of the highest rates of car ownership in Europe (over 650 cars/1000 inhabitants), and the modal share of private motorized mobility reaches 39% at the city level and 62% at the metropolitan level (only 4 out of the 29 cities monitored by the European Metropolitan Transport Authorities have a higher rate; EMTA, 2020). Car circulation is poorly moderated; only one restricted traffic zone, covering 2% of the municipal areas, and few small 30 km/h zones are in operation. Public transport (one metro, 8 streetcars, and about 90 bus lines) and the bicycle network (nearly 200 km of bicycle lanes and paths) are underused; their respective modal shares are 24.3% and 3%. Because of this unbalanced modal share, Turin has one of the worst levels of air pollution in Europe, in particular in terms of NO_2 and $PM_{2,5}$ concentrations (which are respectively due to traffic emissions for 60% and 84%)

Secondly, the urban fabric of the city can be roughly articulated according to three main phases of development: a historical central part, developed around the original Roman core and completed in the 19th century; a first ring around this core, built in the first 40 years of the 20th century; and a second outer ring, developed after the Second World War, mainly in the 1950s and 1960s. As a result, 88% of the city's residential buildings were built before 1971 (Fig. 1): this means that most of the city was developed before the adoption in 1968 of the national law n. 1444, which established for the first time in Italy a minimum amount of local public services (green areas, schools etc.) that have to be provided in new built urban areas.

Fig. 2. Census tracts in Turin.

In other words, a city like Turin can be a significative "stress test" for the 15-minute city strategy, both because of the significant role that automobility keeps playing in the daily lives of its residents compared to active mobility, and because of the historical growth of its urban fabric which was poorly coordinated with the spatial distribution of local services.

3.3. Methodology

The proposed methodology is articulated in 4 steps.

3.3.1. Defining a partition of the city, whose zones are the origins of the trips that citizens make to access a service

In this case, the origins of these trips are assumed to be the residential houses. Data on residents are not available for individual addresses, but only at the level of census tracts, which were therefore chosen as the more appropriate partition. The municipality of Turin is divided into 3851 census tracts (Fig. 2), most of which correspond to the – more or less large – blocks of the city. Some tracts (434) host no residents, as they are industrial areas, parks, cemeteries, rivers etc.; excluding these, the average number of residents in each tract is 253, ranging from 4 to 2,049. The tracts have an average area of 33,766 sqm; their extension increases progressively (from a minimum of 693 sqm to a maximum of 1,771,415 sqm) moving from the historic centre and the urban districts built around it between 1900 and 1940, to the outer edges of the city and its Eastern hillside. The average residential density of the inhabited tracts is 18.8 residents per 1,000 sqm.

3.3.2. Identifying the locations of services for which accessibility is to be calculated

Twenty types of services have been taken into account. They belong to three main categories:

- *Education*: nurseries, kindergartens, elementary schools, middle schools, secondary schools;
- *Health and social services*: neighbourhood health centres, counselling centres, social care services, registry offices, post offices, police stations, churches, open-air markets;

Table 1
Number of locations for each of the twenty services considered.

Education	Locations	*Health and social services*	Locations	*Entertainment*	Locations
Nurseries	120	Neighbourhood health centres	12	Green areas	234
Kindergartens	218	Counselling centres	37	Playgrounds	285
Elementary schools	144	Social care services	151	Playrooms	30
Middle schools	87	Registry offices	15	Sports facilities	451
Secondary schools	162	Post offices	78	Libraries	20
		Police stations	25	Theatres	28
		Churches	174	Cinemas	26
		Open air markets	42		

- *Entertainment*: green areas, playgrounds, playrooms, sports facilities (swimming pools, tennis courts etc.), libraries, theatres, cinemas.

The selection of these services was based on a thorough review of the services that were generally taken into analysis in the literature about the 15-minute city (in particular, Abdelfattah et al., 2022; Balletto et al., 2021; Calafiore et al., 2022; Capasso Da Silva et al., 2020; Caselli et al., 2022; Ferrer-Ortiz et al., 2022; Gaglione et al., 2022; Gower & Grodach, 2022; Moreno et al., 2021; Pozoukidou & Chatziyiannaki, 2021; Stanley et al., 2015; Weng et al., 2019; Whitzman et al., 2013; Zhou, 2019). In this overall list of potential services for the 15-minute city, the twenty services considered in this article were selected according to two main criteria. First, they were supposed to be available at the neighbourhood level; therefore, services such as universities or hospitals were excluded, as they are provided at the scale of the city, rather than the neighbourhood. Secondly, georeferenced data about their spatial locations were available (mainly through AperTo – http://aperto.comune.torino.it –, the open database of the city).

As regards commercial services, only open-air markets (which are widely used at the neighbourhood level in Italy) will be examined in the next sections. Initially, single food shops, restaurants and cafés were taken into account, but the analysis showed that their spatial distribution is so widespread that 95% of Turin inhabitants can access them by a 5 minutes' walk; due to this high accessibility by proximity, they were not considered worthy of further attention in this work.

As shown in Table 1, the number of locations of the twenty services considered varies significantly, from 12 in the case of neighbourhood health centres to 451 in the case of sports facilities.

Each location was georeferenced as a point at the service entrance address. Only open-air markets and green areas were georeferenced as polygons maintaining their actual extension, since they do not have limited entry points; in fact, in Turin they are generally not fenced and can be entered from any point on their perimeter.

3.3.3. Drawing the 5-, 10- and 15-minute isochrones from the census tracts

For each census tract, the geometric barycentre was identified[1]. Then, for each barycentre three isochrones were identified, representing the parts of the city that could be reached by the residents of the tract via a 5, 10 and 15 minutes' walk from the barycentre (Figs. 3,4 and 5). The selection of these three time thresholds could not be based on surveys on the current and desired travel times to access the twenty kinds of services examined, as these surveys were not available in the case of Turin. The 15-minute threshold was adopted as it is the one at the base of the 15-minute city concept; the 10 and 5-minute thresholds were chosen as the high density and walkability levels in Turin allowed to suppose that certain services could be accessible by foot in less than 15 minutes.

[1] In the cases where data about land use inside each census tract are available, these data can be used as a weighting factor to influence the position of the barycentre. For Turin these data were not available, so the mere geometric barycentre was identified.

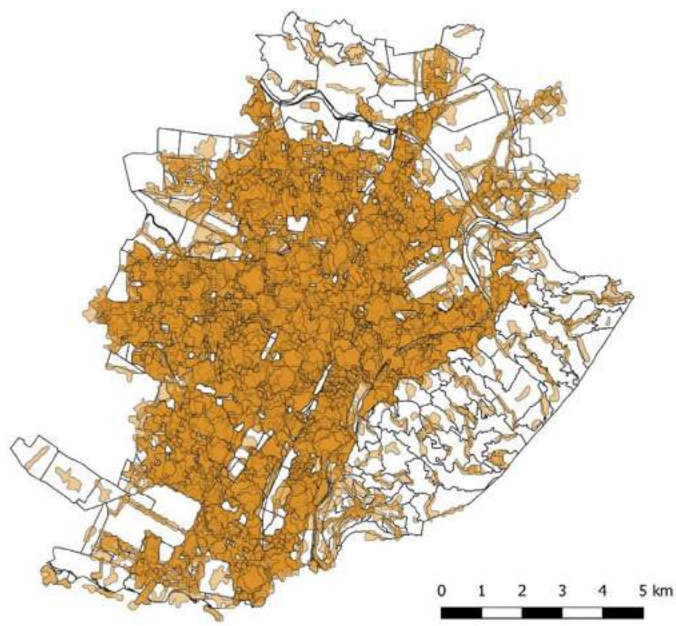

Fig. 3. The 5-minute isochrones.

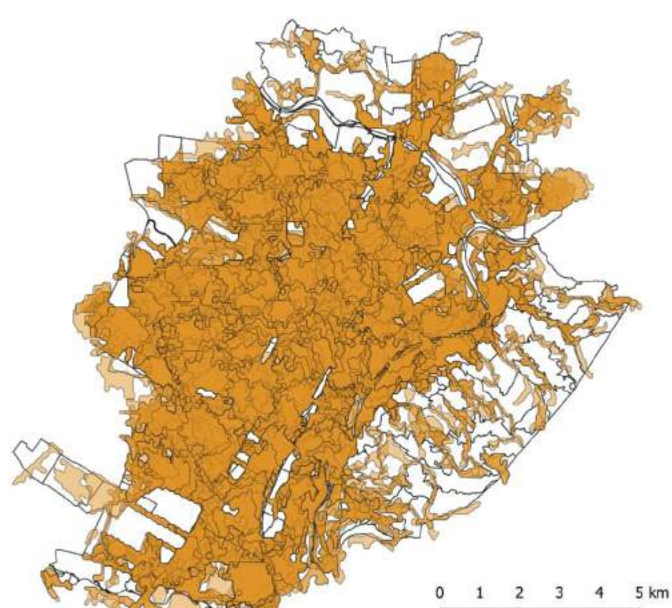

Fig. 4. The 10-minute isochrones.

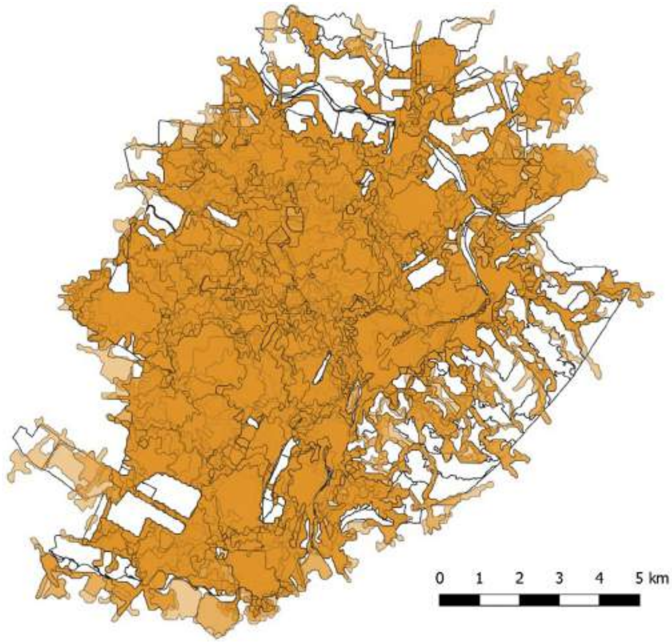

Fig. 5. The 15-minute isochrones.

Fig. 6. Census tracts (in grey) that have access to one or more library locations (orange dots) by a 15 minutes' walk.

The isochrones were drawn using the free HQgis Python plugin for QGis, developed on the HERE Routing API (https://developer.here.com/products/routing), which calculates them using an average walking speed of 4,8 km/h (similar, for example, to the one used by Google Maps, and consistent with common definitions used in walkability studies which equate a 5-minute walk to 400 m; Barton et al., 2002; Thornton et al., 2022) along the sidewalks of the street network. To verify the accuracy of the isochrones, the author compared 10 of them with the corresponding ones obtained by walking personally for 5, 10 and 15 minutes and found a good overlapping.

The average area of the 5-, 10- and 15-minute isochrones turned out to be 0.24, 0.95 and 2.15 square kilometres respectively. This means that the three isochrones calculated along the street network cover 47-48% of perfectly isotropic circles having the same radius of 5, 10 and 15 minutes (i.e., 400m, 800m and 1,200m, due to the considered average walking speed of 4,8 km/h). Doubling the time threshold from 5 to 10 minutes, the average area of the isochrones increases by 290%; the same 5-minute increment from 10 to 15 minutes results in a rather smaller growth of the isochrone area, equal to 127%[2].

3.3.4. Assessing accessibility to services from census tracts

For each of the 20 services and for each census tract, it was calculated (using the QGis "Select by position" function) how many locations of that service were included in the isochrone from that census tract for the three walking thresholds (5, 10 and 15 minutes). In this way, for each kind of service, it was possible to verify whether or not the residents in each census tract had access to at least one location of that service (in the census tract where they live or in another one) within the three time thresholds (see Fig. 6 for an example). By summing up the number of residents of all the tracts having access to at least one location of a service, the percentage of Turin's population that had access to that service within a certain time was calculated.

[2] This is remarkably in line with the geometric progression of the circle's areas: increasing the radius from 400m (i.e., a 5 minutes' walk) to 800m, the area raises by 300%; if the radius increases from 800m to 1200 m, the area grows by 125%.

4. Results

This section does not aim to present systematically and in detail all results for each service and each of the three time thresholds. Rather, it will show the main general findings, which will then be discussed in Section 5.

4.1. Population having access to each service

First of all, it was calculated how many Turin's residents could access one or more locations of each service (Table 2). As can be seen, this percentage varies greatly from service to service. For example, only 2.8% of residents can walk to a neighbourhood health centre in 5 minutes, but 66.4% of them can reach a green area in the same time.

Overall, the average percentage of inhabitants who have a 5-minute accessibility to services is 29.2%; it rises to 61.8% for the 10-minute threshold and to 77.7% for the 15-minute one. In other words, while raising the time threshold from 5 to 10 increases the "served" population by 32.6%, the same increase of 5 minutes from 10 to 15 minutes only allows an additional 16% of inhabitants to access services.

As regards the three categories of services taken into account, education is the most accessible: at least one quarter of the population can access one location for each of the five school degrees in 5 minutes, nearly two thirds in 10 minutes and nearly 90% in 15 minutes. Among health and social services, less than 40% of the population can access a neighbourhood health centre in 15 minutes; post offices and churches are widely accessible in 10 minutes; social care services and open-air markets are available to about 90% of the residents through a 15 minutes' walk. Concerning entertainment, green areas, playgrounds and sports facilities are accessible to over 50% of residents in 5 minutes and nearly 100% in 15 minutes; in contrast, cultural services such as libraries, theatres and cinemas are only available to about 50% of the population even in 15 minutes.

4.2. Accessibility to multiple locations

A second research question was related to the share of Turin's citizens that could access more than one location for each service whiting a given time threshold. As Table 2 shows, for most ser-

Table 2
Percentages of Turin's inhabitants having access to one or more locations of a service within 5, 10 or 15 minutes walking distance.

	5 m			10 m			15 m			Δ% 5-10 m	Δ% 10-15 m
Accessible locations	1	>1	≥1	1	>1	≥1	1	>1	≥1	≥1	≥1
Education											
Nurseries	25.5	9.5	35.0	29.8	48.8	78.6	11.2	81.4	92.6	43.6	14.0
Kindergartens	35.6	22.0	57.6	12.5	81.3	93.8	2.2	96.7	98.9	36.2	5.1
Elementary schools	39.6	8.8	48.4	25.2	66.5	91.8	6.6	91.8	98.4	43.4	6.6
Middle schools	30.8	3.0	33.9	38.0	43.6	81.6	14.8	81.1	95.8	47.8	14.2
Secondary schools	10.0	15.4	25.5	14.4	51.1	65.4	8.9	79.8	88.8	40.0	23.3
Health and social services											
Neighbourhood health centres	2.8	0.5	3.3	15.8	1.4	17.1	34.1	3.9	38.0	13.9	20.8
Counselling centres	4.2	4.5	8.7	14.6	20.3	34.9	17.8	44.8	62.7	26.1	27.8
Social care services	14.2	13.1	27.4	23.4	47.3	70.7	8.6	79.8	88.4	43.3	17.7
Registry offices	5.8	0.0	5.8	22.4	1.1	23.5	39.9	5.7	45.6	17.7	22.1
Post offices	29.9	2.2	32.1	47.5	33.3	80.8	19.8	75.2	95.1	48.6	14.3
Police stations	5.2	5.1	10.3	14.9	20.5	35.4	19.9	42.9	62.9	25.1	27.5
Churches	37.2	9.4	46.6	32.0	60.8	92.8	7.8	91.0	98.8	46.3	6.0
Open air markets			33.2			73.7			90.7	40.5	17.0
Entertainment											
Green areas			66.4			95.8			99.1	29.4	3.3
Playgrounds	37.5	24.9	62.5	11.9	83.4	95.2	3.2	95.9	99.1	32.8	3.8
Playrooms	6.7	2.2	8.8	16.3	11.1	27.5	21.8	26.2	48.0	18.6	20.5
Sports facilities	23.5	28.6	52.1	10.9	80.8	91.7	2.1	96.1	98.3	39.6	6.6
Libraries	6.4	0.1	6.4	26.3	1.1	27.4	41.9	8.9	50.8	21.0	23.4
Theatres	9.7	0.6	10.3	22.8	6.7	29.5	35.0	19.9	54.8	19.2	25.3
Cinemas	7.9	1.6	9.5	22.5	5.2	27.7	33.9	14.0	47.8	18.2	20.1
Mean value	21.6	8.4	29.2	28.5	36.9	61.8	26.0	57.5	77.7	32.6	16.0

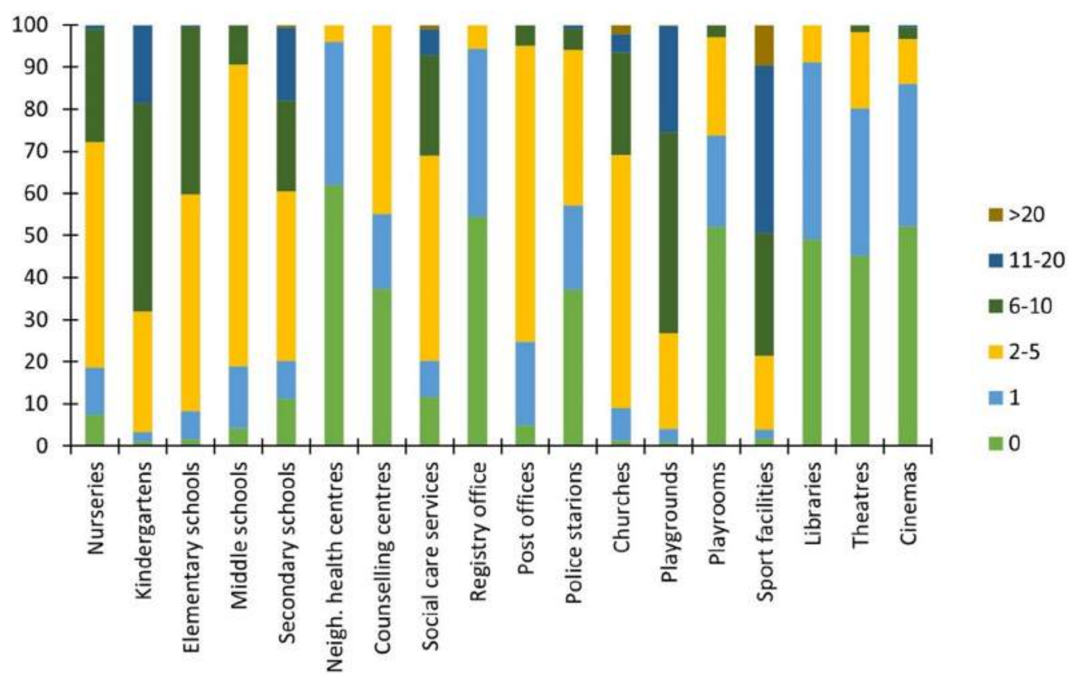

Fig. 7. Percentage of population that can access by foot a certain number of locations for each service within 15 minutes.

vices the inhabitants can reach more than one location. Just to provide some examples (Fig. 7): half of the residents can choose among over 10 sports facilities through a 15 minutes' walk from home; 27.8% can reach more than 5 different nurseries; 31.15% more than 5 social care services Conversely, only 8.7% can access in 15 minutes more than one library, 13,9% more than one cinema (but 0.2% up to 12 cinemas), 19.9% more than one theatre (0.16% up to 10 theatres).

4.3. Relationship between number of locations and served population

Is there a relationship between the number of locations for a given service and the percentage of the population served by this service? Fig. 8 shows a positive trend– as expected –, since the percentage of the population served tends to increase with the number of locations. At the same time, some discontinuities can be pointed out. First, 40 locations seem to be the threshold beyond which it becomes possible – in Turin – to ensure 10-minute accessibility to a given service for about two thirds of the population, and 15-minutes accessibility for over 80% of the population. Conversely, over 450 locations of sport facilities are just sufficient to ensure 5-minute accessibility to half of Turin's population. Secondly, opportunities for rationalising the spatial distribution of locations emerge. For example, 151 locations of social care services are accessible in 10 minutes for 70.7% of the inhabitants, a percentage which is lower than the 80.8% ensured by only 78 post offices. Similarly, 218 kindergartens are sufficient to ensure for all the three time

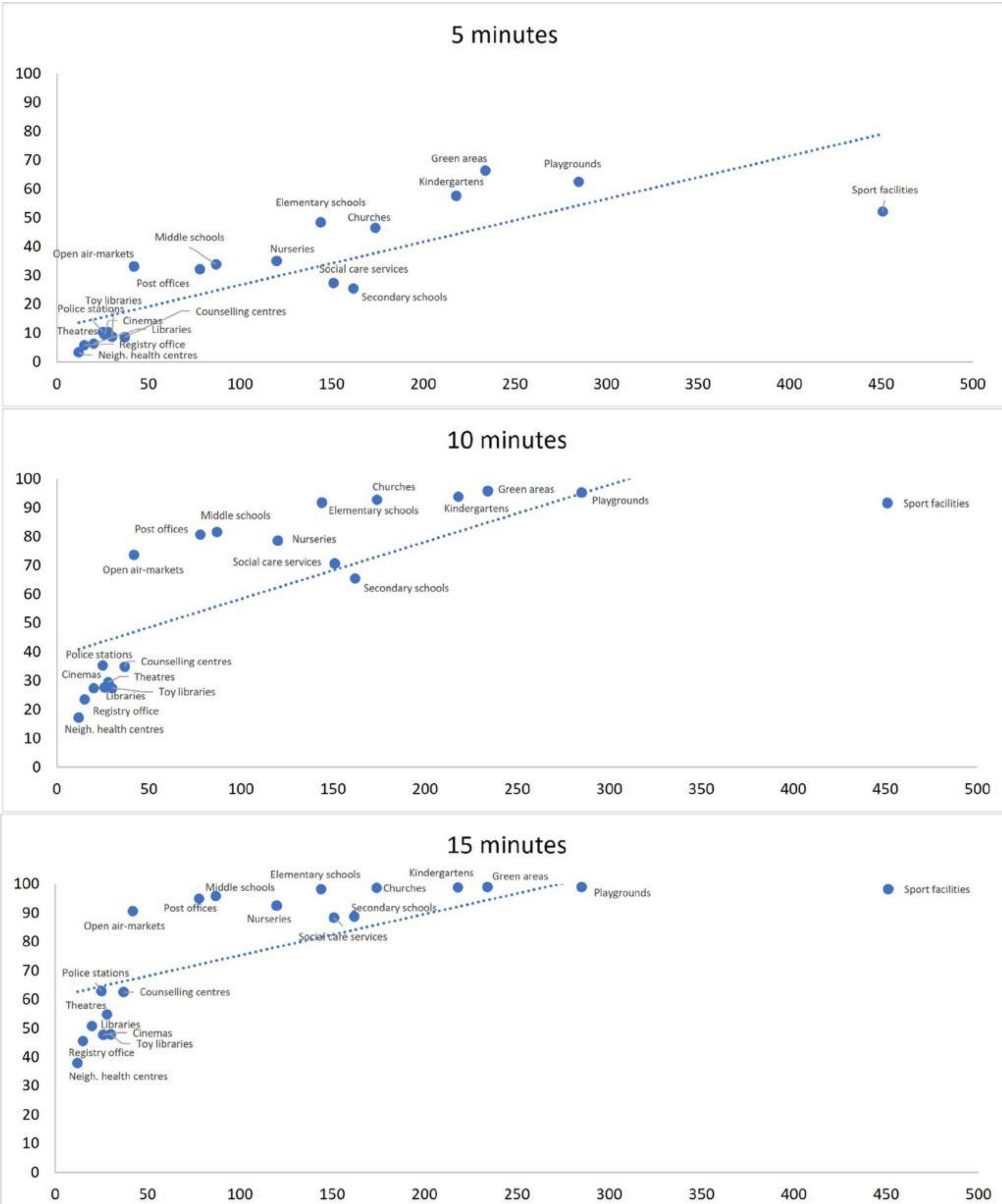

Fig. 8. - Relationship between the number of locations of each service (*x-axis*) and the percentage of the population served by this service (*y-axis*) within a 5, 10 and 15-minute walk.

thresholds greater accessibility than twice the number of locations of sports facilities (451).

4.4. Multi-service analysis

A further elaboration was aimed at calculating how many different services (among the twenty that were considered) could be reached in 5, 10 or 15 minutes from each census tract. Figure 9 shows these results for the three time thresholds. Instead, Figure 10 shows the cumulative percentage of the population of the whole city that can reach at least a certain number of different services within the three time threshold.

From a spatial point of view, it is possible to recognise that most of the least served census tracts are located in the outer part of the city (in particular in the eastern hilly area), where the service locations are less widespread, the road network is less dense and the census tracts are wider. In the inner part of the city, differences among census tracts are more pronounced for the 5-minute threshold, while they become more homogeneous for the 15-minute threshold. In general, anyway, no evident gradient emerges from the centre of the city toward its outer areas; tracts seem to have greater accessibility to multiple kinds of services in the part of Turin built before 1945 (see Fig. 1), where the road network is substantially dense, but in particular for the 5-minute threshold this is not so regular.

Considering the whole city, Fig. 10 shows that a 5 minutes' walk allows to access a maximum of 14 types of services, and this is possible only for 0.1% of the residents. Within this time, 9.5% of the population can access at least 10 different services, 63.9% can reach 5 services, 97% at least 1 service; this leaves 3% of the inhabitants who cannot access any service at all. Increasing the time threshold to 10 or 15 minutes drastically modifies the level of service. In 10 minutes, 84.6% of the population can access 10 services (95.9% in 15 minutes), 25.5% can reach 15 services (71.4% in 15 minutes); 0.3% can access a maximum of 19 services, while in 15 minutes 0.4% of the inhabitants has access to all twenty services.

4.5. Sensitivity analysis on time thresholds

Finally, a rapid sensitivity analysis was carried out to verify how a slight change (±1 minute) in the 15-minute threshold modifies the percentage of the population that can access a given service. Figure 11 shows how much the percentage of the population that can access a given service in 15 minutes (represented on the *x-axis*) decreases or increases (in terms of percentage points, on the *y-axis*) if a 14-minute or 16-minute threshold is adopted respectively[3]. As can be seen, the positive change due to one more minute and the negative one due to one less minute are nearly symmetrical. Moreover, the change is more significant the lower the 15-minute percentage is. Up to a 15-minute percentage of 63%, a ±1 minute variation increases/reduces this percentage by about 4-5 points; between 65% and 95%, this change decreases progressively in absolute terms; over 95%, the same ±1 minute variation modifies the percentage by less than 1 point.

5. Discussion

The analysis of the city of Turin described in Sections 4 and 5 can be used to assess whether or not Turin conforms to the model of the 15-minute city. Given that more than 70% of its inhabitants can walk to 15 out of the 20 considered kinds of services within this time threshold, one

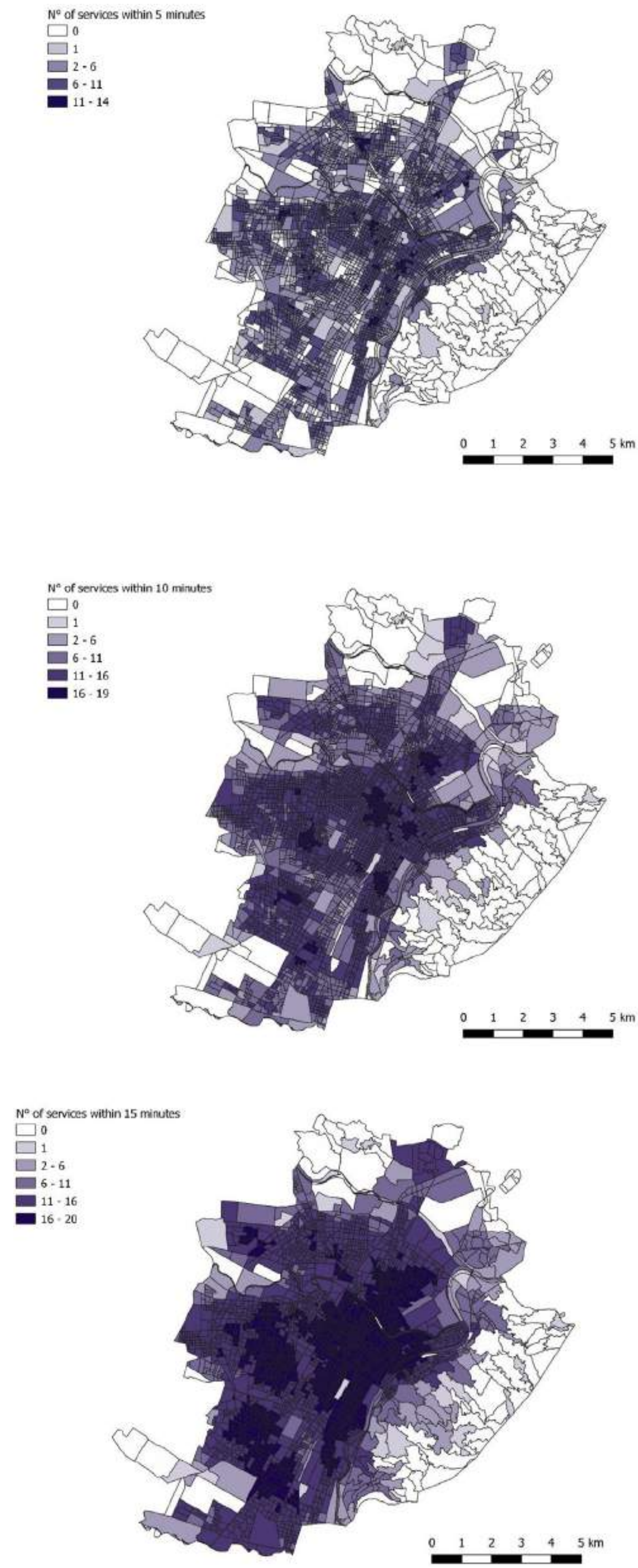

Fig. 9. Number of different services that are accessible from each census tract through a 5, 10 or 15 minutes' walk.

[3] This sensitivity analysis is very time consuming, because it requires repeating the application of the entire methodology for each new time threshold taken into account. This is why we considered only ±1 minute with respect to the 15-minute threshold. In any case, it might be interesting to evaluate further variations (e.g., ±2 or ±3 minute) for each threshold considered.

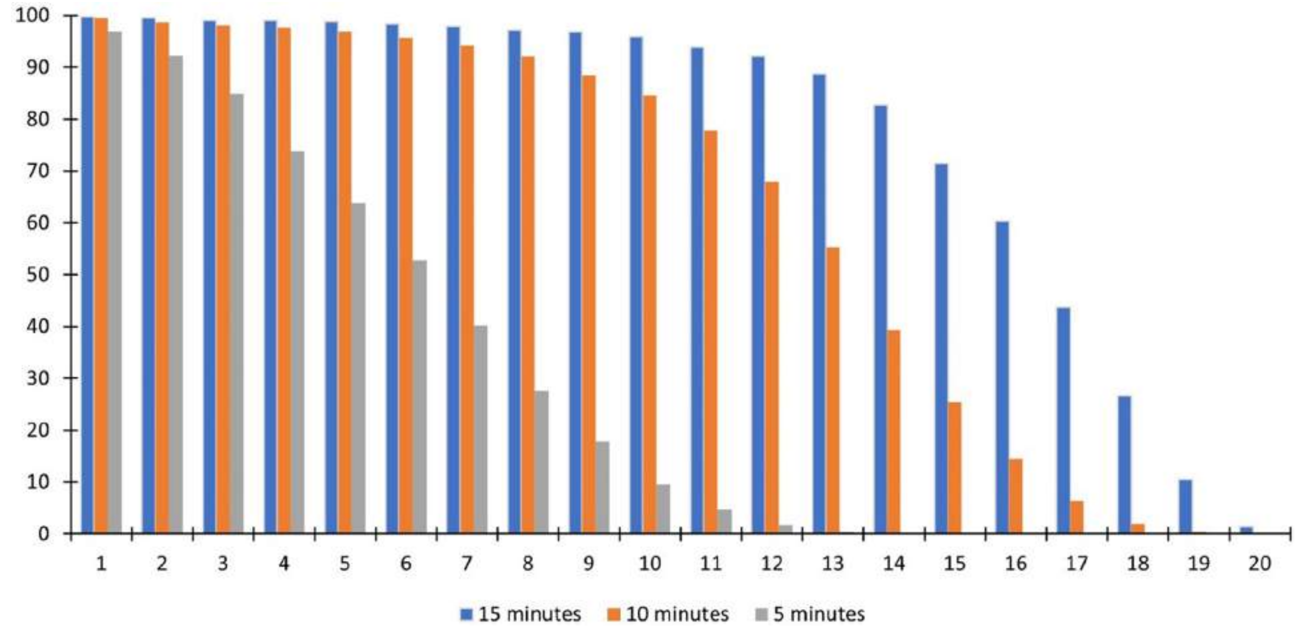

Fig. 10. Percentage of Turin's population (*y-axis*) that can access at least a certain number of different services (*x-axis*) through a 5, 10 or 15 minutes' walk.

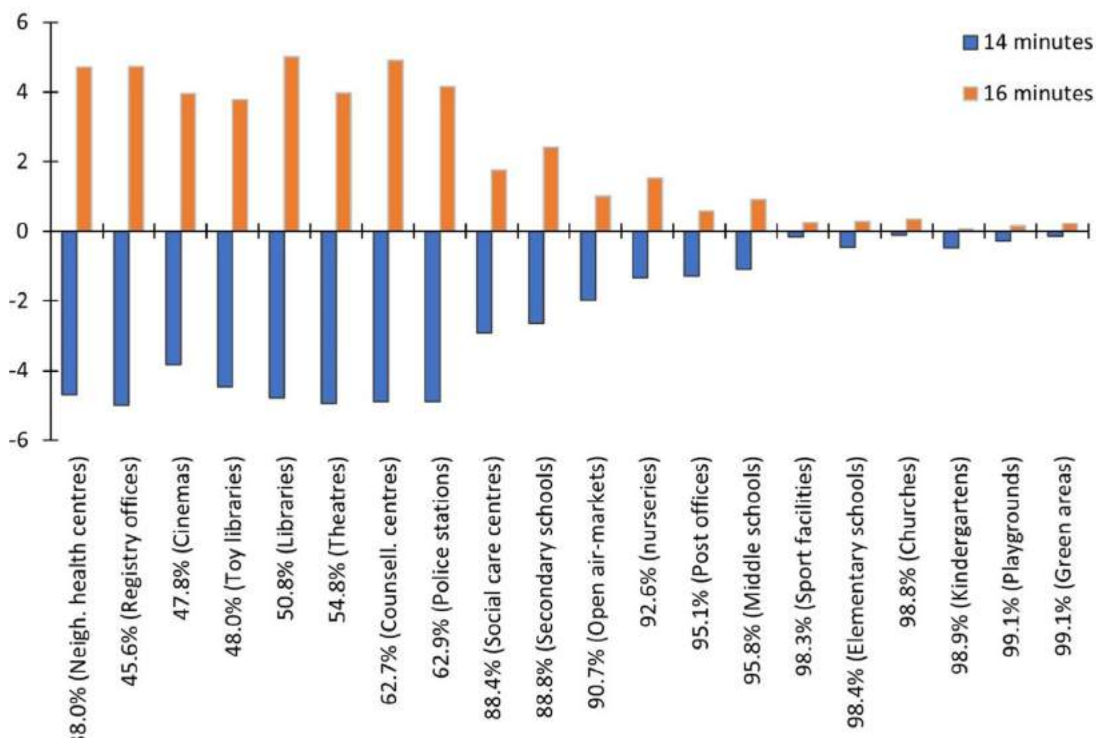

Fig. 11. Change of the percentage of the population that can access a given service in 15 minutes if a 14-minute or 16-minute threshold is adopted.

could imagine that it does[4]. But the answer probably cannot be binarily unambiguous.

Firstly, the percentage of the population that can access at least one location of a given service varies greatly from service to service, as well as depending on the time threshold. Currently, about 9 out of 10 Turin's inhabitants can reach schools of all levels, post offices, churches, green areas, playgrounds, sport facilities by a 15 minutes' walk; some of these services are already accessible by over 90% of residents in just 10 minutes. Then, the 20-minute threshold, often proposed as the target for low-density neighbourhoods, seems poorly appropriate for dense cities like Turin, at most, it could be set for services such as neighbourhood health centres, registry offices, playrooms and cinemas, as these are currently accessible in 15 minutes only to less than 50% residents. In contrast, the 5-minute threshold is probably excessively ambitious for most

[4] Despite most of the city was built before 1971, as anticipated in section 3.2, the current spatial distribution of the services covers most of the residential areas of the city, also thanks to the reuse from the 1990s of a great amount of abandoned industrial areas, which were mostly converted to residences and services.

services, even though some of them (kindergartens, green areas, playgrounds and sports facilities) are at present accessible by a 5 minutes' walk for over 50% of Turin's residents.

In this sense, it is questionable whether a unique time threshold is appropriate, or whether it would be more useful to adopt different target thresholds for different services (for example, 10 minutes for green areas and 15 minutes for cinemas). This would probably weaken one of the key factors for the success of this planning concept, i.e. its extreme simplicity; on the other hand, it would allow identifying different "desired" accessibility time thresholds through surveys, interviews etc., which can be carried out to co-define with residents which services are essential at the neighbourhood level and the maximum time citizens would accept to take to walk to a location of these services. As stated by Capasso Da Silva et al. (2020), "accessibility is a metric, but what are acceptable parameters of what is considered accessible must be set through policies" (p. 1). For example, a survey carried out in Guangzhou (Zhou, 2019) showed that elderly people over 70 were very time-sensitive to the trip distance to public facilities and considered a 15 minutes' walk unsuitable for their age. The normative adoption of the desired thresholds could allow identifying which actions – e.g., walkability improvement or spatial re-distribution of service locations – are primary in the different parts of the city.

Anyway, the identification of the most appropriate time threshold for accessing services cannot be based only on the demand side, but should take also into account the supply side. As a matter of fact, there is a trade-off between these two points of view: on the demand side, a high number of locations of a service would reduce the time threshold to access them, as shown in Section 4.3 (but at risk of worsening the cost efficiency of the service provision); on the supply side, a limited number of locations would allow some economies of scale (in terms of cost reduction for example for water provision, garbage collection, heating etc.; see Gómez-Reino et al., 2021), but at risk of worsening the spatial accessibility of these locations for users.

Accessibility indicators can help to find the balance between these two sides. Since its original definition by Hansen (1959), accessibility links land use (i.e. the location and attractiveness of an opportunity, for example a certain service) and transport variables (i.e. the generalised cost of travelling to reach that opportunity from a certain origin). As anticipated in section 2, in most cases, current approaches to putting the 15-minute city concept into practice focus on the transport variables, i.e. improving accessibility to services by increasing the speed of the trip to these services (through widened pavements, new pedestrian streets and cycle lanes etc.); less attention is paid to land use variables, i.e. the number and size of the service locations which are the destination of the trip. Actually, as seen in Section 4.3, the number of these locations is crucial in determining the percentage of the population which can access a service within a given time threshold. Moreover, these locations are not all the same. They may differ in terms of "attractiveness": for example, the number of screens and seats in a cinema, the number of plays in a playground, the number of stalls in an open-air market, the number of books in a library etc. On the demand side, this might make a location of a certain service more interesting for residents – even if farther away – than another. On the supply side, this attractiveness size can require a minimum number of users/customers that a service location has to attract in order to compensate for its operating costs. In other words, neglecting the different sizes of the locations can alter the cost efficiency of the number and spatial distribution of these locations (which is a key issue in public service provision nowadays, due to the shrinking financial resources of public administrations).

In order to take this dimension into account, cumulative opportunities indicators (which simply sum up the number of locations inside an isochrone, as it has been done in this paper; see also Cervero et al., 1999; Koenig, 1980) could be integrated with classical gravitational indicators. In this approach, for each census tract only service locations accessible within a certain time threshold (for example 15 minutes) would continue to be counted, but each of them would be "weighted" according to both its attractiveness and the generalized cost of accessing it (which includes not only time costs, but also qualitative issues: the same 15 minutes' walk can be much more pleasant if done under the shadow of a row of trees along the road, where car speed is moderated etc.). Accessibility indicators of this kind were proposed, for example, by Black & Conroy (1977) and Breheny (1978).

More complex indicators of accessibility were elaborated by Botham (1980), Fotheringham (1986), Shen (1998), van Wee et al. (2001) and Weibull (1976), in order to weight the attractiveness of service locations in relation not only to their size, but also to the number of their potential users. These indicators can be useful in identifying the optimal balance between the number, size and spatial distribution of service locations (given the spatial distribution of users). In a case like Turin (see Section 4.5), some services are overconcentrated in parts of the city (from which residents can access more than one of their locations within the considered time threshold), while scarce or absent in other parts. Most of the twenty considered services are public (except for cinemas, theatres and private nurseries) and could probably be re-distributed to other abandoned areas to serve the residents of the city more homogeneously and evenly. Balletto et al. (2021), for example, explain how to exploit disused public properties from the perspective of the 15-minute city.

As anticipated in Section 3.1, in this paper the attention has been focused on the diagnostic application of the methodology; however, in the planning phase it can be easily used to simulate how adding a new location of a given service in a certain (currently poorly served) part of the city, or modifying the spatial distribution of a few locations, could increase (or not) the percentage of Turin's population that can access the service, so increasing the spatial equity of accessibility.

6. Conclusions

This paper has tried to develop a methodological framework to analyse the levels of walking accessibility to services throughout a typical dense and walkable European city such as Turin. Most issues of the 15-minute city can be traced back to more or less past planning ideas such as the garden city, the neighbourhood unit, the superblock etc., which were generally conceived for designing new districts or urban areas, rather than being applied to existing cities. In the latter, the distribution of services is much more scattered and less homogeneous between one neighbourhood and another, so it can be more appropriate to address the issue throughout the whole city, and not at the level of the single neighbourhood.

The analysis of the city of Turin carried out in this paper has been aimed at identifying the level of walking accessibility to twenty kinds of local services from each census tract of the city. As just one case study has been considered, any claim of exhaustiveness and systematicity must be excluded; moreover, the analysis could be further articulated by including other transport means (e.g., cycling), more kinds of services, more disaggregated service users (children, elderly etc.). Nevertheless, some general conclusions can be drawn.

Firstly, the results show that, at least in dense and walkable European cities such as Turin, the 15-minute threshold cannot be always assumed as the necessarily most appropriate target, as many services can already be reached by foot within this time, or even in 10 minutes, by the majority of the population. Different thresholds could have to be set in different cities, or even in the same city for different services. In this sense, involvement of urban actors can be desirable to identify which local services are considered essential, which different time thresholds are acceptable to reach each of them and so on.

Secondly, it is true that in European cities such as Turin, probably more than in many Australian or American cities, walkability is often already widely assured throughout the city, as nearly all streets have pavements and spaces reserved for pedestrians. Although there is often ample room for further improvement in this walkability, the current levels of accessibility to services are significantly determined by another factor, namely the number and spatial distribution of the locations of these services. As anticipated in Section 2, this variable is currently given little consideration in the narrative, literature and practices of the 15-minute city. In this sense, it could be useful to recover some tools and approaches to complexify the operationalisation of the 15-minute city and plan it with reference not only to the demand side, but also to the efficiency of the spatial distribution of services and opportunities.

Finally, in the last two decades, the concept of accessibility has received renewed attention also in theoretical terms, by researchers who outlined how accessibility cannot be reduced only to the two dimensions of land use and transport; conversely, it is entrenched with spatial, economic, social, and personal factors, which influence the affordability of services and opportunities (Handy, 2020; Lucas et al., 2019; Silva et al., 2019). These factors are often neglected in the 15-minute city approach; however, they are crucial in order to design this city first of all for the most vulnerable citizens such as children, the elderly, the disabled etc., precisely those who often cannot use the car to access essential services (Calafiore et al., 2022; Guzman et al., 2021; Weng et al., 2019).

In conclusion, a major challenge for future academic research on the 15-minute city seems to be finding a set of accessibility indicators to operationalise the concept in all its complexity, without losing the simplicity and communicability of its narrative.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Approach for simulating vehicle-based supply of sellable data products in smart cities – Parking space data as a use case

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Data quality

ABSTRACT

Mobile devices, sensors, 5G networks, digital platforms and data marketplaces provide emerging possibilities for smart cities and data business. This paper introduces a novel Data Market Simulation (DMS) approach that assists data suppliers in the following: optimising vehicle-based supply of sellable data and creation of value from data; evaluating vehicle routes and the quality of data that the vehicles on these routes will produce; and reviewing how well the routes will serve the potential data users before beginning the supply of data in cities. The DMS approach supports iterative development and optimisation of routes and route parameters. If the goals are not achieved in the route plan, the data user can use the previous simulation results as a start point, develop the routes and route parameters in the simulation model, and then evaluate the updated route plan in simulations. The route development and simulation can be continued until the desired targets are met in the route plan. The DMS approach is evaluated in a small-scale experiment that simulated the use of autonomous busses and drones for the supply of parking space data in the LuxTurrim5G+'s smart pole pilot network in the city of Espoo in Finland.

1. Introduction

Mobile devices, sensors, 5G networks, digital platforms and data marketplaces (DMPs) provide new possibilities for creating value from data. Vehicles, such as autonomous busses and drones, contain a growing number of sensors to capture situational data in cities. There are advanced digital platforms, processing components and algorithms for data processing and preparing sellable data products to DMPs. 5G networks offer low latencies and high data transmission rates and enable the use of local, cloud and edge computing in sensor data processing and the creation of highly responsive applications for near real-time situational data.

There are three key actors in data business (Schroeder, 2016): *data suppliers* create, collect, mash-up and process data for various purposes; *data users* find new possibilities for utilising data in their own business; and *data facilitators* provide technologies and support for finding and exploiting new data. *Data quality, data freshness* and *data price* (QFP of Data) affect the use and value of data. Time-critical applications, such as traffic and public safety-related services, require fast response times and near real-time situational data. Cost-centric users may want low-cost and low-quality data, but value-centric users, such as professional users, may, in turn, want to use high-quality, but also more expensive, data in applications.

QFP of data depends on the quality and volume of sensors that can be in fixed positions, mobile devices, or vehicles. The latencies, data transmission rates and reliability of network connections can affect the data freshness and quality. Unreliable network connections can cause breaks in data delivery and lacks and faults in the transmitted data and the low data transmission rates can limit the data value in near real-time applications and resolution of the data (e.g., image or video data) that can be delivered.

Thirdly, the data processing components and algorithms used in local computational units, cloud and/or edge cloud affect QFP of data. DMPs and payment methods affect the delays related to data trade, pricing of data and use of data in different use cases.

Data suppliers can have autonomous vehicles that move in a city and are capable of producing sensor data via their embedded sensors (e.g. LiDARs and cameras), processing the data, and publishing the data as sellable data products in DMPs. This paper focuses on simulations that enable data suppliers to optimise the vehicle-based supply of sellable data products and creation of value from data before starting the supply of data in a real environment. The supply of sellable data products can be based on two processes that enable data suppliers to earn revenue from produced data (in Fig. 1):

1) **– Data production process** that gathers sensor data, processes the data, and prepares sellable data products to a DMP.

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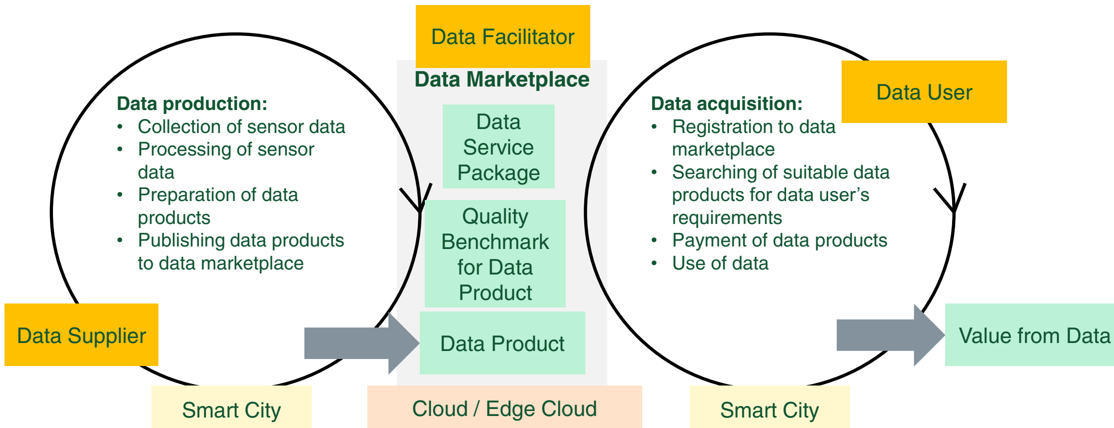

Fig. 1. Two key processes to create value from sensor data in a smart city.

2) **Data acquisition process** – Data users register to a DMP, search and purchase needed data products from the DMP and finally use the purchased data.

The creation of value from data requires that the data suppliers supply sellable data products that fulfil the requirements of data users. This paper focuses on these challenges and makes the following contributions:

- Presents the novel Data Market Simulation (DMS) approach to support the planning of vehicle-based supply of sellable data products.
- Presents the Data Product Quality Benchmark (DPQB) and Data Product Iron Triangle (DPIT) concepts. DPQBs assist quality-aware supply and use of data products and DPITs provide the QFP (*Data Quality, Freshness*, and *Price*) visualisations for the produced data.
- Introduces the DMS tool prototype that assists data suppliers in developing routes for vehicles to produce the following: a) more value from data and b) data products to satisfy end-user requirements for value, costs, quality and coverage.
- Evaluates the approach using a simulated supply of parking space data produced by autonomous vehicles and drones.

This paper is organised as follows: Section II provides the background for this work. The DMS approach is described and evaluated with a use case in Sections III and IV, and results are discussed in Section V. Finally, concluding remarks and recommendations are provided in Section VI.

2. Background

This work relates to the Neutral Host Pilot and LuxTurrim5G+ projects (https://www.luxturrim5g.com/). LuxTurrim5G+ develops smart lighting poles equipped with integrated antennas, 5G base stations, cameras, air quality and weather sensors, screens and drone docking stations, and builds a pilot smart lighting pole network in the Kera area in the city of Espoo in Finland. Neutral Host Pilot studies smart city data business and develops a data platform and data marketplace to manage and publish the data produced by the pilot network, as well as devices and vehicles connected to it. The following subsections discuss the key components of the development, such as data business, digital platforms and data marketplaces, 5G networks and solutions that enable the production of situational data of parking spaces.

2.1. Data business

The core idea of data business is to create value from data by enabling the sharing of data between actors in the markets and to obtain more users for the data. Data business provides direct business benefits for data suppliers that will earn revenue from supplied data and for data users, such as third-party developers that can access data more easily and cost-efficiently from DMPs and digital platforms. Standardised licensing models for data trade and regulations for data access and usage provide a base for data economy (Spiekermann, 2019) and may lower the transaction costs of gathering data (Pitkänen et al., 2019).

The number of companies sharing data within their business networks has been growing steadily alongside new technological innovations, such as Electronic Data Interchange (EDI), Internet EDI and Web service APIs (Application Programming Interfaces), being now 49% in Finland, for example (Huttunen et al., 2019). Data sharing creates a significant market in Europe, and according to Micheletti and Pepato (2019), the value of the data economy exceeded 300 billion euros in 2018 for EU28; with an annual growth of 12%, the market will reach 680 billion euros by 2025. Data business and its importance is reflected by the EU strategies, such as Digital Single Market, European Data Economy, Digitizing European Industry and the Internet of Things (EC, 2017).

2.2. Digital platforms and data marketplaces

Digital platforms are often referred to as "electronic marketplaces" that facilitate the exchange of goods by using pricing strategies (Fruhwirth et al., 2020). The platform participants co-create value between each other and create a "network effect", which is when a good or service acquires more value to its user as more users adopt it. Network effects create self-reinforcing mechanisms that lead to market leadership, a large customer base and the establishment of boundaries for other players (Fruhwirth et al., 2020).

Data marketplaces (DMPs) are becoming increasingly important as the data business and data sharing technologies are emerging. Spiekermann compares in (Spiekermann, 2019) DMPs based on selected characteristics, e.g. whether they are transaction-centric or data-centric, cross-domain or domain-specific, or whether their architecture is centralised or de-centralised. DMPs offer a data exchange infrastructure by acting as intermediaries that create a link between data providers and data buyers (Spiekermann, 2019). Many marketplaces have emerged and are growing (e.g., Dawex and IOTA).

Many marketplaces are dedicated to static datasets, but some are also considering the use of real-time data sources and streams. BDEX Data Exchange Platform is a dedicated marketplace for consumer data, enabling focused marketing and selling. Streamr is creating a data economy for real-time data streams, where a data supplier can sell data and receive data coins in return and using the coins to buy data from other sources.

2.3. 5G Networks

The 5G networks offer wireless connectivity with tremendously increased data rates, substantially reduced latencies and improved quality-of-service (QoS) for new devices and applications (Zhang et al., 2020). The 5G networks enable creation of real-time immersive applications (Lema et al., 2017) and remote interaction over networks, use of services without feeling any distance between the client and the connected machine, and they provide more flexibility to manage connections in Machine-to-Machine (M2M) services and interactions (Gahlot et al., 2017).

The 5G networks support data economy and trading of near real-time data via DMPs and provide more flexibility for data processing. For example, mobile devices can deliver captured video feeds over 5G connections for edge computing components that perform more complex data processing (e.g., ML-based segmentation for detecting physical objects in the video feeds) and prepare data products available to DMPs.

2.4. Solutions for producing situational data of parking spaces

It is often difficult to find a parking space in busy city environments. Fluent parking requires situational data of parking spaces. Cameras or ultrasonic sensors can capture data of several parking spaces and thus provide a scalable solution for parking space detection (Baroffio et al., 2015). The following paragraphs discuss a few existing parking space detection solutions:

a) **Ultrasonic sensors in vehicles** – The ParkNet system is based on the vehicles that are equipped with GPS receivers and passenger-side-facing ultrasonic rangefinders to determine parking spot occupancy while driving by (Mathur et al., 2010). The data is aggregated at a server that builds a real-time map of free parking spaces. The ParkNet system has achieved 95% accuracy for parking spot counts and over 90% accuracy for occupancy maps (Mathur et al., 2010).
b) **Smart cameras in fixed positions** – mAlexNet uses Convolutional Neural Network (CNN) for detecting parking space occupancy on smart cameras in fixed positions (Amato et al., 2017). The classification of 50 parking spaces and the transmission of the results to a Web server takes about 15 seconds on the Raspberry Pi 2. The mAlexNet reached over 90% accuracy for the CNRPark dataset, but changes in lighting conditions, weather conditions, occlusions and reflection patterns might decrease the accuracy of camera-based occupancy detection of parking spaces (Amato et al., 2017).
c) **Structural similarity (SSIM) decision scheme and CNN-based low-latency outdoor parking occupancy detection for camera feeds** – The solution enables parking occupancy detection in real-time from live camera feeds without causing deterioration of the detection accuracy (Ng et al., 2020). The computation time of detection application is shortened by more than six times when compared to the pure CNN classification when there is only a single instance of parking occupancy change, registering a processing time of 0.45 seconds when running on a Raspberry Pi 3.

The rest of this paper focuses on the vehicle-based supply of sellable data of parking spaces that is based on the following: a) 5G networks; b) autonomous vehicles that have sensors, such as cameras, depth sensors, LIDARs or ultrasonic sensors to capture sensor data of parking spaces; and c) processing components that use the sensor data and prepare data products for parking spaces to DMPs.

3. Method for optimising vehicle-based supply of sellable data products

The supply of sellable data products that provide fresh enough data with the needed quality level for different data users requires planning for maximising creation of value from data. The DMS method was developed to assist in the planning of vehicle-based supply of sellable data products. The method consists of the following steps (see, Fig. 2):

1) **Development of data product** – This step develops a sellable data product to create value for data users and data suppliers.
2) **Determination of data users** – This step determines potential data users and their requirements (DPIT parameters) for the data product.
3) **Creation of simulation model** – The data supplier adds observation targets and routes to the simulation model that will then describe how data products are produced on the routes of vehicles.
4) **Simulation** – This step uses the simulation model and simulates the vehicle-based supply of data products, calculates estimates for the value creation on the routes and finally visualises the results that assist a data supplier to compare the routes from the viewpoints of value creation, specified data users and observation targets. The simulation can also generate sample data to assist in the development of applications/services for data products.

The simulations support iterative development and optimisation of vehicle routes and route parameters. If the goals are not achieved in the route plan, the data user can use the simulation results, modify the routes and route parameters in the simulation model, and evaluate the updated route plan in simulations. The route development can be continued until the goals are achieved.

The following subsections describe the steps of the DMS method in more detail.

3.1. Development of data product

There are many practical issues that must be solved in data product development. A data supplier can have raw or processed data that potentially have value for data users. They must select DMPs for the data product and create a data product specification determining data models, licencing conditions, terms of use and SLAs for the new data product. A feasibility study must be also performed for ensuring that there are enough processing capabilities for preparing the data products to the DMPs and APIs and network capacity for delivering the data for data users.

The data supplier can have ideas of use cases (UCs) that could benefit from the data product. For example, two clear use cases for the parking space data exist: parking of vehicles and traffic planning. The data supplier can evaluate UCs and identify requirements that these UCs set for data products. For example, searching for a parking space requires fresh enough data of parking spaces. Traffic planning requires, in turn, that there is a needed volume of statistical parking space data available for traffic planning tasks.

The value of data depends on the data freshness and quality in many use cases. For example, it is important for motorists to get fresh and accurate information about the occupancy of parking spaces, as the situation changes continuously. The data supplier can analyse UCs, determine parameters that affect the quality and value of data products in UCs and finally determine Data Product Quality Benchmark (DPQB) and quality categories for the data needed in the use cases

DPQB supports quality-aware supply and use of sellable data products. DPQB (see, DPQB in Fig. 3) determines a *name* for DPQB and the *type* and *quality categories* in a prioritised order for the data products associated with DPQB. A quality category determines a reference price and requirements for data products that belong to the category. The requirements can cover the quality, freshness (max. age parameter) and accuracy of the data, and determine the maximum time (max. response time parameter) it takes to deliver a purchased data product for data users.

Fig. 3 and Fig. 4 depict DPQB that has four quality categories for parking space data:

- **High-quality data category**: Data products in this category offer fresh, near real-time data (under one-minute-old data) and thus provide very valuable data for motorists.
- **Medium-quality data category**: Data products in this category provide quite fresh data (under three-minute-old data) and offer signifi-

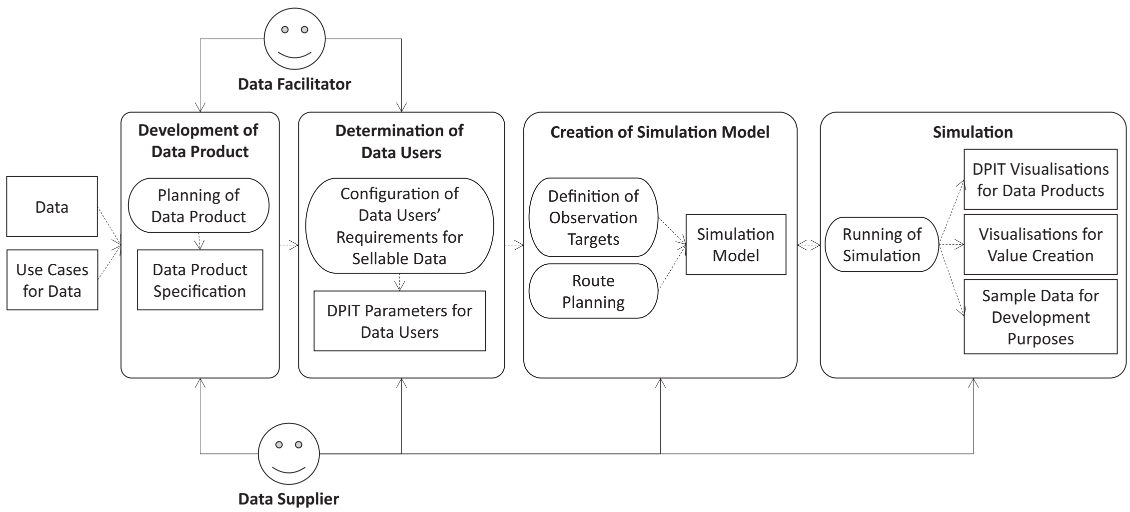

Fig. 2. The steps of the DMS method.

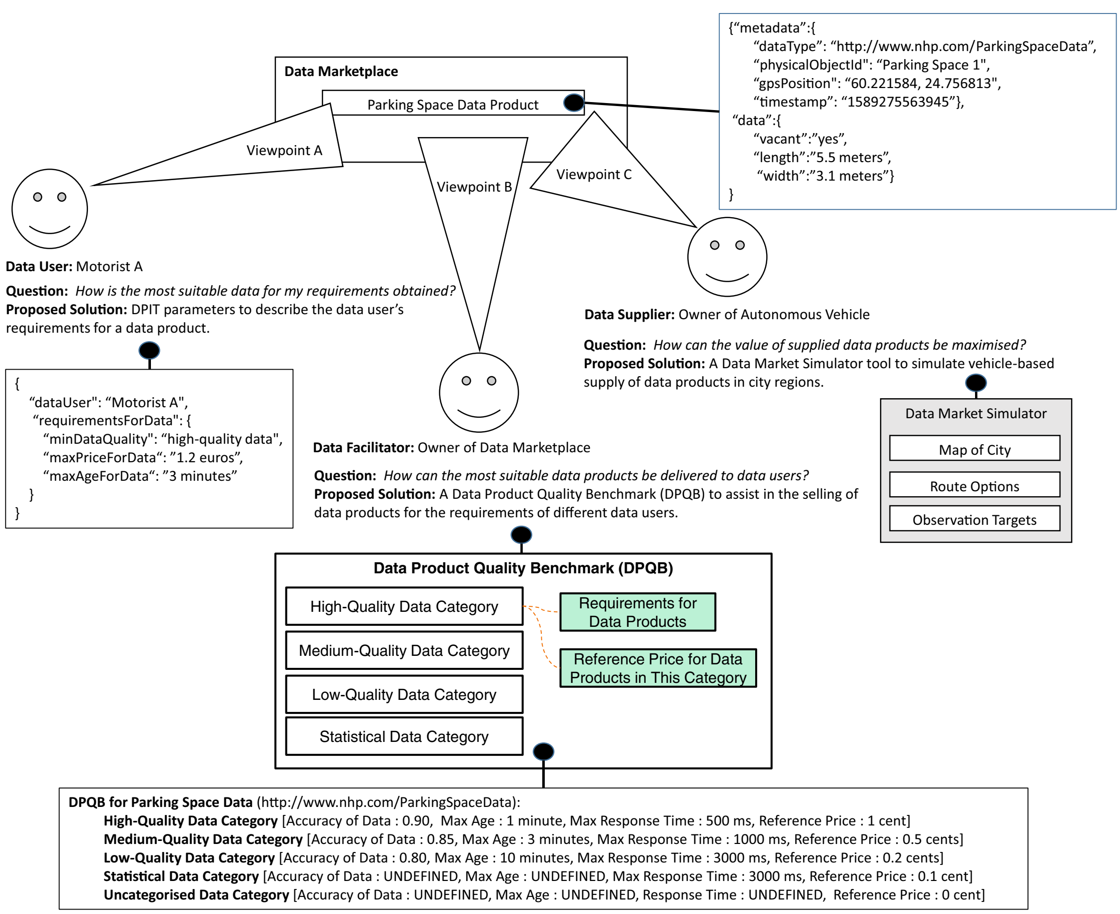

Fig. 3. Example of quality-aware supply of sellable parking space data.

cant value for data users. However, the data can be outdated if there is a lot of traffic and the parking situation changes rapidly in the region.

- **Low-quality data category**: Data products in this category offer under 10-minute-old data and provide some value for data users as it assists in the finding of free parking spaces in some cases.
- **Statistical data category**: Data products in this category provide over 10-minute-old data and can have value in traffic planning or in the development of data-driven products and services.

3.2. Determination of data users

A data user can have requirements for QFP of data that can be determined in Data Product Iron Triangle (DPIT) parameters. Firstly, they can have a certain amount of money for purchasing the data products and certain requirements for data freshness and data quality. Fig. 5 depicts DPIT parameters for data user A, B and C. A value-oriented data user A is ready to pay the full price for high data quality and freshness. More cost-oriented data user B is ready to pay a medium price for

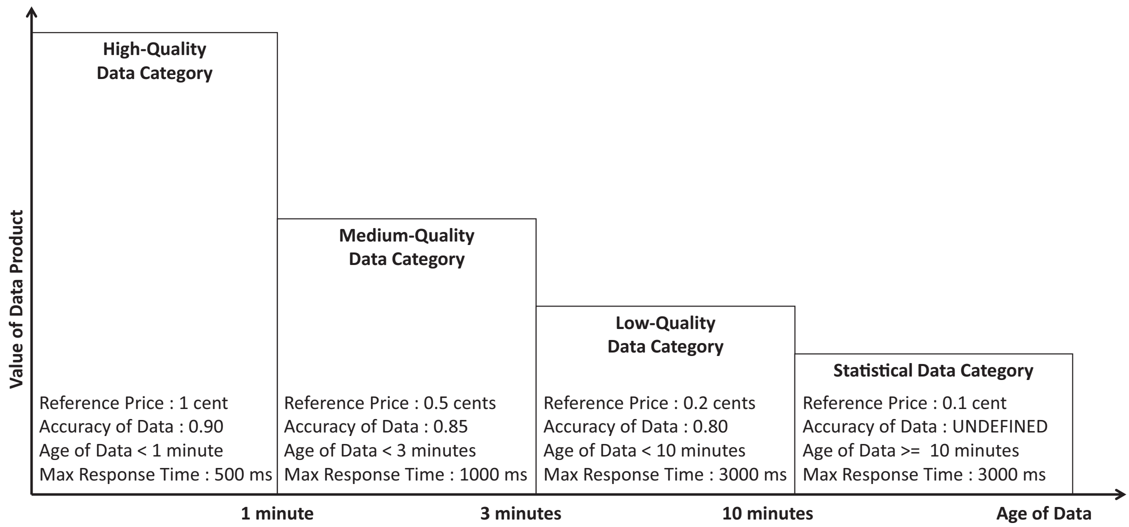

Fig. 4. Four quality categories for parking space data.

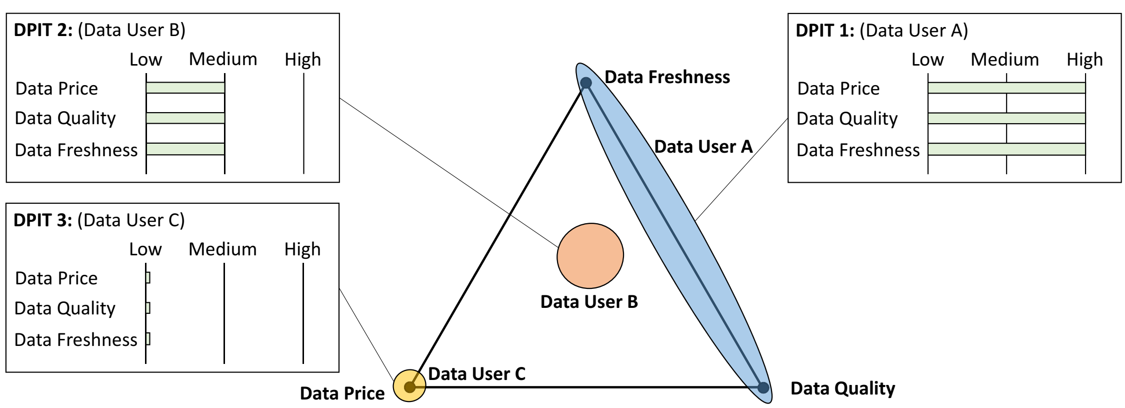

Fig. 5. DPIT parameters for data user A, B and C.

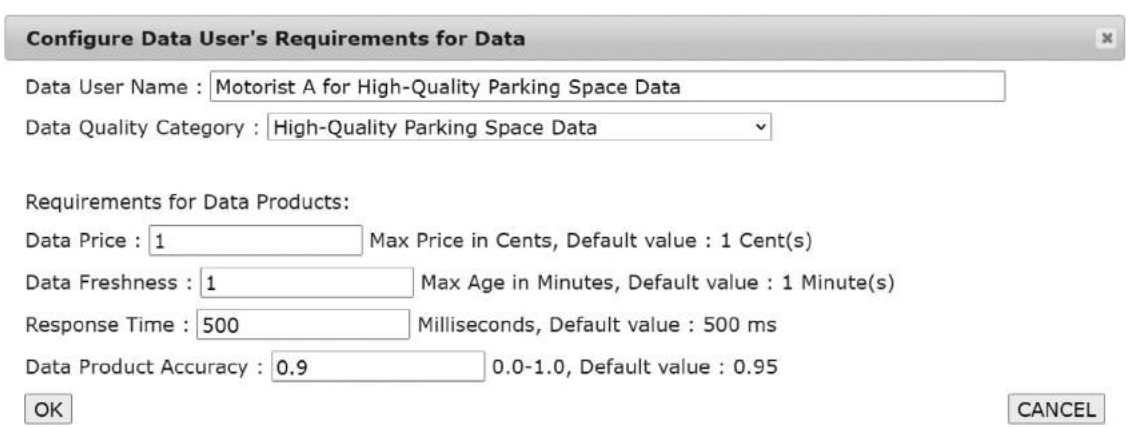

Fig. 6. Configuration of DPIT parameters for a data user.

medium data quality and freshness. A cost-oriented data user C wants to minimise costs and use older, low-quality data.

In the determination of data users, a data supplier first selects the most suitable data quality category for each data user. The quality category determines the default DPIT parameters for the data in the category. The data supplier can modify these parameters for determining user-specific requirements for QFP of data considering, for example, the freshness and accuracy of the data (see, Fig. 6).

3.3. Definition of observation targets

Vehicles produce data products for observation targets (e.g., for parking spaces) in simulation. The DMS tool provides editing tools for inserting observation targets and routes into simulation models in the satellite map view of Google Maps (see, Fig. 7). If needed, the data supplier can also configure plug-in components or random sample data models for observation targets to generate sample data in a simulation

Fig. 7. A simulation model that comprises four routes, five observation targets groups and 455 observation targets for the parking spaces in parking areas A and B in the satellite view of the DMS tool.

that assists the development of applications/services for data products. However, the plug-in components or random sample data models are not needed to be determined if the simulations are used to serve the route planning purposes only.

Fig. 8 depicts a random sample data model (as JSON) for the generation of parking space data that consists of the *vacant, length*, and *width* fields. The *vacant* field will have a random value so that there is an 80% possibility for value “yes” and a 20% possibility for value “no”. The *length* and *width* fields define the dimensions for the parking space. The *length* field will have a random numeric value in the range of 3.0–6.0 metres and the *width* field will have a random numeric value in the range of 2.5–4.0 metres.

3.4. Route planning

The data supplier draws the planned routes in the DMS tool (see, Fig. 7) and defines the following parameters for each route:

- **Route name**
- **Route enabled** – to select the route to be used in simulation.
- **Route type** – to be “round-trip route” or “ring route”.
- **Vehicle type** - for a vehicle (e.g., “Bus” or “Drone”) that uses the route.
- **Vehicle’s speed** – determines the average speed (km/h) for the vehicle on the route.
- **Max. observation distance** – determines (in metres) the maximum distance between a vehicle and an observation target for which there are produced data products.
- **Data product preparation delay** – time (in milliseconds) that it takes to prepare a data product to DMP.
- **Accuracy of data** – has a decimal value between 0.0 and 1.0 to define the accuracy of the sellable data. For example, the quality of sensors and algorithms used in data processing affect the accuracy of data.
- **Start time for route** – is used for synchronising routes in simulation.
- **Repeats for route** – determines the number of repeats for the route.
- **Stop time at route’s end-points A and B** – determines the stop time at the beginning and at the end of the route.
- **Service break time** – determines the duration for a service break on the route.
- **Number of repeats to service break** – determines how often there is a service break on the route.

3.4. Simulation

The DMS tool uses the simulation model, DPIT parameters, DPQBs and reference prices of the quality categories in simulation of the vehicle-based supply of data products. The simulation produces data products for the observation targets and calculates the following estimates for each time step in the simulation:

- **Value of all data products (ADP_{Value})** – that are produced in the simulation. For example, there can be three high-quality data products for the same observation target. ADP_{Value} assumes that all these data products have value for data users.
- **Value of the best data products in all categories (BDP_{Value})** – BDP_{Value} is based on the assumption that only the best (e.g., the

```json
{
  "type": "Random Data Model",
  "dataType": "http://www.nhp.com/ParkingSpaceData",
  "fields": [
    {
      "fieldName": "vacant",
      "type": "RandomDataField",
      "possibleValues": [
        {
          "value": "yes",
          "probability": 0.8
        },
        {
          "value": "no",
          "probability": 0.2
        }
      ]
    },
    {
      "fieldName": "length",
      "type": "RandomNumericField",
      "unit": "meters",
      "minValue": 3,
      "maxValue": 6
    },
    {
      "fieldName": "width",
      "type": "RandomNumericField",
      "unit": "meters",
      "minValue": 2.5,
      "maxValue": 4
    }
  ]
}
```

Element Type	Attribute	Description	Example Value
Random Data Model	dataType	Determines type for the data element that is generated from the model.	"http://www.nhp.com/ParkingSpaceData"
	fields	Determines the data fields that are included in the generated data elements.	
Random Numeric Field	fieldName	Determines a name for a data field that is included in generated data elements.	"lenght" or "width"
	unit	Determines a unit for a data field that is included in the generated data element.	"meters"
	minValue	Determines lower range for the random numeric value that is included in the data field.	"2.5"
	maxValue	Determines upper range for the random numeric value that is included in the data field.	"4"
Random Data Field	fieldName	Determines a name for a data field that is included in the generated data element.	"vacant"
	possibleValues	Determines the possible values for a data field.	
Possible Value	value	Determines a possible value for a data field.	"yes" or "no"
	probability	Determines a probability for the possible value.	0.2

Fig. 8. A random sample data model for parking space data generation and a table that describes the elements and attributes used in the model.

newest) data product for an observation target in each quality category have value for data users. For example, there can be three high-quality data products for a parking space. Now, in the calculation of BDP_{Value}, a search is made for the best data products for each observation target in each quality category and then the total value for the found data products is calculated.

- **Value of all data products on a route ($ADP_{Value\ for\ Route}$)** – This is a calculated value for all data products that are produced on a specific route.
- **Value of data products that are suitable for a specific data user ($ADP_{Value\ for\ Data\ User}$)** – This is a calculated value for data products that are suitable for a specific data user's requirements and DPIT parameters.
- **Near real-time data coverage for observation targets ($DCOT_{Near\ real\text{-}time\ data}$)** to determine the share of observation targets for which data products in a certain near real-time data category are provided.

The DMS tool visualises the calculated values as line graphs that assist data suppliers to evaluate the creation of value from data from the viewpoint of all data products, from the viewpoint of routes, from the viewpoint of specified data users and from the viewpoint of observation targets (see, Fig. 12, Fig. 13, Fig. 14 and Fig. 15).

The cost, time and quality (The Iron Triangle) are commonly used for measuring the success of project management (Atkinson, 1999). The same requirements relate to the supply of sellable data, too. There are conflicting requirements for data price, data freshness and data quality, because typically it is difficult to produce very fresh and high-quality data with minimum costs. For example, increasing data freshness requires investments in fast network connections to provide high bandwidth and low latencies for data delivery and in processing power for preparing data products timely for data users. Similarly, improving data quality requires investments in better sensors, algorithms and processing components, causing costs to rise and increasing the price of data.

Using the Iron Triangle as a starting point, the Data Product Iron Triangle (DPIT) was developed for visualisation and classification of a) data users (see, Fig. 5) and b) data products (see, Fig. 9). DPIT in Fig. 9 depicts low-cost data products (open data and free sample data), near real-time data products (time-critical data for traffic safety or data used in high-frequency trading) and high-quality data products (high-quality statistical data and accurate point cloud data that is produced by professionals with high-quality laser scanners).

The DMS tool composes data products that have coherent Quality, Freshness, and Price (QFP)-values (there is less than a 5-per-cent difference in the QFB-values) to groups and visualises the groups in DPIT that assist data suppliers to perceive the properties and common characteristics of the data products produced in the simulation (in Fig. 10).

4. Evaluation of DMS method

The DMS method was evaluated in a small-scale experiment that simulated the use of autonomous busses and drones in the supply of parking space data in the LuxTurrim5G+'s smart pole pilot network in the Kera area in Espoo, Finland. The goal was to simulate the production of data of parking area A that contains 423 parking spaces nearby the Nokia Campus in Kera and parking area B that contains 32 park-and-ride spaces nearby the Kera railway station.

4.1. Use case - Supply of sellable parking space data in a smart city

It can be challenging to find situational data of parking spaces, because this data is often located in separate parking management systems or is not available at all. The actors within smart city data economy can offer a solution to the problem (see, Fig. 11). Firstly, a data facilitator can have DMP for the exchange of situational data of parking spaces. Data suppliers can have autonomous vehicles that capture sensor data (e.g., video feeds or point cloud data) in a city and components that use the data, detect vacant parking spaces and measure dimensions for parking spaces, and finally prepare sellable data products for parking spaces to DMP. Thirdly, data users such as motorists can use parking applications that purchase data products from DMPs and search the most suitable (e.g., the closest, cheapest or safest) parking spaces for motorists.

4.2. Use of DMS method

The following paragraphs discuss the use of the DMS method in the experiment in more detail.

Development of data product – The use of the parking space data in parking and traffic planning was analysed, use case requirements were identified for the data, and a Data Product Quality Benchmark

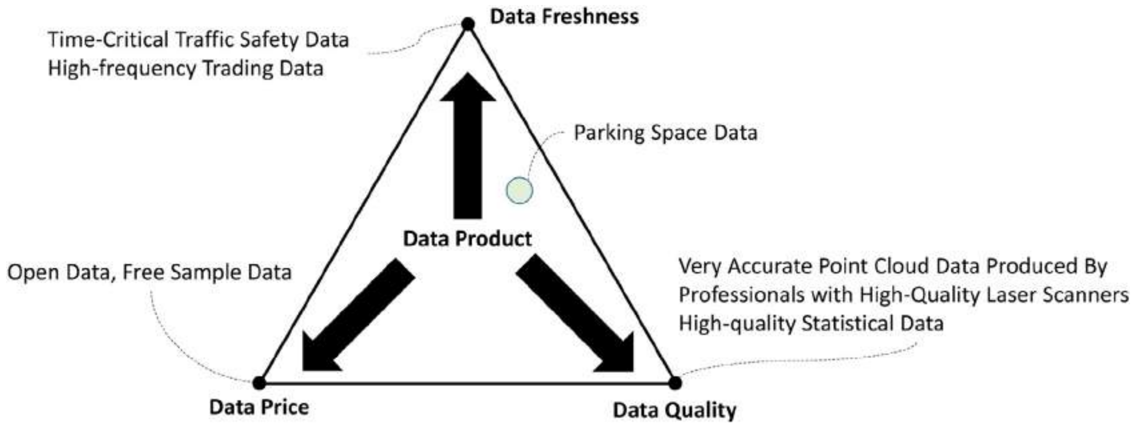

Fig. 9. Examples of data products in a data product iron triangle.

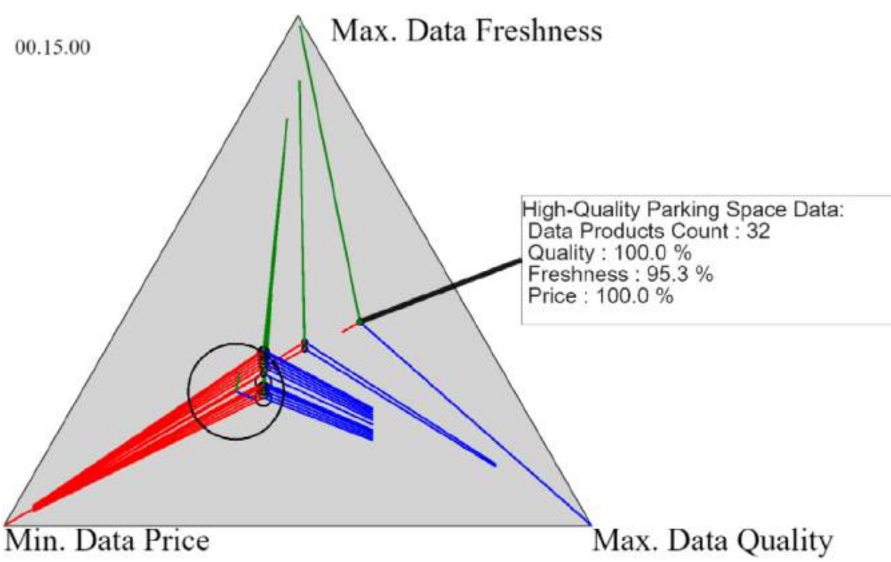

Fig. 10. A DPIT visualisation for the data product groups in a simulation at time 15 minutes. A black circle presents a group of data products that have coherent quality, freshness and price values (there is less than a 5-per-cent difference in the QFB-values). The size of a black circle presents the share of data products in a group of all data products produced in a simulation. The lengths of the blue, green and red lines illustrate how well the quality, freshness and price targets are achieved in a certain data product group. For example, for the data product group that has 100% quality, 95.3% freshness and 100% price, there are longer green and blue lines and a shorter red line as minimum price target is not achieved in the group.

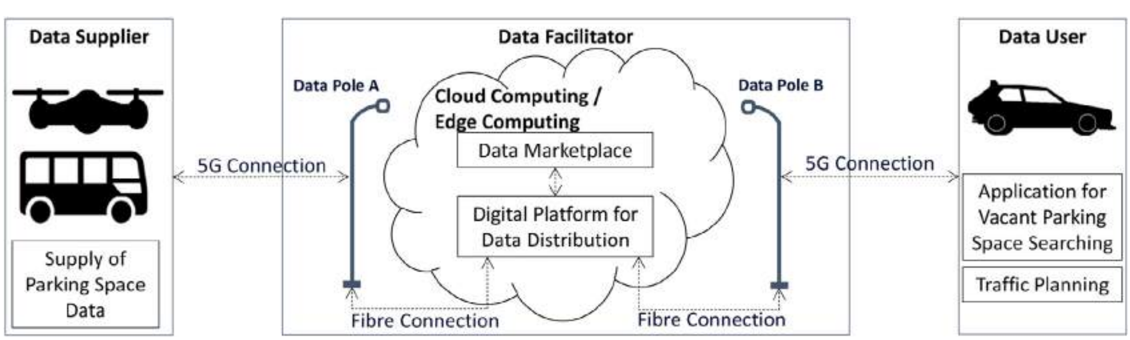

Fig. 11. Supply of sellable parking space data in a data pole network.

(see, Fig. 3) was created for the data and added to the simulation model in the DMS tool.

Estimation of use of data products – Potential data users were identified for parking space data. As a result, the following four data users and their requirements (DPIT parameters) were added to the simulation model:

a) **Value-oriented motorist A** that wants to use high-quality data in parking.
b) **Value- and cost-oriented motorist B** that is ready to pay a medium price for medium data quality and for medium data freshness and wants to use medium-quality data in parking.
c) **Cost-oriented motorist C** that wants to use a low price and low-quality data in parking.
d) **Traffic planner** that wants to use statistical data in traffic planning tasks.

Definition of observation targets – Information was collected about parking spaces in Kera and five observation target groups (e.g., "Parking Area A - Section 1" and "Parking Area A - Section 2") and 455 observation targets for the parking spaces were added to the simulation model (see, Fig. 7).

Route planning – The bus and drone routes were estimated and four routes were added to the simulation model:

1) **Bus Route** is a round-trip route (0.8 km) that follows the route of the LuxTurrim5G+'s smart pole pilot network from the Nokia Campus to the train station in Kera and produces data of 58 parking spaces.
2) **Drone route A** is a ring route (1.9 km) for producing data of 423 parking spaces in parking area A.
3) **Drone route B** is a round-trip route (0.5 km) for producing data of 32 parking spaces in parking area B.
4) **Drone route C** is a ring route (3.0 km) for producing data of 455 parking spaces in parking areas A and B.

The drone routes start from a data pole that contains a docking station, which is capable of charging drones. Subsequently, the following parameters were determined for the routes:

- **Vehicle's speed**: 20 km / h for the bus route and 40 km / h for the drone routes.
- **Repeats for route**: 100 repeats for the bus and drone routes.
- **Stop time at route's end points:** A bus will have a 5-minute stop time at the route's end points. The drone routes do not have stop times at the end points, only service breaks that are used for charging the batteries of drones.
- **Service break time and number of repeats to service break**: a bus has a 30-minute service break after the bus has 20 repeats for the route and a drone has a service break after each time it has completed its route. The length of a route affects the use of batteries and the charging time for maintaining sufficient charging level in batteries. Thus, a service break time is 20 minutes for the shorter drone route B, and 25 and 30 minutes for the longer routes A and C.

The max. observation distance, data product preparation delay and accuracy of data products depend on the methods and sensors used in the parking space detection. The following values were determined for the bus and drone routes:

- **Max. observation distance**: 6 metres for the bus route and 5 metres for the drone routes.
- **Data product preparation delay**: 1000 milliseconds for the bus and drone routes.
- **Accuracy of data products**: 0.9 (in the scale of 0.0 to 1.0) for the bus and drone routes.

4.3. Results

The DMS tool was used in a Google Chrome browser on a laptop computer with a 1.9 GHz Intel Core i7-8650 processor and 16 GB of main memory. It took 2 working days to prepare the experiment. It took 4 hours to create DPQB for the parking space data, 4 hours to collect information about the parking spaces in Kera, and 4 hours to specify the data users, routes and observation targets for the simulation model.

A 1-second step size was used in a simulation where there was an 8-hour duration in the DMS tool. The time step size affects the resolution of the simulation results, and the time elapsed in the 8-hour duration simulation was:

- 21 minutes and 41 seconds for 1-second step size,
- 4 minutes and 20 seconds for 5-second step size,
- 2 minutes and 16 seconds for 10-second step size,
- 49 seconds for 30-second step size, and
- 28 seconds for 1-minute step size.

The simulation produced 18 984 data products and calculated estimates for (see, Fig. 12):

1) **Value of all data products** is 20.19 euros at the end of the simulation. The volume of statistical data increases during the simulation and there is linear-growth in ADP_{Value}. There is also a smaller fluctuation in ADP_{Value}: new high-quality data products increase ADP_{Value} but ageing puts the data products to lower-quality categories and lowers the ADP_{Value}.
2) **Value of the best data products in quality categories** is 2.11 euros at the end of the simulation. There is not a continuous-growth in BDP_{Value} but the value fluctuates in a certain range in the simulation. The theoretical maximum is achieved for BDP_{Value} if a data product in each quality category for each observation target exists. Thus, the theoretical maximum BDP_{Value} can be calculated by multiplying the count of observation targets by the sum of reference prices of the quality categories. Thus, in the experiment, the theoretical maximum for BDP_{Value} is 454 * (1+0.5+0.2+0.1) cents = 8.172 euros.

Fig. 13 shows that there is linear-growth and fluctuation in the value of data products produced by different routes. The following compares absolute value creation on the routes and creation of value relative to the driving/flying distance on the routes:

1 Drone route A created 9.05 euros and 26 cents / km,
2 Drone route C created 6.81 euros 15 cents / km,
3 The bus route created 3.27 euros and 8 cents / km, and
4 Drone route B created 1.06 euros and 6 cents / km.

The best route in value creation is Drone route A that produces data products for parking area A, which contains 423 parking spaces in a relatively small region. The drone docking station is in the region and so almost all of the flying time is used for capturing the sensor data of parking spaces. The bus route got the third position in the simulation. Drone routes A and C are better in value creation because the bus has only limited visibility to parking spaces in the Nokia Campus region and cannot produce data of all parking spaces. The drones use higher speeds and focus on production of data; whereas, the main function of the bus is to drive passengers, and the production of data is a secondary function for the bus.

Drone route B focuses on parking area B and is the worst route in value creation. Firstly, the drone had to use more time for flying from the docking station to the parking area B to capture sensor data of 32 parking spaces.

The simulation shows (see, Fig. 14 and Fig. 15) how well the routes together serve the data users:

a) **Motorist A, B, and C** – There is not continuous growth in the volume and value of near real-time data products. New data products and ageing of existing data products cause great fluctuation to the volume and value of near real-time data products. Fig. 15 shows that there are great gaps in the availability of high-quality data products and a need for better route planning and synchronisation of routes for ensuring a steadier supply of high-quality data. In the beginning, there is high-quality data for motorist A, but then there is an almost 25-minute gap in the availability of high-quality data. The data supplier can attempt the following: a) improve synchronisation of the routes and set drone route C to start 10 minutes later, ensuring a steadier delivery for high-quality data, b) determine shorter service breaks for drones and/or c) add new routes to ensure a steadier and more reliable supply of high-quality data. There are gaps in the availability of medium-quality and low-quality data, too. There is a need for methods that fluently select the best available high-quality, medium-quality and low-quality data products for the data users' requirements. For example, motorist B can occasionally use high-quality or low-quality data products when there are gaps in the availability of medium-quality data.
b) **Traffic planner** – The highest value, 18.47 euros, is achieved at the end of the simulation. The volume and value of statistical data increases during the simulation, and at the end, there is more value in the statistical data than in near real-time data. However, near real-time data can produce greater revenue streams for data suppliers, because there can be more demand and users for near real-time data than for statistical parking space data.

The information produced in simulations assist the data supplier to optimize the vehicle-based supply of data. First, the data supplier can see

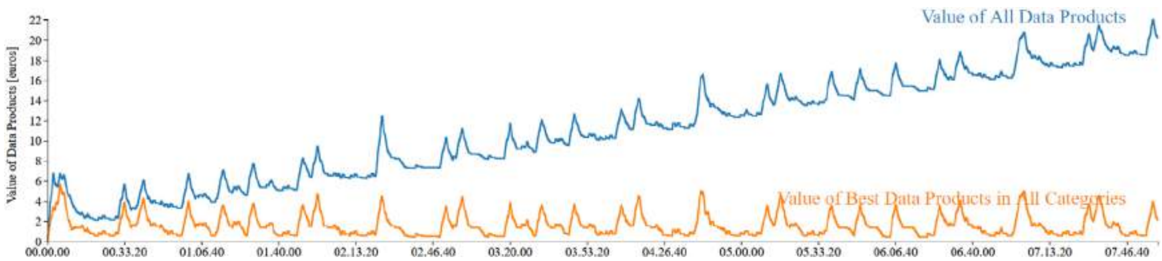

Fig. 12. Calculated value for all data products and for the best data products in all categories.

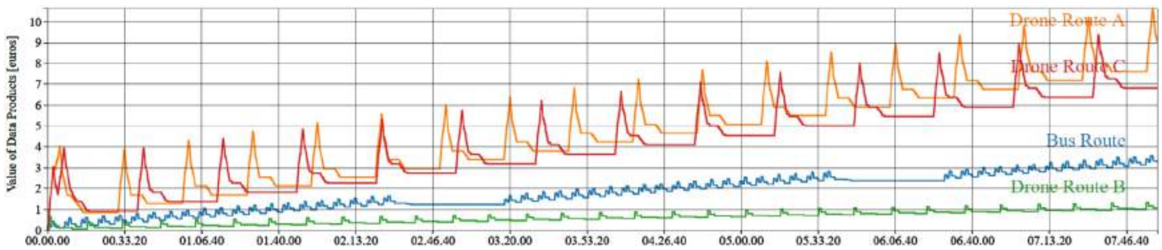

Fig. 13. Calculated value of data products on the simulated routes.

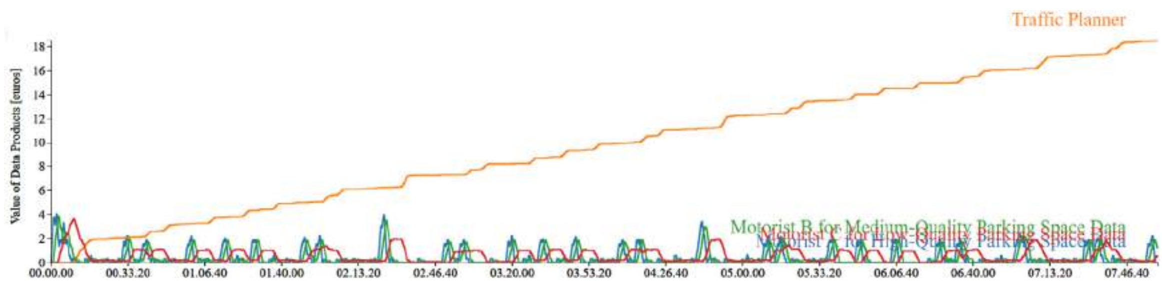

Fig. 14. Calculated value of data products for specified data users.

how much value route options create and use the simulation results in comparison, selection and development of route options. The DMS tool calculates estimates for the absolute value that is created on each route option and for the value that is relative to the driving/flying distance on a route. Second, the simulations assist a data supplier to develop supply of sellable data in a case in which there is a fleet of vehicles to supply data. The data supplier can determine and simulate route combinations and use the simulation results in the development of the routes and route parameters for improving the quality, freshness and value of data that is produced on the routes. Third, the DMS approach assists data suppliers to develop a vehicle-based supply of data for identified data user types. For example, the data supplier can develop a vehicle-based supply of data for value-oriented data users, for value and cost-oriented data users, for cost-oriented data users or for data users that have a need for statistical data.

4.4. Accuracy of simulation results

The following issues affect the accuracy of the simulation results:

Accuracy of the reference prices – Errors in reference prices will have a significant effect on the calculated value of data products. Realistic reference prices were attempted to be determined for the quality categories in the experiment that estimated the use of parking space data products in the identified use cases. However, there is uncertainty in the given reference prices.

A data supplier can estimate the costs related to the supply of data products in each quality category, the value that the data products will provide for the data users, and finally try to determine a reasonable price for the data products in each category. DMPs can offer information on a) the pricing of similar data products on the market, b) the volume of potential data users for the planned data product, and c) the applications and use cases that could potentially benefit from the data product. This information can assist determination of more accurate reference prices for the quality categories in DPQBs.

Accuracy of routes and route parameters – The changes in urban environments should be considered in simulation models. There were 19 data poles in the pilot network during the simulations. The pilot network is under construction and will evolve in the future. This can affect the routes of autonomous busses and drones, too. For example, the positions of drone docking stations can change when new data poles are added to the network.

The speed of a vehicle affects the data production rate. In the DMS method, an estimated average speed is determined on a route. Adding real information about vehicles' speeds on the route sections, about service breaks and about stop times on the route sections to simulation models could improve the accuracy of simulation results in the future.

Errors in the positions of observation targets – It takes time to add observation targets to simulation models, and there can be errors in the positions of observation targets. Thus, new tools are needed to import information about observation targets from other sources and add observation targets to simulation models.

Visibility of observation targets – Visual obstructions such as trees, buildings and traffic can cause occlusions and prevent capturing of sensor data about observation targets. There should be methods for estimating the probability for real-life situations that prevent production of data products for observation targets, and for using these estimates in simulations for improving the accuracy of simulation results in the future.

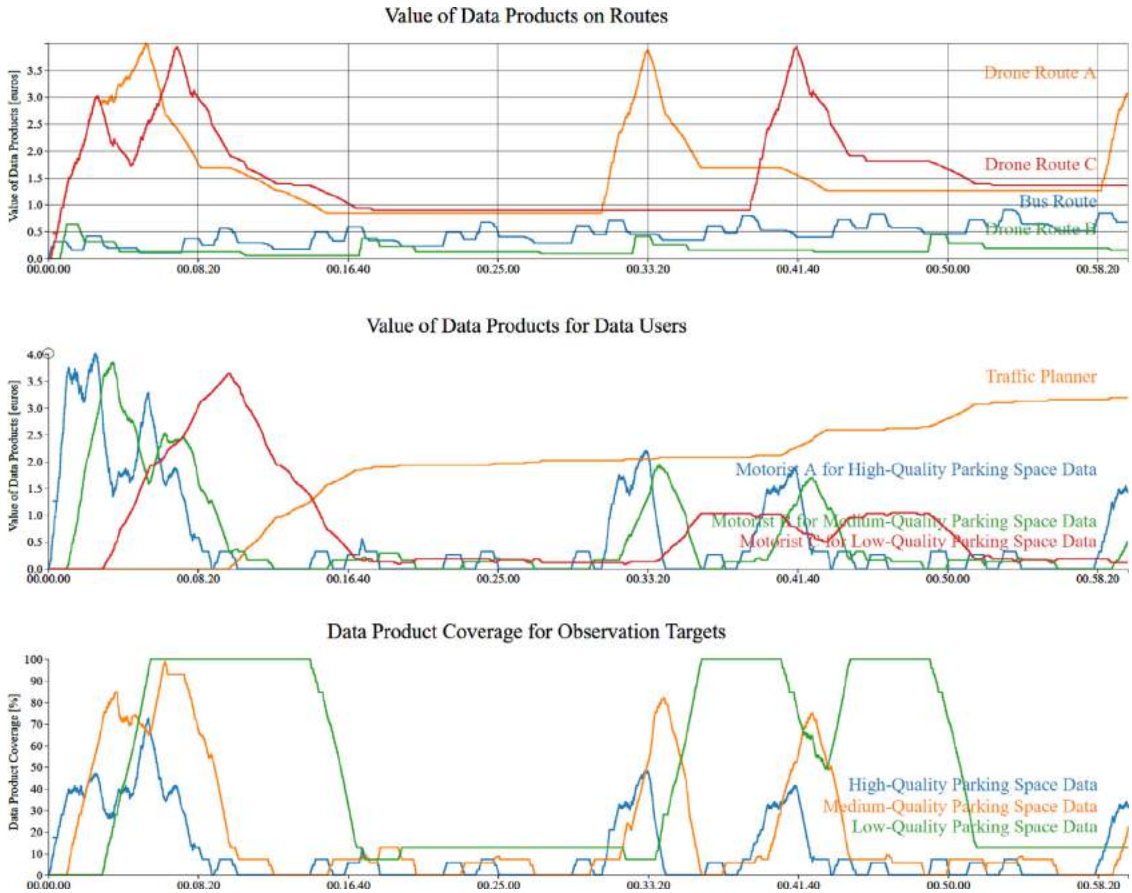

Fig. 15. Calculated value of data products on routes, value of data products for data users and data product coverage for the observation targets during the first 60 minutes of the simulation.

5. Discussion

The DMS approach eases the planning of vehicle-based supply of sellable data products. The simulations can provide many benefits for data suppliers and assist optimisation of vehicle-based supply of data products from the viewpoint of:

a) **Routes** – The DMS method enables data suppliers to see the estimated volume and value of data products on the routes, to compare the routes and finally to select or develop routes that create more value from data. The DMS tool aids creation of alternative routes for vehicles: a data supplier can make a copy of an existing route, modify the new route and finally run simulations for comparing the original and new route.
b) **Data users** – The DMS method supports optimisation of the supply of data products for different data users, such as for value-driven or cost-driven data users. The data suppliers can determine data users' requirements for data products, simulate production of data products for the data users and finally see the volume and estimated value of data products for the specified data users.
c) **Observation targets** – The DMS tool visualises the availability of (high-quality, medium-quality, low-quality) near real-time data products for the observation targets during simulations.
d) **Quality of data products** – The DPIT visualisation provides an overview for the produced data products and enables data suppliers to see how well the quality, price and freshness objectives are achieved in the data products.

Although the DMS tool is a prototype, it shows the possibility to iteratively, smoothly, and cost-effectively simulate the vehicle-based supply of data products. It took typically few working days to build a simulation model and a few dozen minutes to run a single simulation. Of course, the time that it takes to build a simulation model and run simulations depends on the count of observation targets and the number and length of routes. The DMS tool is a browser and map-based simulation environment that can be used without installing any simulation components on a computer. Our goal is to continue the development of the DMS tool and make it available for actors that develop vehicle-based supply of sellable data in smart cities.

5.1. Considerations

The approach offers a new quality-aware way to simulate vehicle-based supply of data products. Although the approach has been applied in route planning, it has not yet been validated in a real case as the vehicle-based supply of parking space data is in the planning phase and has not yet been decided if it will be started in the LuxTurrim5G+'s pilot network. However, simulations assist in decision making and help in taking steps towards the vehicle-based supply of sellable data products. In addition, the following issues may limit the use of the approach or require further development for the approach.

- *Simulation models are developed from scratch* – It takes time and effort to build simulation models. New wizards and tools are needed to automatise the creation of simulation models and import information about routes and observation targets from other sources (e.g., from open APIs) to simulation models. For example, tools that import information about parking spaces and insert observation targets for these would greatly assist in the creation of simulation models. Similarly, tools that import route data about autonomous vehicles to simulation models would minimise the errors related to routes and route parameters and finally improve the accuracy of simulation results.

- *Lack of reusable DPQBs* – It takes time and effort to develop DPQBs. There is a clear need for reusable DPQBs and tools that assist the searching of DPQBs. In the best case there exists DPQB for a data product or for similar kinds of data products assisting the development of DPQB for the new data product. In the future, (e.g., industrial) a standard-based DPQBs may emerge. Data facilitators and DMPs can offer reusable DPQBs to boost the business related to specific kinds of data. In addition, smart cities can determine standard DPQBs to provide frameworks for quality-aware data trade, data supply, and data use in cities.
- *Need for a wider set of quality parameters* – The DMS tool provides support for a set of basic parameters determining the quality of data products. However, there are use cases requiring simulation support for a greater number of quality parameters. For example, the quality aspects, such as reliability and availability, affect the use and selection of data products and should be considered in simulations, too.
- *Need for more advanced pricing mechanisms* – The simulation requires realistic reference prices for quality categories. In addition to using fixed reference prices in DPQBs, there is a need for the following:
    - *Data volume-specific pricing mechanisms* – The increase in the volume of data products can lower the price of a single data product. This can be true especially in the case of statistical data products and requires data volume-based pricing mechanisms for data quality categories so that the simulation could produce more accurate estimates for the value of different volumes of data products.
    - *Observation target-specific pricing mechanisms* – There can be high value observation targets such as parking spaces that have a very short walking distance to the trip destination. It should be possible to determine the value of an observation target and to use this parameter in the pricing of data products that are produced for the observation target.
    - *Use context-specific pricing mechanisms* – The use context should be considered in pricing of data products. For example, there can be only a few vacant parking spaces available during rush hours, whereas on the evenings and weekends, there can be a lot of free parking capacity available that affects the value of parking space data, too. The motorists can be ready to pay more for parking space data during rush hours, whereas during quiet times, there can be lower prices for data products. Thus, it should be possible to use time-dependent pricing mechanisms in simulations.

5.2. Guidelines for planning vehicle-based supply of sellable data products

Data markets set very heterogeneous requirements for data products. Data suppliers must consider issues such as the following:

- *Applications / use cases that benefit from the sellable data* – The threshold for supplying data as sellable data products is lower if demand, users and use cases for the data are identified. UCs assists determination of DPQBs for data products, too.
- *Revenue streams and costs* – The production of data products creates revenue streams but also causes costs for data suppliers. The size of revenue streams depends on the pricing, volume, freshness and quality of data products and the volume of data users. The routes, quality of sensors, processing components and network connections affect the volume and quality of data products but also incur costs. A data supplier can estimate the volume of data users and use the simulation results of the value and volume of data products in coarse-grained estimation of revenue streams. The DMS tool calculates the driving/flying distance for a vehicle in a simulation. Data suppliers can estimate the costs related to the driving/flying distance, sensors, computing components and network traffic and calculate coarse-grained estimates for data production costs, too.
- *Supply of statistical data and near real-time data* – Simulations assist data suppliers to develop routes to produce suitable data for market demand. For example, the data supplier can develop routes to produce data when there is greater demand for near real-time data. Alternatively, if there is more demand for statistical data, the data supplier can develop routes that steadily produce statistical data of observation targets.
- *Quality of data and volume of data* – A data user can prefer the quality of data or the volume of data. For example, motorists may want to use only the best and newest data products in searching for parking spaces. A service that detects dimensions for parking spaces benefits from the volume of data products that provide measured dimensions for a parking space, as it can use all the data products and calculate averages for the length and width of the parking space for minimising the errors related to the measured dimensions of the parking space.

A data supplier can focus on increasing the volume or quality of data products. For example, the data supplier can adjust the drones to use higher speeds or higher-flying altitudes for capturing video feeds of parking spaces on larger areas and for increasing the freshness and volume of produced data products. However, the use of higher speeds or higher-flying altitudes can decrease the quality of sensor data and the free parking space detection accuracy and cause more errors to the data products. In addition, it can be difficult to measure accurate dimensions for parking spaces from camera feeds (e.g., from RGB-D feeds) that are captured from longer shooting distances.

5.3. Future research directions

The following lists possible future research directions for the DMS approach:

- *Accurate estimation of revenue streams and costs* – The future work should study the more accurate estimation of revenue streams and costs related to vehicle-based supply of data products. For example, methods are needed to assist estimation of the volume of data users for data products in a certain quality category during busy hours and quiet hours. The pricing of data products requires methods to capture real information about data markets and the use of data products.
- *Simulation support for various observation targets* – Observation targets are added to fixed positions in the DMS tool. Vehicles can capture the sensor data of moving objects, such as humans or cars, road condition data of road sections, or air quality data of greater urban regions. It should be possible to simulate the supply of data products for various observation targets, such as for moving objects, route sections or geographical areas in the future.
- *Use of DPQBs in quality-aware DMPs* – DMPs must serve different kinds of data users and use cases. DPQBs could be used in the configuration and tailoring of DMPs, classification of data products and composition of data product packages that contain data products at desired quality levels.

6. Conclusions and recommendations

This paper presents a novel Data Market Simulation (DMS) approach that enables data suppliers to simulate the vehicle-based supply of sellable data products, Data Product Iron Triangles (DPIT) to provide overview visualisations for the data Quality, Freshness and Price (QFP) of produced data products, and Data Product Quality Benchmark (DPQB) for quality-aware supply and use of data products. The DMS tool assists data suppliers to optimise the supply of data and creation of value from data, evaluate vehicle routes and the value and quality of produced data products, and to see how well the routes serve the specified data users, and how good data product coverage is achieved for the observation targets on the vehicle routes.

There are many promising research directions for the DMS approach. Firstly, there should be support for producing estimates for revenue streams and costs related to the vehicle-based supply of data products. Secondly, simulations should consider the behaviour of different actors in smart city data economy. For example, simulating how data users will act and use data in a city can provide important guidance for the supply of data products. Thirdly, integration of the DMS tool to produce simulated data products for data marketplaces will provide a way to create development environments for new service concepts that use possibly emerging data products in future smart cities.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Optimizing local and global objectives for sustainable mobility in urban areas

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ABSTRACT

Cities are growing and sustainable urban mobility planning (SUMP) is gaining in importance with it. The problems in the domain often involve multiple stakeholders with conflicting or competing objectives. The stakeholders and objectives can be local to certain neighborhoods or apply to the global city-wide scale. We present a methodology to address such problems with the help of modern simulators and multi-objective evolutionary algorithms. The methodology brings all stakeholders to the table and presents to them a near optimal set of alternatives to choose from. As an example, we consider the problem of minimizing vehicular noise in a particular neighborhood while also minimizing city-wide emission for heavy vehicles. We describe the requirements and capabilities of the simulator and the optimization algorithm in detail and present a methodology to model both local (noise reduction) and global (emissions) objectives simultaneously. We apply our methodology on two large city scale case studies and present our findings.

1. Introduction

Growing size of cities and increasing population mobility has led to a surge in the number of vehicles on roads (Berry, 2008; Eurostat, 2019; Lerner, van Franã et al., 2012). The growing motorisation has led to increase in traffic congestion, noise, carbon emissions and concerns of road safety resulting in social, environmental and economic costs (Okraszewska et al., 2018; van Wee & Ettema, 2016). These problems are broadly classified under the umbrella term *sustainable urban mobility planning (SUMP)*.

A key complexity in these problems is number of stakeholders involved. The stakeholders often have different point of views of the problem. For example, the local/community representatives may be biased towards improving their neighborhoods (Liu, Liao, & Mei, 2018; Xu & Lin, 2020) while the policy makers usually have a mandate coming from the state or national level. The business representatives may be focused primarily on the efficiency of the logistics while environmental activists may give more weight to the sustainable solutions. A typical example of such competing and conflicting objectives is the desire to reduce the noise levels in a particular neighborhood while also minimizing the city-wide emissions.

In literature, participatory modelling has majorly been used as reflexive, descriptive or normative study (Andersson, Olsson, Arheimer, & Jonsson, 2008; Hare, Letcher, & Jakeman, 2003; Jones et al., 2009; Malekpour, de Haan, & Brown, 2013). However, with the increase in computational power available today, analytical studies to support the decision-making have come to the forefront of participatory modelling (Grogan, 2021; Middya, Roy, Dutta, & Das, 2020). For complete literature in the field of simulation-based participatory modelling, the reader is referred to Singh, Baalsrud Hauge, & Wiktorsson (2021).

In this paper, we present an approach combining (i) simulation and (ii) Multi-Objective Evolutionary Algorithms (MOEA). The objective of the combined approach is to support the stakeholders develop a common understand and agree upon a compromise. We believe that this methodology will lend itself readily to solving other multi-stakeholder problems in the domain of urban mobility.

A primary component of the solution we propose is a simulator. Changing transport and mobility behaviour in the real world not only involves significant monetary costs and is time-consuming, but usually also has negative consequences for citizens when building or testing the new scenarios. For example, the new scenarios created might not be the most cost effective route, in terms of time and money, for citizens living in the area as it disrupts the regular optimized traffic flow (Okraszewska et al., 2018; Péres, Ruiz, Nesmachnow, & Olivera, 2018). This is where the ability to simulate traffic on a large scale with the help of traffic simulators (Behrisch, Bieker, Erdmann, & Krajzewicz, 2011; Cameron & Duncan, 1996; Holm, Tomich, Sloboden, Lowrance et al., 2007; Milojicic, 2018; Santana, Lago, Kon, & Milojicic, 2017; Simulator, 2005) can aid the process. Microscopic (Li, Yu, Tao, & Chen, 2013; Sánchez, Galán, & Rubio, 2008; Zhou & Cai, 2014) and macroscopic (McCrea &

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Moutari, 2010) representation of traffic views have been done in many simulation studies. It has become increasingly clear that microscopic simulators offer superior fidelity than macroscopic simulators, esp. with a large number of intersections and vehicles and when the effects of having multiple vehicles is either super-linear (e.g., increase in waiting time due to congestion) or sub-linear (e.g., amount of noise produced by multiple vehicles crossing a road simultaneously) (Ratrout & Rahman, 2009). The microscopic simulators can model a wider variety of scenarios and emergent phenomenon than a macroscopic one and, hence, we present our methodology for such a microscopic simulator. Simulation is chosen over analytical solutions because even a simple act like blocking of roads can have second order effects which can make analytical solutions inaccurate by violating the assumptions they make. For example, while an analytical solution may assume that the vehicles will choose the shortest path for each vehicle, with the help of a simulator, it is possible to capture the evolving nature of vehicles re-routing as the traffic on the roads dynamically changes.

The other component of our solution is Multi-Objective Evolutionary Algorithm for optimization and for finding a landscape of solutions. Introduction of multiple objectives from different stakeholders means that there is likely no single solution that is optimal for everyone. Hence, the optimization algorithm has to find a *set* of solutions (Abraham & Jain, 2005). This set (called the Pareto optimal front) will allow the stakeholders to come together, see the problem from the point of view of others, and help them agree on a compromise which serves all of them well. Over the past few years, efforts have been made in combining microscopic traffic simulation with evolutionary algorithms to optimize for vehicular emissions together with traditional costs metrics (De Coensel, Can, Degraeuwe, De Vlieger, & Botteldooren, 2012; Garcia-Nieto, Olivera, & Alba, 2013; Olivera, García-Nieto, & Alba, 2015; Péres et al., 2018; Wu, Deng, Du, & Ma, 2014). However, the use of evolutionary algorithms in large and heterogeneous case studies is still an open issue (Kutz, 2004). In this work, we show that with judicious use of parallelization, we can perform this optimization at a city scale.

In a nutshell, the primary contributions of our work are:

- Presenting a methodology for solving complex problems in the emergent domain of sustainable urban mobility that go beyond optimising for the traditional cost metrics.
- We show how multiple stakeholders can be brought to the table and be presented with several Pareto optimal solutions to choose between. Importantly, the stakeholders can be global or local but their constraints and desires can be adequately represented in a uniform manner.
- Lastly, we present two case studies applying our methodology to solving a multi-stakeholder problem, *viz.* reducing noise in certain neighborhoods while also minimizing the emission on the scale of an entire city.

The article is organized as follows: Section 2 presents the system definitions and mathematical formulation of the problem. Section 3 has an overview of the research methodology followed in this work. Later in Section 4, case studies are described followed by the discussion of results. Section 5 concludes the article by presenting the possible future works while briefly touching on the limitations of the proposed approach.

2. System description

2.1. Definitions

An urban traffic network is composed of intersections and roads which connect them. These roads have multiple physical (e.g., number of lanes, paved/concrete, etc.) and logical attributes (e.g., one-way traffic, heavy vehicles allowed, speed limits, etc.) associated with them. A network is represented as a directed graph $\mathcal{G} = (\mathcal{J}, \mathcal{E}, \mathcal{A}, \mathscr{A}, a)$, where the set $\mathcal{J}$ contains the junctions, the set $\mathcal{E}$ contains the roads and $\mathcal{A}$ is the set of all attributes that the edges can have and $\mathscr{A}$ is the set of values that the attributes can take. In addition, there is a mapping $a : \mathcal{E} \times \mathcal{A} \to \mathscr{A}$, which lists the attribute values for all edges. These logical attributes of the roads are under the control of the city and roads are often reclassified temporarily, e.g., disallowing heavy vehicles to allow for constructions or blocking complete traffic for public manifestations. Such a reclassification of a subset $\mathcal{C} \subseteq \mathcal{E}$ of edges is represented as using a partial map $\boldsymbol{x} : \mathcal{C} \times \mathcal{A} \to \mathscr{A}$. The resulting reclassified network is represented using the notation $\mathcal{G}(\boldsymbol{x})$, where the roads in $\mathcal{C}$ have some of their attributes changed, but other roads retain their original attributes.

Similar to roads, the junctions $\mathcal{J}$ also have attributes (as shown in Fig. 1). One of the most familiar to the readers may be Traffic Light Control phase vectors. While they can easily be considered as an extension of this work, it is omitted to keep our exposition simple.

The traffic on the roads is composed of individual vehicles moving along the network. These vehicles also have physical (e.g., weight, engine type, position, etc.) and logical (e.g., commercial vehicle classification, starting time, etc.) attributes associated with them. The set of vehicles in the network is represented as $\mathcal{W} = (\mathcal{V}, \mathcal{B}, \mathscr{B}, b)$ where $\mathcal{V}$ is the set of available vehicles, $\mathcal{B}$ is the set of attributes of the vehicles, and $\mathscr{B}$ is the set of values that the attributes can take. Additionally, $b : \mathcal{V} \times \mathcal{B} \to \mathscr{B}$ is the mapping between vehicles and their attributes. Some attributes of the vehicles (e.g., departure time) are under the control of the individual inhabitants of the city or the commercial transport operators in the city.

The route a vehicle takes through the network is dictated by a complex interaction between objectives of each vehicle and constraints imposed by the city on the roads. We make an assumption that the objective of all vehicles is to minimise the time it takes to travel from the source to the destination and it may re-route if the traffic conditions on their path deteriorate due to congestion. The constraints are often imposed through the logical attributes set on the roads, disallowing flow of traffic in one direction, or limiting speed on others, etc.

The traffic as it drives through the city, produces emissions and noise, and suffers delays due to congestion in the city (or due to certain routes being unavailable due to restrictions imposed by the city on the roads). The emission *cost* of the traffic is defined as $f : \mathcal{G} \to \mathbb{R}$. An example of such a cost is the amount of emissions NO_x produced by the traffic on the network $\mathcal{G}$. The local *cost* of the traffic observed at an edge $e \in \mathcal{E}$ in the city is defined with $h : \mathcal{G} \times \mathcal{E} \to \mathbb{R}$, for example, the amount of noise produced on a particular road. Finally, using $g : \mathcal{G} \to \mathbb{R}$, we denoted the *cost* of the attributes of the roads in the network. For example, the cost of the attributes of the roads in the network may be the number of vehicles which are able to reach their destination during the course of the simulation. This simple cost is a good proxy of the amount of congestion on the roads of the city. Other measures which capture different aspects of the same metric may be the total *waiting time* experienced by the cars on the road or the overall fuel consumed. For our example problem, we focus only on the binary property of roads, which is whether trucks are allowed or not allowed on a particular road. We do not consider other properties of the network or roads, for example, taking into consideration the maximum speed allowed on a particular road, etc.

In this section, we have presented a general methodology which can both (i) capture a wide variety of problems in the SUMP domain, and (ii) be easily translated to a program which can run on a simulator. We will describe the details of the simulation tool in later sections. The model can capture the concerns of local as well as global stakeholders, can model hard constraints that the stakeholders impose, and allow the stakeholders to manipulate the logical as well as physical attributes of the network to run *what-if* scenarios.

2.2. Mathematical formulation

The task of determining the attributes of roads in $\mathcal{C}$ now can be framed as a multi-objective optimisation problem as:

$$\underset{\boldsymbol{x}}{\text{minimize}}\, \tilde{\boldsymbol{f}}(\boldsymbol{x}) = \{ f(\mathcal{G}(\boldsymbol{x})), g(\mathcal{G}(\boldsymbol{x})) \} \cup \left\{ h(\mathcal{G}(\boldsymbol{x}), c) \mid c \in \mathcal{C}' \subset \mathcal{E} \right\} \quad (1)$$

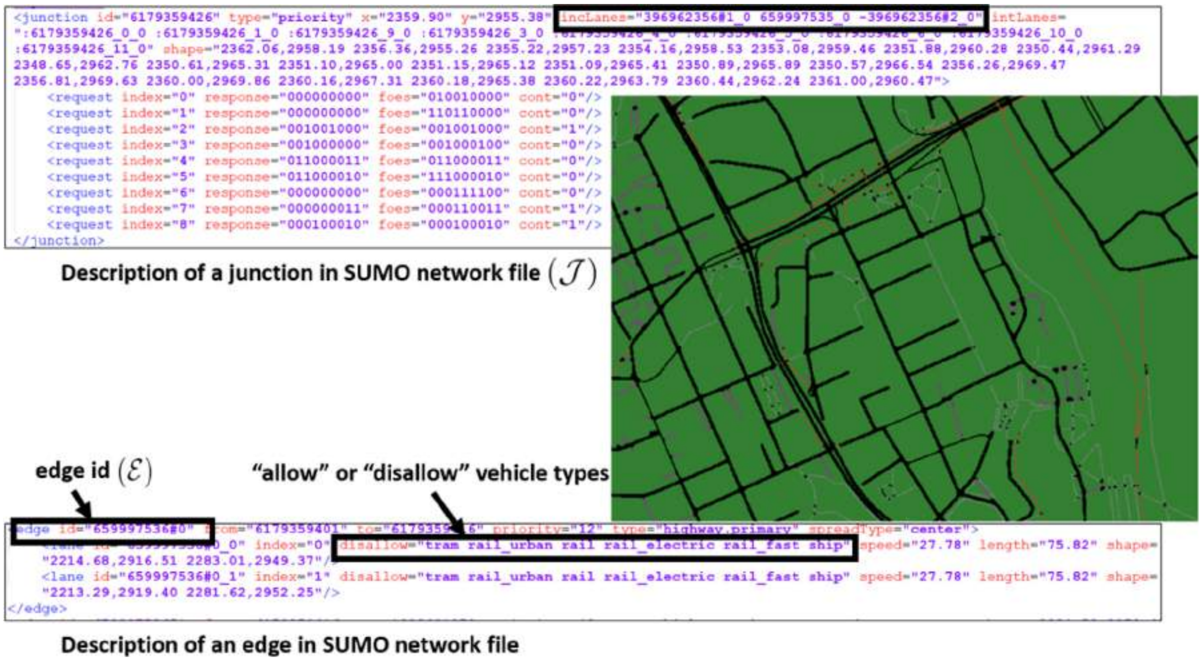

Fig. 1. A sample of data used and its corresponding structure.

where:

- $\boldsymbol{x}$ is the state of the traffic network which we want to evaluate. It encodes, for example, which roads allow trucks and which do not.
- $\mathcal{G}(\boldsymbol{x})$ is the traffic network which respects the state $\boldsymbol{x}$.
- $f(\mathcal{G}(\boldsymbol{x}))$ is the emission cost of one day of traffic in network $\mathcal{G}(\boldsymbol{x})$. It is clearly a function of the state of the network, e.g., disallowing trucks on certain paths may increase the emission by making the trucks take a longer path.
- $g(\mathcal{G}(\boldsymbol{x}))$ is the global cost of one day of traffic in the network $\mathcal{G}(\boldsymbol{x})$. This maps to the traditional costs which are often the objective of dynamic vehicle routing problems (VRP). An example is the total number of vehicles reaching their destination (as in this article) or total waiting time: Changing which paths disallow trucks results in different congestion patterns which may limit the number of vehicles reaching their destination.
- $\mathcal{C}'$ is the subset of roads that the stakeholders are particularly interested in. For example, a hospital or a school may be interested in the noise being produced on the road(s) on which it is situated.
- $h(\mathcal{G}(\boldsymbol{x}))$ is the local cost of one day of traffic in the network $\mathcal{G}(\boldsymbol{x})$ affecting the stakeholders. In this article, we have considered the total noise produced on a particular road, i.e., $\int_0^{1\text{ day}} \text{harmonoise}(t)dt$ where harmonoise is defined in Harmonoise (SUMO documentation) (2021).

At this point, we can describe the objective functions and the setup of a typical SUMP problem, which includes the description of the constraints. In the later sections, we will describe how we can let an optimization algorithm modulate the setup and pass input to a simulator and how we can process the output of the simulator to calculate our objective functions. However, we would like to stress at this point that the simulator would make some additional assumptions about the operation of the vehicles on the network, i.e., which route they take after starting. There are certain rules that the simulator imposes on the traffic by the virtue of how the simulator is built. This includes the intrinsic properties of the simulator itself, for example, the model of how vehicles flow in the simulation. In particular, we enforce the following assumptions on the simulator:

- Vehicles always obey traffic rules such as speed limits and avoid collisions.
- Vehicles take the path that takes them the shortest amount of time to reach their destination.
- All vehicles recalculate their chosen route after a period of π seconds.

The last assumption approximates the realities of the present world where periodically the information on navigation apps updates to reflect the true congestion on the route. Incidentally, this is what also allows our vehicles to re-route through the network in case their initially desired path is no longer available, e.g., for a truck when a road is re-classified to disallow heavy vehicles.

With these constraints on the routing of the vehicles, a fully specified multi-objective optimization problem is obtained. However, since the optimization problem involves multiple objectives which may be mutually incompatible, it is unlikely that there will be a single point which will minimize all costs simultaneously.

2.3. Pareto optimal front

Before we can determine what we seek as a result of the optimization procedure, we need a few formal definitions.

Definition 1 (Dominance operator (. $\prec$)) Define a point $x \in \mathbb{R}^n$ as being dominated by point $y \in \mathbb{R}^n$ if

1. $\forall\, i \in [1, \ldots, n].\; y_i \leq x_i$, and,
2. $\exists\, i \in [1, \ldots, n].\; y_i < x_i$, i.e.,

x is element-wise less than or equal to y, but at least at one element, strict inequality holds. If x is dominated by y, we refer to it as $x \prec y$.

With this definition of dominance, points are defined in the control space of an optimization problem which are dominant in terms of their *fitness*, or costs.

Definition 2 (Dominant point (. $\prec_{\tilde{f}}$)) Given a vector function $\tilde{\boldsymbol{f}}(x) : \mathcal{D} \to \mathbb{R}^m$, and two points $x \in \mathcal{D}$ and $y \in \mathcal{D}$, we say $x \prec_{\tilde{f}} y$ if and only if $\tilde{\boldsymbol{f}}(x) \prec \tilde{\boldsymbol{f}}(y)$.

Definition 3 (Pareto optimal point)**.** For a given vector valued function $\tilde{\boldsymbol{f}} : \mathcal{D} \to \mathbb{R}^m$, a point $x \in \mathcal{D}$ is called in its domain *Pareto optimal* if and only if $\forall\, y \in \mathcal{D}.\, \neg\left(y \prec_{\tilde{f}} x\right)$.

A set of finite members is referred in the domain $\mathcal{D}$ as a population $\mathcal{X} = \{x_i \mid x_i \in \mathcal{D}\}$. With Definition 3, the output of our optimization process as a *set* of points $\mathcal{X}^* \subset \mathcal{D}$ which are Pareto-optimal according to the relationship $\prec_{\tilde{f}}$ is defined where

$$\tilde{\boldsymbol{f}}(x) = [f(\mathcal{G}(\boldsymbol{x})), g(\mathcal{G}(\boldsymbol{x}))] \oplus [h(\mathcal{G}(\boldsymbol{x}), c) \mid c \in \mathcal{C}] \quad (2)$$

is a vectorized version of all our objective functions from Eq. (1).[1]

The set of points obtained as a result of the optimization is called *the Pareto optimal front*. These points represent the characteristics of different network configurations. The Pareto optimal points give the stakeholders the possibility to understand what each network configuration i.e.blocking and unblocking of roads would mean in terms of costs, for example, waiting times and fuel consumption together with CO_2, CO, NO_x, PM_x and noise emissions. For additional reading on multi-objective optimization and the Pareto optimal front, the reader is referred to Abraham & Jain (2005).

We highlight here that such a Pareto front is very useful for discussions among stakeholders. The city administration and its policy makers may look for environmentally best solutions, operations and logistics management from companies require most cost efficient solutions, and local stakeholders may want the solution which is best for their particular neighbourhoods. However, their best possible compromise will necessarily be a solution on the Pareto optimal front. These mutually competing demands require different stakeholders to come to a discussion and decide the best plausible solution(s). We will describe its use with concrete results from our experiments in Section 4.4.

In the ensuing Sections, we describe how to calculate the function $\tilde{\boldsymbol{f}}(x)$, i.e., $f(\mathcal{G}(x))$, $g(\mathcal{G}(x))$, and $\left\{h(\mathcal{G}(x), c) \mid c \in \mathcal{C}' \subset \mathcal{E}\right\}$, using a simulator (SUMO) for a given choice of x, and how we can then iteratively uncover the Pareto optimal front $\mathcal{X}^*$.

3. Research methodology

In the previous section, we described how to formulate a general SUMP problem, along with a particular problem of noise minimization by allowing/disallowing trucks on roads. In this section, we describe how we represent the control variables, evaluate the objective functions, and perform the optimization.

3.1. Control variables

Control variable are the partial reclassification of a (fixed) subset of roads $\mathcal{C} \subseteq \mathcal{E}$ on the network, denoted by $x : \mathcal{C} \times \mathcal{A} \to \mathscr{A}$. Changing x allows us to simulate various what-if scenarios: in one mapping, we may disallow trucks on certain subset of roads (as done in this article), or increase the speed limit on certain roads, while in another, we may allow the trucks, or decrease the speed limits. However, representing x as a function, while flexible, does not allow us to directly use optimization methods to uncover it. In the most general setting, the mapping can be embedded as a vector with binary, categorical, ordinal and floating point numbers. The embedding scheme will differ from problem to problem, and will play a crucial role in the interplay between the optimization algorithm and the simulator. The control variables in the example problem we have chosen are intentionally limited to allowing or disallowing trucks on roads.[2] Hence, the mapping x is represented as a binary vector, where each bit corresponds to an edge in the subset $\mathcal{C}$. Trucks are allowed to travel on the edge in the simulation only if the bit corresponding to it is 0. The task of the optimizer is to uncover various values of x which result in solutions which lie on the Pareto optimal front. In the next section, we describe how x is conveyed to the simulator and is optimized using evolutionary algorithms.

[1] $\oplus$ acts as the concatenation operator.

[2] See Péres et al. (2018) for examples of how real values can be embedded, e.g., for controlling traffic light phases and offsets.

3.2. Function simulator: SUMO

Our SUMP problem is to minimize pollution emissions along with noise in a neighbourhood via multi-objective optimization. We have seen in earlier sections how to formulate this problem mathematically. In this section, we will describe the simulator that we used, its structure, capabilities, and limitations.

The simulator should have the capability to model both traditional costs metrics and environmental sustainability aspects on a city-wide scale. Keeping these criteria in mind, SUMO emerged as a good fit for the choice of simulator to model common SUMP problems. In particular, it can completely model the example problem at hand.

Simulation of Urban Mobility (SUMO) (Behrisch et al., 2011) is an open source and highly portable software which allows different modes of traffic simulation including pedestrians and a large set of tools for creating scenarios. It integrates well with other software and also has a programmable API (Krajzewicz et al., 2005). SUMO accepts as input the parameters to run a simulation in form of configuration files, runs the simulation as per the specification, and then writes the requested output files back to disk, as shown in Fig. 2. Helpfully, SUMO supports describing the road network $\mathcal{G}$ (including full attribute mapping $a : \mathcal{E} \times \mathcal{A} \to \mathscr{A}$) in the OpenStreetMap (Haklay & Weber, 2008) (OSM) format.

In simulation each vehicle $v \in \mathcal{W}$ moves individually through the network. The characteristics $b(v) \in \mathscr{B}$ of each vehicle v can be customized individually as well. To simplify this process, each vehicle can be represented with the help of existing vehicle types (e.g.,`car`, `truck`, etc.) and further can be customized with respect to vehicle configuration, e.g., vehicle speed, acceleration, deceleration, etc. The core logical attributes which determine the path of a vehicle v are referred to as ***a trip*** which consists of a start edge, an end edge and a starting time. We will describe how we arrive at these logical attributes for the vehicles while describing our exact experimental setup below. Such a trip can be transformed into a *route*, which is a start edge, end edge and a starting time together with all the edges $e \in \mathcal{E}$ that a vehicle traverse from starting point to end point. This conversion can be done statically once at the beginning of the simulation (using tools shipped with SUMO, e.g., `duarouter`), or dynamically while SUMO is running by periodically allowing vehicles to modify their routes given the existing congestion on the network. For a comprehensive review of the routine algorithms, the reader is referred to Golden, Raghavan, & Wasil (2008). As mentioned before in Section 2.2, vehicles in the simulation follow dynamic routing and choose the route which minimizes the time to destination from the current location of the vehicle and the vehicles recalculate the routes with a period of π seconds to account for changing congestion conditions.

An additional file (`.additional.xml`) can be included in the configuration to obtain better visualizations, to provide additional vehicle attributes and for SUMO to output additional data for processing. SUMO can produce a variety of output from the simulation it runs.[3] This work concentrates on the following outputs:

1. `summaryData` output to calculate the overall emission cost $f(\mathcal{G}(x))$
2. `tripsData` to determine how far each vehicle $v \in \mathcal{W}$ progressed toward its respective destination, and, hence, calculate $g(\mathcal{G}(x))$
3. `edgeData` output for all edges $c \in \mathcal{C}'$ to be able to calculate the edge specific costs $h(\mathcal{G}(x), c)$

It is worth mentioning that SUMO can produce much more detailed output for any simulation in form of `full emissions output` and `full output`, from which these objectives could be extracted. For even small simulation runs, the size of the full emissions output can get prohibitively large (e.g., 2GB for a 1 day of simulated time) such that more CPU compute is spent processing the file instead of actually running the simulation. Hence, we opted for the alternate summary output

[3] https://sumo.dlr.de/docs/Simulation/Output.html

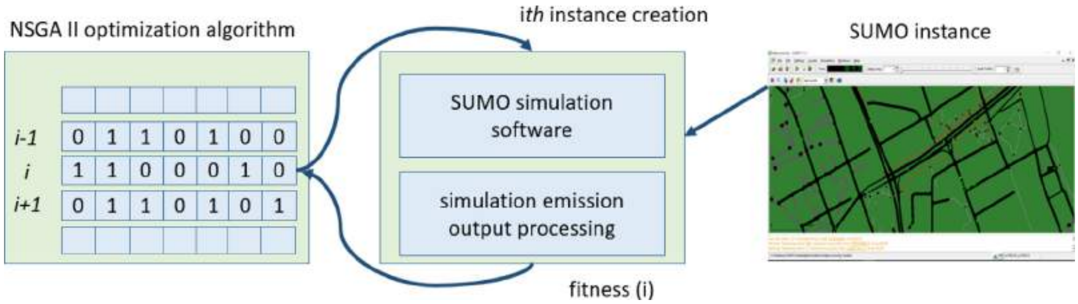

Fig. 2. SUMO instance creation and evaluation of the objective function.

formats for our experiments. However, there are methods available e.g., see TraCI (Krajzewicz, Erdmann, Behrisch, & Bieker, 2012) which can be used to extract data as the simulation is running via sockets instead of reading it via disk. Hence, SUMO can act as an effective evaluator for almost any arbitrary objective function. Investigating which class of objective functions SUMO *cannot* be used to evaluate is an interesting area of future work which could be pursued to improve SUMO itself. An example of such an objective is light pollution.

Following the structure of network adopted by SUMO, the blocking and non-blocking of roads can easily be encoded by means a vector of binary values where each binary value represent the state of a particular edge from the provided list of edges where “0” means trucks are allowed and “1” means trucks are not allowed on a particular edge as shown in Fig. 2.

3.3. Evolutionary algorithms

Evolutionary algorithms (EAs) (Abraham & Jain, 2005) start with an initial population $\mathcal{X}_0 = \{x_i \mid x_i \in \mathcal{D}\}$ of feasible assignments to the control variables. This initial population could be randomly generated or hand-crafted, or a mix thereof. For the problem at hand, for example, each member of the populate x is encoded as a bit-string with each position $x[i]$ encoding the blocked or unblocked nature of a particular lane/edge $e_i \in C$ (the mapping of the index i to the edge e_i can be arbitrary). Then the domain of the control variables is $\mathcal{D} = \{0, 1\}^n$ where $n = |C|$ is the number of bits in each x.

Starting with this initial assignment $\mathcal{X}_0$, the algorithms proceed in an iterative manner with each step producing a set of points called a *generation*. Given a population $\mathcal{X}_g$ at generation g of assignments of control variables, first the fitness of each member $x \in \mathcal{X}$ as $\tilde{f}(x)$ is calculated. For the example problem we have chosen, the fitness depends on the emissions and noise levels on certain roads along with how diverse the solutions are in the solution space. This fitness influences the likelihood of that member being selected for producing an offspring, or being included as-is in the next generation. The exact mechanics of the mutation and cross-over operations depend on the flavor of EA being used. Then the algorithm produces the next generation of assignments $\mathcal{X}_{g+1}$. Additional considerations are usually taken into account to ensure a level of diversity among the members of the population to both explore the control variable space $\mathcal{D}$ better (e.g., random mutations), as well as to provide as precise description of the Pareto optimal front $\mathcal{X}^*$ as possible (e.g., crowding distance (Deb, Pratap, Agarwal, & Meyarivan, 2002)). After a fixed number of generations G, a set of the *fittest* members over the entire history are produced as the output. They represent an approximation to the Pareto optimal front of solutions for our stakeholders.

The simulator SUMO is treated as a black box in this setting: the EA is completely unaware of how a control variable x is mapped to its fitness $\tilde{f}(x)$. This makes the genetic algorithms well suited for our problem setting: the EA is oblivious to the choice of the evaluator and simulators allows us to capture the nuances of the changes with more granularity than an analytical model while still being computationally tractable as compared to deploying the solution in the real world. The interplay between the optimization algorithm and the simulator, hence, is mediated by the embedding of the control variables x. The optimization algorithm uses the runs so far to determine which x to explore next and the simulator returns the value of the objective functions at those x. In doing so, the onus lies on the optimization algorithm to ensure that (i) the points yield diverse values for the objective functions, and, (ii) improve the objective functions (iteratively).

Finally, we choose NSGA-II (Deb et al., 2002) as it is a general purpose optimization algorithm as it produces high quality Pareto optimal fronts for a variety of difficult optimization problem. It remains an interesting area for future work to evaluate how the choice of the optimization algorithm will affect the quality and tractability of the problem.

4. Case studies

To experimentally evaluate our method, we run large scale realistic experiments for two cities A and B. This section will describe the experimental setup, followed by details on the two case studies performed.

4.1. Experimental setup

We first fix the maximum number of vehicles running in the cities by using daily averages number of vehicles (Eurostat, 2019; Turku Statisical Data, 2019). We configure each simulation to run for 86,400 s (1 day). For each vehicle $v \in \mathcal{W}$, the following attributes $b : \mathcal{W} \times \mathcal{B} \rightarrow \mathscr{B}$ are assigned (all dependent on a random seed):

1. **starting position** as an edge chosen at random from $\mathcal{E}$
2. **ending position** as another edge chosen at random from $\mathcal{E}$
3. **starting time** as a random second, i.e., $t_v^{\text{start}} \in [0, 86, 400]$
4. **vehicle type (`vtype`)** as one of {`car`, `truck`} (equally probable)

A script called `randomTrips.py` which comes bundled with SUMO is used to generate these easily. Three different set of these attributes $b_1,\ b_2,\ b_3$ by using three different seeds as input to the script are generated. The $\tilde{f}(x)$ value calculated for each x are the average of the values generated for $b_1,\ b_2,\ b_3$. This prevents the optimization algorithm from over-fitting for one particular distribution of starting and ending points. In each city, we select 21 *salient* roads for C which saw significant traffic as the edges which we will reclassify to allow or disallow vehicles of type `truck`. We also selected *one* central road $C' = \{c\}$ for each case study for minimizing the total noise. To measure the aggregate noise level on the street, we calculate the noise level at each second interval on the road in dB (note that noise does not scale linearly with the number of vehicles driving on the road, but SUMO can make a good approximation using internal algorithms Krajzewicz, Erdmann, Behrisch, & Bieker, 2012), and aggregate it to come up with an average measure $h(x, c) = \text{AvgNoise}(\mathcal{G}(x), c)$. The other metrics we optimized for were $g(x) = \text{NumVehicles}(\mathcal{G}(x))$ and $f(x) = \text{CO2Emitted}(\mathcal{G}(x))$, resulting in the final objective function:

$$\tilde{f}(x) = [\text{NumVehicles}(\mathcal{G}(x)), -\text{CO2Emitted}(\mathcal{G}(x)), -\text{AvgNoise}(\mathcal{G}(x), c)] \quad (3)$$

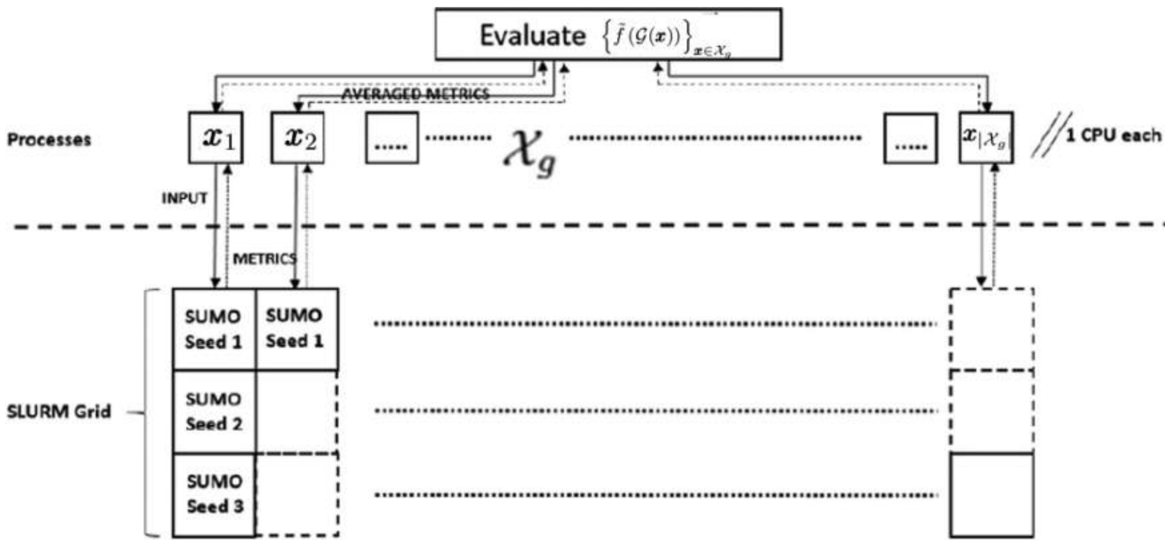

Fig. 3. The figure shows how we perform the evaluation of fitness for one generation $\mathcal{X}_g$ of assignments of control variables.

so that maximizing $\tilde{f}(x)$ maximizes the number of vehicles reaching destination (i.e., reduces congestion), minimizes CO_2, and noise produced on the edge c.

We evaluated a generation $\mathcal{X}_g$ of assignments in parallel by using a Grid-cluster and a dedicated machine for pre and post-processing data. A single process spawns $|\mathcal{X}_g|$ processes, and sends each process one member $x_i \in \mathcal{X}_g$ to evaluate the fitness of, i.e., $\tilde{f}(x)$. Each process starts three instances of the simulator SUMO on a Grid cluster, and gives it as input files generated for the different seeds, i.e., for x_i and b_1, b_2, b_3. After the SUMO simulator completes, the same process collect the output written to disk, process it, and return $\tilde{f}(x_i)$ to the main process. A brief illustration of the setup is shown in Fig. 3.

The implementation of the method is done in Python using the DEAP library (De Rainville, Fortin, Gardner, Parizeau, & Gagné, 2012) and the variant of the Evolutionary Algorithm we employed was Non-Sorting Genetic Algorithm (NSGA-II) (Deb & Jain, 2013). We fix the population size to be 40 and we run the experiment for a total of 40 generations, i.e., $\forall\, g \in [0, \dots, 40]\,.\, |X_g| = 40$) with crossover probability $p_x = 0.9$ and mutation probability of $p_m = 0.1$. We experimented with different values of population and probabilities of crossover and mutation and it was found that with the above mentioned values the optimization was the best trade-off in terms of time and computational power. Note that this requires at most $40 \times 40 = 1600$ runs of the simulator as opposed to $2^{21} \approx 2 \times 10^6$ executions which would be needed for a brute force search of the domain of the control variables.

The experiments were run on two cities with different parameters in terms of their size and characteristics. Details of these two cities are given as City A and City B are given below.

4.2. City A case study

City A is a medium-sized town in northern Europe with a population of approximately 70,000 inhabitants. The city is inherently an industrialized area with major industries from different sectors. See Fig. 4 to see which roads in C, and C'.

The results of the optimization are shown in Figs. 5 and 6. The evaluation of one generation for City A took ~60 min. Fig. 5 shows that as the number of vehicles reaching the destination increases from 1760 to 2900, which indicates that the congestion on the roads overall falls, the noise level on the considered road also increases, albeit non-linearly, from 20.1 dBA to 25.3 dBA. Fig. 6 shows that while the noise falls from 25.3 dBA to 20.1 dBA, the total CO_2 emitted increases from 0.91×10^6 kg to 1.16×10^6 kg.

4.3. City B case study

In comparison City B is a large city in northern Europe with a population of 200,000 inhabitants and an area of 250 sq. km. The city is characterized by a major harbour and serves as input to influx of both import/export and tourists from neighbouring countries. The city is currently undergoing a renovation plan and there are new routes being planned for the city. The optimization model proposed in this work, thus, helps in understanding the different scenarios for to-be built roads and provides stakeholders with a tool to discuss the trade-offs associated with them (Fig. 7).

The results of the optimization are shown in Figs. 8 and 9 . The evaluation of one generation for City A took ~300 min. Fig. 8, similar to Fig. 5, shows that as the number of vehicles reaching the destination increases from 24,950 to 30,840 the amount of noise on the road also increases non-linearly from 20.94 dBA to 26.1 dBA. Fig. 9 shows that while the

Algorithm 1 Finds non-dominated points $\mathcal{X}^*$ for a given multi-objective fitness function $\tilde{f}(x)$.

```
Input: Population size P, No. of Generations G, Prob. of mutation p_m, Prob. of crossover p_x
Requirement: P is divisible by 4
Output: Non-dominated Points
X_0 ← RandomPopulation(P)        ▷ Initialize using random binary vectors
F_0 ← Evaluate(X_0)
for g ∈ [0, …, G − 1] do
    U ← SelTournamentCDC(X_g, F_g)        ▷ Off-spring Tournament selection~(Deb et~al. 2002)
    X_{g+1} ← ∅
    Z_1, Z_2 ← Extract(U, P/2), U        ▷ Partition U into 2 equal sets
    for i ∈ [1, …, P/2] do
        o_1, o_2 ← Extract(Z_1, 1), Extract(Z_2, 1)
        X_{g+1} ← X_{g+1} ∪ ({Mate(o_1, o_2)} if Random() < p_x else {o_1, o_2})
    end for
    X_{g+1} ← {Mutate(o) if Random() < p_m else o given o ∈ X_{g+1}}        ▷ Random binary noise
    F_{g+1} ← Evaluate(X_{g+1})        ▷ Get the fitness of the generation
end for
return Pareto(⋃_{g∈[0,…,G]} {X_g})
```

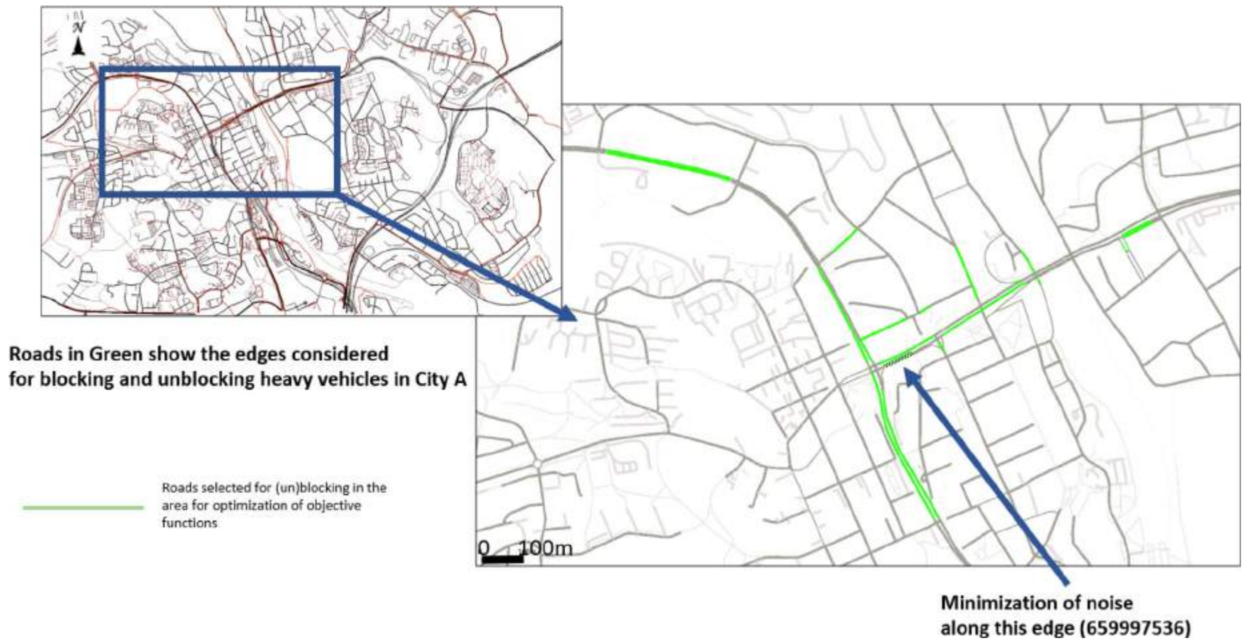

Fig. 4. The figure shows maps of City A in the SUMO simulator (full view) and the small area where we re-classify the roads to allow/disallow trucks C and the road on which we try to minimize the noise C'. [*Source:* OpenStreetMap].

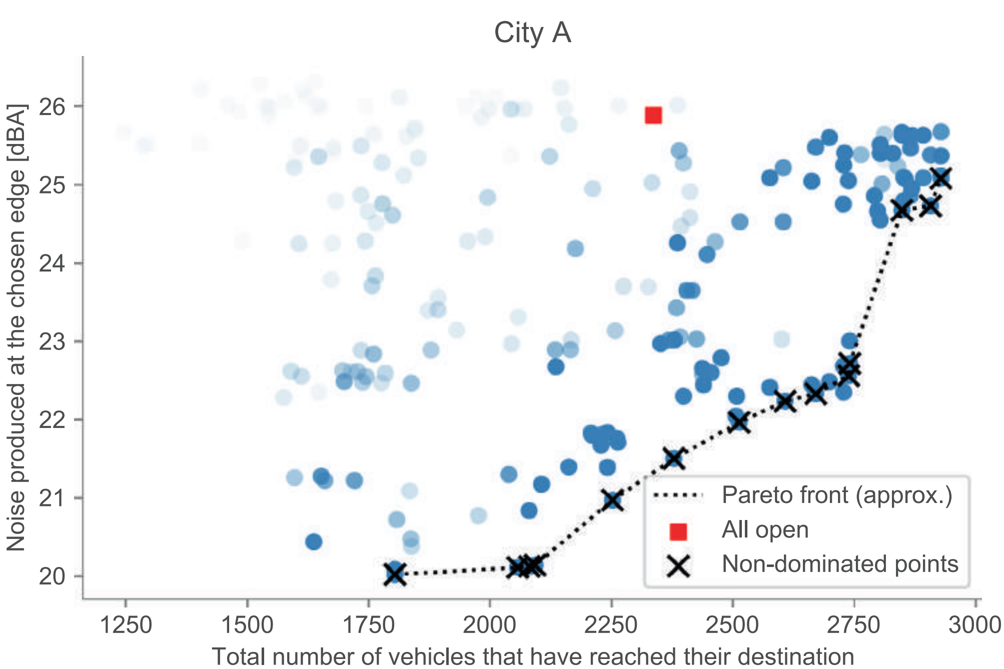

Fig. 5. Graph of the total number of vehicles that have reached their destination (before the simulation ends) and noise produced at the chosen edge.

noise falls from 26.5 dBA to 20.94 dBA, the total CO_2 emitted increases from 1.201×10^6 kg to 2.25×10^6 kg. The status-quo, which allows trucks on the all roads can also be seen in the graphs to not be the optimal solution in *any* of the metrics. The results of the simulations have currently been presented twice to expert groups. The first presentation was carried out as a part of a meeting with the project board on September 9, 2020. Here a first draft of the model, the possible options and how it could be used was briefly outlined. The second meeting was organised as a workshop with the problem owner on September 17, 2020. Two experts participated here, and presented additional information related to routes and vehicle restrictions. Furthermore, they confirmed that the overall approach was reasonable and provided valuable insights.

- In Figs. 5 and 8, it can be seen that paradoxically blocking some roads often leads to a better solution on *all* fronts than not blocking any roads. It can be understood as a variant of the famous Braess's Paradox (Braess, 1968; Braess, Nagurney, & Wakolbinger, 2005), where adding an additional road (i.e., unblocking a road in our case) to a network may reduce overall traffic flow.
- Another curious thing to note is that there is a much stronger inflection point in case of City B seen in Figs. 8 and 9 than for the corresponding Pareto optimal front for City A. This can be attributed to larger effect blocking of seminal roads has in the city. This inflection point is common for both the Noise / vehicles Pareto optimal front, as well as the Noise / CO_2 front in Figs. 8 and 9.

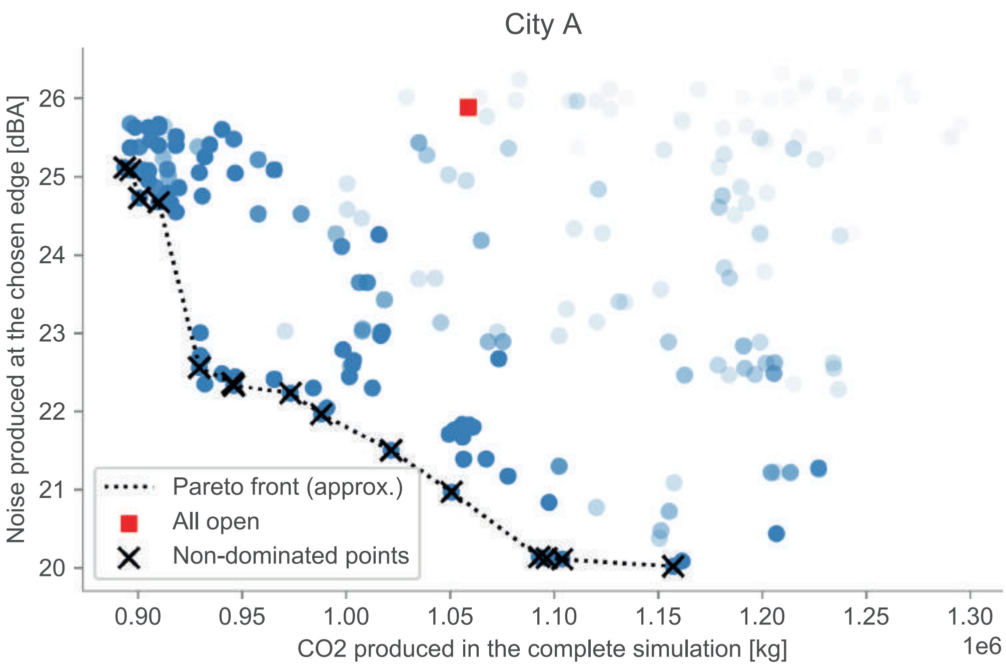

Fig. 6. Graph of total CO_2 produced in the complete simulation and noise produced at the chosen edge.

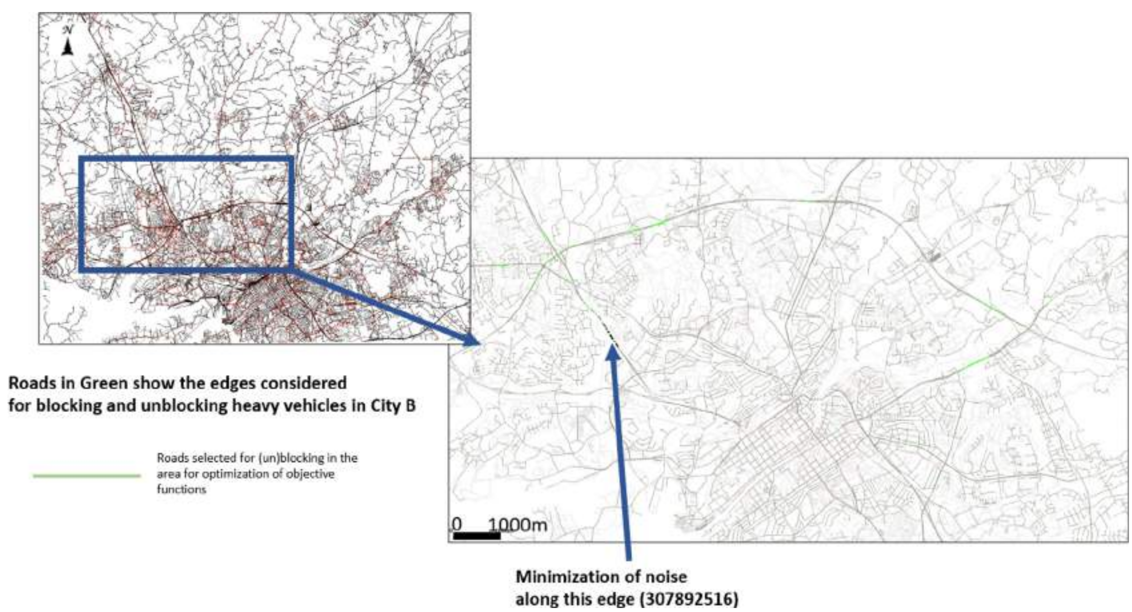

Fig. 7. The figure shows maps of City B in the SUMO simulator (full view) and the small area where we re-classify the roads to allow/disallow trucks C and the road on which we try to minimize the noise C'. [*Source:* OpenStreetMap].

4.4. Results and discussion

The experiments performed in this work simultaneously optimize the local and global objectives, thus enabling bringing together the stakeholders from the two levels. The results from the optimization are presented in the form of approximate Pareto optimal curves which serve as the basis for discussion towards blocking/non-blocking of roads in the cities. On the one hand, stakeholders like residents, schools, hospitals can come together and discuss the local objectives in the form of noise pollution. On the other hand, the global objectives of minimizing the costs together with minimizing the carbon emissions serve as the decision-making criteria for stakeholders like personnel responsible for logistics from companies, policy makers for the city, traffic management system owners, etc. We indeed were able to find multiple solutions on the front with different compromises. The simulations ran in reasonable amount of time for both cities and, for City B, the results were validated by talking to experts.

Now we discuss some shortcomings of the approach for our method for solving this particular concrete problem, especially those which may generalize to other applications of our approach. It is of utmost importance that the roads identified for the encoding of blocking and unblocking are seminal roads for the city and it should be discussed among all stakeholders which roads are significant in this regard. These roads have to be decided before designing the experiments and thus requires preparatory work. The same will be true for other problems as well: deciding the control variables, and the constraints upfront with the stakeholders will be of utmost importance. The algorithm parameters have to be chosen such that the solution is a diverse set of points in the solu-

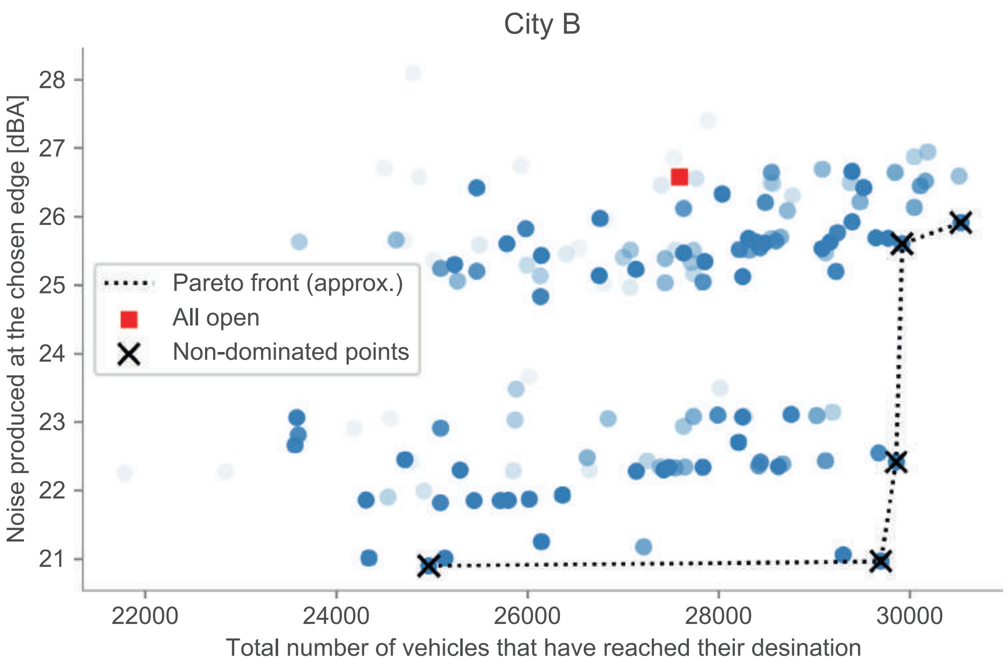

Fig. 8. Graph of total number of vehicles reaching destination (before the simulation ends) and noise produced at the chosen edge.

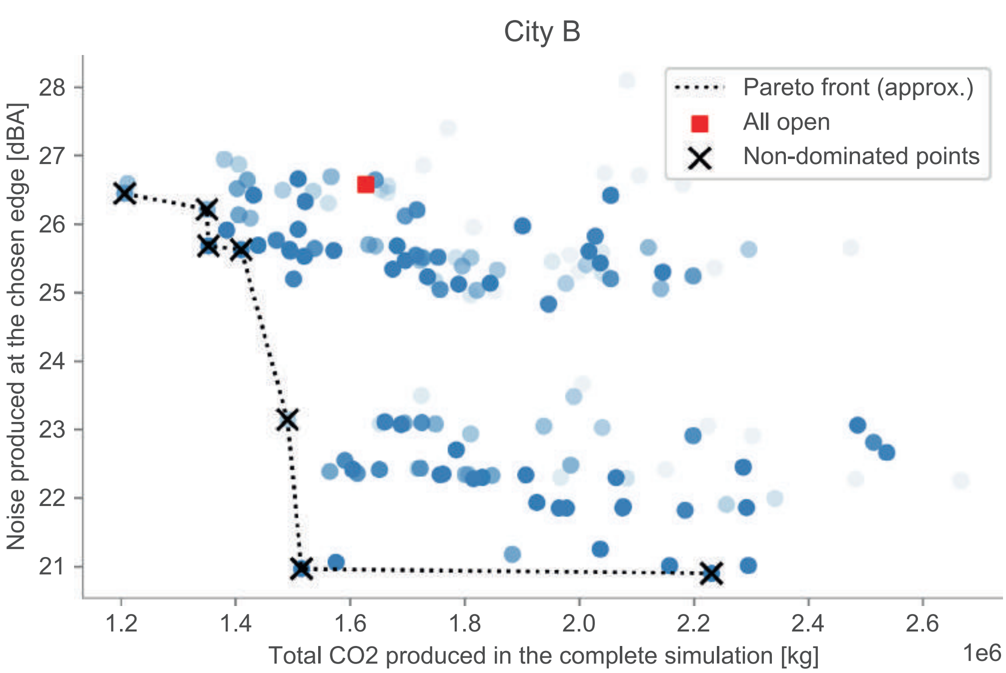

Fig. 9. Graph of total CO_2 produced in the complete simulation and noise produced at the chosen edge.

tion space, i.e., the diversity of solutions does not disappear after some generations. This usually requires some hand-tuning though a judicious choice of the algorithm which automatically does this (e.g., NSGA-II) can address this problem. Another weakness of the method is shared with all other simulation based approaches: that of having access to high quality input data. The experiments for our example problem were performed for the daily average traffic numbers to simulate a typical day, but we spread the vehicles uniformly at random throughout the day and gave them random start and end points in the city. Real traffic does not behave so: there are clearly defined peak hours, and the vehicles follow a set route in the morning and a different one in the evening. These can be addressed by having access to improved data about the traffic. Another limitation which springs from the nature of evolutionary algorithms is that the Pareto optimal front found iteratively cannot be guaranteed to contain the best solutions always. We can mitigate this by running the optimization for more generations: there is a trade-off between the computational power required by the optimization and its quality. Lastly, we have made an assumption about the routing policies followed by the vehicles and have exclusively looked at regulations for heavy vehicles. For other problems, we will have to rigorously test the assumptions of the simulator similarly.

As the next steps, adding the type of engines and vehicles to the control variables can be done to permit a particular types of engine, e.g., Euro 5 or Euro 6 engines (Keller, Hausberger, Matzer, Wüthrich, & Notter, 2010), on a road. In the proposed methodology, network or road attributes play a crucial role. However, we have limited our work to changing the binary properties of roads i.e., whether heavy vehicles are allowed or a particular road or not. In further research, changing other road attributes (e.g., speed limits) for roads would also be an interesting area.

5. Conclusions

In this work, we have presented a methodology for formulating complex multi-stakeholder SUMP problems and shown how they can be solved using simulators and Multi-Objective Evolutionary Algorithms. In particular, we presented an evolutionary algorithm based multi-objective optimization of the competing objectives of minimizing vehicular noise in a particular neighborhood together with minimizing city wide emissions. The research methodology was developed for the simulation-based optimization approach and was further demonstrated with the help of two case studies. Results from the experiments were discussed with the help of the non-dominated solution set on the approximate Pareto optimal front. This set of near-optimal solutions allows different stakeholders including the policy makers, traffic management and city administration to discuss the different options from the solution set and quantify the noise and carbon emission levels trade-offs.

While we believe that our methodology, as well as tool/algorithm selection, lends itself well to other urban mobility problems, there may be better simulators or algorithms which could be utilized for particular problems. Therefore, it would be of interest to look at the performance and tractability of different evolutionary algorithms. Similarly, other simulators may be faster or better at simulating certain objective functions or constraints. We believe that applying supervised learning, reinforcement learning, Bayesian optimization and particle swarm optimization on the problem may also result in interesting insights. Another important direction of research could be to try to reduce the search space by including more domain specific knowledge into the model.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Pedaling through a virtually redesigned city: Evaluation of traffic planning and urban design factors influencing bicycle traffic

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ABSTRACT

To achieve the 1.5-degree target of the Paris Climate Agreement, it is of great importance to promote environmentally friendly means of transport. In urban areas, shifting motorized trips to active transport modes (i.e., walking and cycling) is essential. Therefore, knowledge of walking and cycling is indispensable for planning and policy, which is the basis for targeted promotion of active forms of mobility. This paper aims to identify factors that specifically influence cycling and to derive recommendations for action for planning and policy in a virtual testbed. Specifically, the influence of traffic planning measures (i.e., structural infrastructure facilities for stationary and moving traffic as well as traffic regulations) and urban design measures (i.e., the design of public space) on the promotion of cycling will be shown. For this purpose, a virtual reality simulation was used, independent of different external conditions during field surveys and the necessity of time-, cost- and regulation-intensive structural changes. Using an improved bicycle simulator, 93 people cycled through 20 variations of an approximately 680 m long road section, surveying the effect of selected traffic planning and urban design parameters. Special attention was paid to the subjective safety of the cyclists and the attractiveness of the urban environment. Furthermore, three types of infrastructure were differentiated: No bicycle infrastructure (riding on the roadway), a bicycle lane, and a structurally separated cycle path next to the sidewalk. The virtual road section represented a real location. In addition to the findings gained from the physiological optimization of the simulator, the results show that roadside greenery had the highest effectiveness in terms of subjective safety and attractiveness. Other factors with a high influence were a speed reduction from 50 to 30 km/h when riding on the roadway with cars and the red coloring of the bicycle lane, each increasing the perception of safety. In contrast, a lack of a boundary line between the cycle path and the sidewalk was unsettling for those who rarely or never ride bicycles in their daily lives. In addition, restaurant and recreation areas increased the attractiveness of the road section, although entailing a lower perception of safety. Other factors, such as motor vehicle traffic volume or vehicles parked at the roadside, showed no significant effects on the evaluation of cycling.

With the help of these findings, the consequences of traffic planning and urban design measures can be better assessed in subsequent virtual testbeds. Also, initial trends can be identified as to which planning instruments should be used as a priority to promote cycling in urban areas. Future work should validate the transfer of these insights into physical urban spaces to support further the mid-term transformation towards sustainable urban mobility using scientific evidence.

1. Introduction

The need for cycling promotion is reflected in the increased number of research papers published on this topic (Fishman, 2016; Handy et al., 2014; Pucher & Buehler, 2017). Here, the recurring question is how limited urban space can be redesigned to be more responsive to the needs of cyclists. To answer this, the interactions between active mobility and the built environment must be examined in more detail. Preliminary results collected through household surveys (Aldred et al., 2019; Blitz, 2021; Goodman et al., 2014) or through analysis of GPS data (Krenn et al., 2014; Moudon et al., 2005) suggest that improved, high-quality infrastructure measures and the quality and use of public space increase cycling. Yet specific measures in terms of transport planning or urban design are only formulated very vaguely. Moreover, with these survey designs, it cannot be ruled out that the increased active mobility of the respondents is based on other factors (for example, personal reasons, changed life situations, weather, etc.). A most unambiguous cause-effect relationship can only be established under laboratory conditions, so we decided to use a virtual reality (VR) simulation to investigate the effect of specific traffic planning and urban design measures on cycling in more detail. VR offers the advantage that identical and almost freely definable (virtual) urban spaces can be simulated with methodically varied traffic

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planning and urban design scenarios. This virtual testbed ensures that all participants experience the same traffic situation and that the data are comparable. Traffic ordinances and time-consuming and costly construction measures that would be necessary in reality for a correct comparison of the situation before and after the measures are not required in VR. To this end, we first discuss related work and second define the research questions and the methodology used to answer them. Third, we explain how we created a digital representation of a real street and implemented virtual traffic as realistically as possible. Since the application of VR technology in mobility research is still comparatively new, and it has not yet been conclusively clarified to what extent the results can be transferred one-to-one to reality, we also highlight the challenges and possible solutions in VR simulations. To this end, the presentation of the results obtained will also examine the extent to which they are consistent with those from non-VR research insights. Moreover, we point out that the results presented here have not yet been validated conclusively. Therefore, for the time being, these results should only be interpreted as trends. Finally, the potential for further research is addressed.

2. Related work

2.1. Effects of traffic planning and urban design factors on promoting cycling

The behavior of cyclists has been investigated through field surveys or online surveys to understand mode choice and route selection better and to be able to model them accordingly. Because of their flexibility and confrontation with tactical choices (e.g., whether to accept a detour that goes through a park instead of along a major road), simulating cycling is a complex challenge and dependent on numerous influencing factors. Therefore, cyclists are often modeled in a simplified way applying the same behavioral models used to represent motor vehicle traffic (Twaddle et al., 2014). With this method, only the travel speeds need to be adjusted. However, this leads to unrealistic decisions in the bicycle traffic modeled for the reasons stated above. In recent years, however, progress has been made in developing bicycle route choice models (Yeboah & Alvanides, 2015). In addition to easily measurable travel time and objective safety (e.g., accident statistics), an increasing amount of research is being conducted to incorporate individual perceptions and feelings, such as subjective safety, in different built environments into traffic models (Kang & Fricker, 2018; Zacharias & Zhang, 2016; Maldonado-Hinarejos et al., 2016). These factors are crucial for mode and route choice, and their knowledge is essential to further the goal of promoting cycling. Furthermore, the socio-cultural background of road users also influences transport behavior. However, this is not the subject of the present research project. Therefore, studies are discussed that deal with the subjective safety of cyclists under different traffic planning and urban design conditions. On this basis, influencing factors are derived, whose effect will be investigated in the later course of the work using a VR simulation.

A study commissioned by the German Federal Highway Research Institute (Alrutz et al., 1998) conducted interviews on subjective safety with about 1500 cyclists at 11 different survey sites. The results showed that **cycle paths** or **bicycle lanes** are the most important criterion when choosing a route. The subjective perception of safety is almost exclusively determined by the existence or absence of a cycle facility. In another on-site survey by Richter et al. (2018), over 700 cyclists were asked about their safety rating as a function of land use. 77% of bikeway users and over half of the roadway users rated bikeway riding as safe, while they predominantly rated **roadway riding** as dangerous. Other studies in Graz (Austria) (Krenn et al., 2014) and in Portland (USA) (Dill, 2009) came to a similar conclusion. They determined that cyclists even accept detours in order to avoid having to ride on the roadway. For this purpose, actual routes taken by cyclists were recorded using GPS signals and compared with the existing infrastructure. Regarding the subjective safety of riding on bicycle lanes compared to riding on the roadway or on the cycle path next to the sidewalk, Jensen et al. (2007) surveyed cyclists in Copenhagen (Denmark), who rated bicycle lanes as a "middle path so to speak." They are perceived as slightly less safe than cycle paths next to the sidewalk but significantly safer than riding on the roadway. Similar results are shown in an online survey by FixMyCity (2020). Over 21,000 participants (both cyclists and non-cyclists) rated their subjective safety in different types of infrastructure and environment using model images. On average, 76% of participants rated the scenarios with any bicycle facility type as safe. The situations without a bicycle infrastructure were rated as safe by only 14% of participants. If a further distinction is made according to the type of cycling facilities, structural separations from the flowing motor vehicle traffic using curbs, flower boxes, or bollards, for example, score better than those without structural separation. Furthermore, different design variants (width, color, pictograms, safety dividing stripes) were combined with different traffic regulations (maximum permitted speed, parking on the roadside, right-of-way regulations). Here, it was shown that a clear separation between the sidewalk and cycle path by a marked line increases the subjective safety for both cyclists and pedestrians. Another survey result was that the traffic volume and the change in the maximum permitted speed (from 50 to 30 km/h) played a comparatively insignificant role in the subjective safety assessment. The InfRad survey of the German Aerospace Center (Hardinghaus, 2021) showed the same result regarding speed. However, since the changes were only visualized in both of these studies through static images, according to the authors' statement, the perceptions could only be conveyed abstractly - as was the case with traffic volume. In contrast, Broach et al. (2012) found in a user study with 164 cyclists that they reacted "very sensitively" to high vehicle traffic loads on road sections without bicycle lanes and accepted longer detours to bypass roads with more than 20,000 vehicles per 24 h. Also, Christmas et al. (2010) concluded within the framework of a qualitative workshop that the traffic volume, in addition to the speed driven and the behavior of other road users, is the greatest obstacle for the participants to use a bike. This shows that the results vary depending on the study design. Field studies also show different results than the FixMyCity online survey, depending on the speed driven. Wahlgren & Schantz (2012) conducted a questionnaire-based survey in Stockholm (Sweden) with over 800 participants. The aim was to evaluate the influence of different factors on everyday routes. In addition to vehicle traffic volume, vehicle speed and the associated air and noise pollution were assessed most negatively and revealed as the main reasons for the uncertainty stated. This finding is consistent with the survey conducted by Winters et al. (2010a) and Sener et al. (2009) in Vancouver (Canada) and Texas (USA), respectively. Besides vehicle traffic volume, vehicle speed was also an important factor influencing route selection. Other factors, such as parking at the roadside, were classified as less relevant in Vancouver. According to Graser et al. (2016), the popularity of main thoroughfares among the cyclists surveyed depends heavily on the prevailing parking situation. This is explained by the fear of accidents caused by opening car doors. However, subjective safety was primarily influenced by the volume of vehicle traffic. Only the explicit query about the influence of parked vehicles provided the result just mentioned. This issue shows how the choice of study design can affect study results and illustrates the necessity of formulating neutral queries to prevent biased responses.

Moreover, urban design factors affect the cyclability. In this paper, this term is understood to mean the design of public space. This design does not refer to the urban morphology, i.e. the settlement and building structure, but to different building uses, which entail different designs of the first floor zone, or to an enhancement of the urban space through greening or color. Specifically, the influence of restaurant areas with seating, green spaces and different (colored) floor markings will be investigated. Here it seems obvious that beautifying streets with green spaces, for example, could also increase the attractiveness of cycling. Krenn et al. (2014), 2015) investigated this possible connection as part of two studies in Graz (Austria) by recording participants' everyday

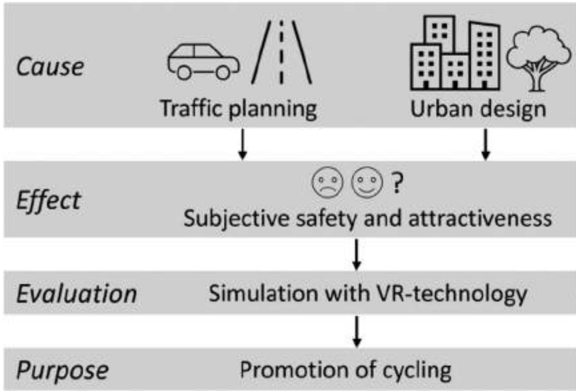

Fig. 1. Proposed mechanism of action for identifying measures that promote cycling.

cycling routes using a GPS signal and comparing them to the shortest possible routes. They found out that the routes chosen had a higher proportion of green and water areas than the shortest possible ones. Another study by Nawrath et al. (2019) found that cyclists prefer green roads, and even detours are accepted to avoid gray roads. For this purpose, they conducted an online survey in which respondents were asked to rate standardized photo collages showing street scenes with different levels of greenery in terms of attractiveness for cycling. In addition to the influence on route choice, Wahlgren & Schantz (2012) determined in their previously mentioned study that greenery on streets positively influences the willingness to cycle. Green spaces along a route or as a destination had a positive and stimulating effect on cycling for those surveyed. In contrast, Moudon et al. (2005) found no demonstrable relationship between the likelihood of bicycling and the presence of parks within a 3-km radius of the residence of 608 respondents from King County (Washington, USA). Another study from Maastricht (Netherlands) by Wendel-Vos et al. (2004) also analyzed the physical activity and living environment of over 11,000 residents. Here it was shown that people who live near sports facilities and parks spend more time on their bikes. The question of the cause-effect relationship, i.e. whether cyclists consciously choose greener residential areas or whether green spaces increase bicycle use, could not be answered in the context of the study.

In addition to green spaces, cycling infrastructure design also affects safety and attractiveness. For example, the coloring of cycle lanes was carried out in an online survey from Chile (Vera-Villarroel et al., 2016) with over 400 persons. They were asked to rate their safety at three real junctions and the conspicuousness and personal preference of the corresponding color using images. Each bicycle lane was colored in four different colors: yellow, blue, red, white, and green. On all three crossings, the color red was the most popular and the most conspicuous, while white performed the worst. Another study by van Goeverden & Godefrooij (2011) examined the effect of different cycling infrastructure designs using before-and-after analyzes in Tilburg and The Hague (Netherlands). They also concluded that a red coloring of the bicycle lane increases a route's subjective safety. Regarding the effect of restaurant and leisure areas, only isolated research results are available for pedestrian traffic. Knoflacher (2013) found out that pedestrians in an attractive urban environment are willing to accept a longer walk to a bus stop. What exactly "attractive" means in this context and whether this also applies to the travel time in cycling traffic remains to be evaluated.

Based on the state of research just presented, the representation in Fig. 1 can be derived, which summarizes the connection between cause and effect under the overarching goal of promoting cycling. For the reasons mentioned at the beginning of this paper, this relationship is evaluated using VR technology. Previous research on this application is presented in the next section.

2.2. Bicycle simulators and kinetosis issues

In recent years, VR technology has become increasingly important as a planning and evaluation tool in various research fields. In transport planning, however, it is still a rather new and rarely used tool, but one that shows great promise for scaling up (Pritchard, 2018). Several approaches with different user input and output possibilities in bicycle simulators are shown as an overview in Table 1. Schramka et al. (2018) developed a bicycle simulator that allows the basic functions of acceleration, braking, and steering. However, because the flywheel caused delays in visual simulation and thus virtual motion, users were given only visual feedback via an HMD (head-mounted display), without performing the motion of riding a bicycle. Nazemi et al. (2021) continued to work with this setup. They conducted a larger user study to examine cyclists' perceived level of safety and willingness to cycle on different infrastructure types and with varying pedestrian and motor vehicle traffic volume levels. However, steering was still disabled due to severe kinetosis (i.e., a discrepancy between actual and expected motion, also known as motion or simulator sickness). Researchers from Munich (Germany) found similar HMD-associated problems with dizziness and nausea in their bicycle simulator, so they implemented visual feedback through a static screen in front of the simulator (Busch et al., 2019). Bialkova et al. (2018) from Utrecht University (Netherlands) conducted user studies with their simulator and investigated how different types of infrastructure and environments affected the cycling experience. However, the participants were unable to control the direction of virtual cycling. The simulator's design and possible solutions regarding the challenges in terms of driving dynamics were not addressed here. A study specifically investigating the issue of kinetosis in simulations (Geršak et al., 2020) found that an HMD did not induce significantly higher levels of VR sickness compared to a 2D monitor when viewing a video clip without any physical but only virtual motion on a roller coaster. However, in this study, participants did not move physically but purely virtually without being able to control the ride. Thus, this result does not necessarily apply to bicycle simulation with active motion. The issue of VR sickness due to steering was recently explored in more detail by Matviienko et al. (2022). They compared three different steering methods and concluded that directional control via the handlebars was the best option. Controls via the HMD (the head position) or the upper body (leaning into the curve) increased kinetosis.

There is also the possibility of mounting the bicycle on a motion platform. Chen et al. (2007), Schulzyk et al. (2009), and Dialynas et al. (2019) built such a CAVE (Cave Automatic Virtual Environment) system with different degrees of freedom and the possibility to simulate different surface geometries physically. However, this setup is complex and challenging, as at least three projection surfaces are needed to wrap around the platform. According to Colombet et al. (2016), a CAVE offers no advantages in terms of motion sickness compared to an HMD. Table 1 gives a concise overview of previous work and its characteristics in terms of implementation and research questions.

2.3. Contribution to existing research

The research results presented in Section 2.1 are all based on field surveys, GPS evaluations, or online surveys. With the first two methods, there is the problem that in reality, many different circumstances affect the evaluation of the surveyed cyclists or the behavior, and these can change daily (e.g., traffic volume, time of day, weather). Therefore, the direct comparability of data collected in the field is doubtful. Online surveys either ask about behavior in reality or evaluate static images with different traffic situations. As already mentioned, the information can only be conveyed abstractly, without being able to realistically assess the degree of compliance with speed limits, for example. On the other hand, VR simulations combine the advantages of these methods: A common testbed is created for all participants (as in the evaluation of static images), which allows cycling to be experienced immersively (as

Table 1
Selection of bicycle simulators specifically developed for traffic research.

Ref	Sensors	Simulator Type	Kinetosis considered	Research subject
Schramka et al.	Acceleration, Braking, Steering	Stationary bicycle with flywheel + HMD	√	Bicycle simulator development, behavioral reactions while cycling
Nazemi et al.	Acceleration, Braking, Audio feedback	Stationary bicycle with flywheel + HMD	√	Safety depending on infrastructure and traffic volume
Busch et al.	Acceleration, Braking, Steering	Stationary bicycle with flywheel + static screen	√	Bicycle simulator development, accident research, autonomous driving
Bialkova et al.	Acceleration, Braking	Stationary bicycle with flywheel + HMD	×	Urban traffic planning
Schulzyk et al.	Acceleration, Braking, Steering, Declination	Dynamic CAVE + 3 projection walls	×	Bicycle simulator development, road safety education

in field surveys / GPS evaluations). Accordingly, VR represents a promising method to investigate influencing factors in cycling under improved conditions. Except for the user study by Bialkova et al. (2018), there is no existing literature on traffic research, which specifically considers urban conditions (apart from infrastructure and traffic volume) and the participants' subjective sense of safety in different virtual environments. However, Bialkova et al. (2018) focused not on a realistic implementation of cycling but exclusively on studying the effect of the urban environment on cycling. Therefore, the validity of these results can be doubted, also due to missing statements on kinetosis. To the authors' best knowledge, there is no investigation of the influence of various traffic planning and urban design factors under clearly defined laboratory conditions that are reproducible. Our paper addresses this research gap.

3. Methods

3.1. System layout and scientific objectives

Based on previously discussed related work and kinetosis issues when VR cycling with an HMD, the authors experienced similar issues with HMD-based pretests. On the one hand, this limits the degree of immersion and thus the potential validity of the survey. On the other hand, the number of users is not affected by the difficulties mentioned above. The authors weighted the latter more strongly and decided against an HMD-based solution. Also, it is ensured that the participants can better concentrate on the perception of the urban environment and do not have problems with possible kinetosis. This in turn also affects the validity of the study results, as participants' ratings could be influenced by kinetosis. The authors attached great importance to flawless speed and direction control and the most realistic possible driving resistance when starting off and on inclines, as described below, to achieve sufficient immersion and convey the feeling of real cycling.

The simulator setup was based on an existing system (Ullmann et al., 2020) and optimized to provide a most realistic and immediate transfer of the physical interface into the virtual simulation. The simulation aimed to allow pedaling and independent steering to increase realism, immersion, and thus the perception and evaluation of an urban environment. In addition, an eye-tracking analysis was planned but omitted due to above mentioned HMD-related kinetosis problems. Instead, audio feedback supplemented visual feedback, and a static roller trainer without lateral suspension was chosen. Thus, the visually transmitted image (i.e., non-tilted horizon) matched the physical motion (i.e., no lateral leaning) during cornering. Certainly, this raises the question of how realistic the simulation as a whole accurately replicates cycling in a real place. Achieving a high-level realism of the simulation was not the primary purpose of this work. This study investigates to what extent characteristics which influence cycling as found in the literature can be applied to a baseline in a virtual testbed. The user study aimed to derive causal connections in which environmental parameters quantitatively influence cycling, using a methodical-varying virtual representation of a real urban street in three different forms of bicycle traffic guidance. Therefore, a large-scale between-subject user study was conducted. The following sections will present individual methodological and technical aspects in detail.

3.2. Selection of representative urban street

In the city of Fuerth, a section of the Schwabacher Strasse (from Karolinenstrasse to Herrnstrasse) was chosen as an urban street to be redesigned virtually. With a population of around 130,000, Fuerth is a major city in Germany and forms a metropolitan region with the neighboring cities of Erlangen and Nuremberg. Schwabacher Strasse itself is a densely built-up arterial road leading south of the main train station out of town. It was selected for the research project because there is sufficient cross-sectional width to redistribute road space, and there is currently no cycling infrastructure and very narrow sidewalk widths. Furthermore, the street runs mainly straight, facilitating virtual locomotion and not requiring large steering movements on the bicycle simulator. The selected section has a homogeneous street character with a uniform cityscape so that no additional, undesirable stimuli affect the participants, which is one of the main arguments for initially focusing on this one street segment. One might also think of simulating an entire cycling network, but the cause-effect relationships would no longer be present in the evaluation of the respective trip since the cityscape would change significantly, and, for example, the trip through side streets would be evaluated quite differently again. In addition, the duration of the trip should remain manageable in the context of the user study. Thus, it was decided to use a microscopic approach, which can be scaled to a macroscopic level in further research.

The street is one of the most important connections in Fuerth and is characterized by a high traffic density. Two lanes are available for motor vehicle traffic in each direction. A maximum speed limit of 50 km/h applies to the entire section. By virtually varying different traffic layouts and urban space designs in the model, their effects on subjective safety and attractiveness can be queried as part of a user study.

3.3. Technical implementation

In a first step, all static objects such as buildings, road markings, sidewalks, and trees were manually modeled in a 3D city model. Then, for a realistic representation of traffic situations, all moving objects (i.e., pedestrian, cyclists, and motorized private transport) were modeled in a microscopic traffic simulation program. This includes all road users as well as the traffic signals' control.

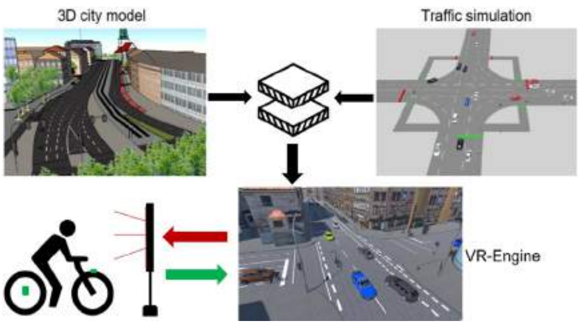

Fig. 2. Schematic structure of the bicycle simulation and interaction of the hardware and software components.

The underlying traffic behavior, such as average speed, right-of-way rules, overtaking and distance behavior, degree of compliance, and route selection, was set to meet real-world data of the particular urban street in its current condition. Most importantly, the city and traffic models must be georeferenced in the simulation environment, which requires a precise alignment of coordinates. The VR-Engine *Unity* renders the visual and audio feedback to the user (red arrow), see Fig. 2. However, to ensure an interactive cycling simulation, the users' (or bike's) movement and position are updated in the virtual space according to the speed measured and steering angle (green arrow).

3.3.1. User interface

Analogous to the setup described in Ullmann et al. (2020), an easy-to-use and comfortable bike, i.e., a women's bike with a low entry, was used and mounted vertically on a roller trainer (*Tacx Genius Multiplayer Smart T2010*) in front of an 86 inch screen; see Fig. 5. The front-wheel steering angle was measured via an *HTC Vive* tracker and a *Lighthouse* tracking system. The tracker was attached to the front wheel using a Velcro strap, see Fig. 3. The front wheel was latched in a turntable on the floor (*Kinetic Riser Ring*) to perform the steering movement on the spot, which was additionally fixed by non-slip rubber mats. The rear wheel's speed was measured via an *ESP32* microcontroller with a Hall sensor and magnets on the spokes.

3.3.2. Static objects: photorealistic virtual environment

Rhinoceros 3D and *Google SketchUp* were used as modeling and texturing tools for the three-dimensional creation of the streets and adjacent buildings. As a reference, site plans were provided by the city's traffic planning department of the city of Fuerth. In *Rhinoceros 3D*, the basic building structures along the urban street and those of the side streets were modeled, which are identical in all scenes. Also, a ground plate with curbs, traffic islands, and road markings was created independently of the buildings. Since the distance between the opposing building lines does not change and to create different variants in later tests, only the ground slab with the adjusted traffic routine hat to be replaced, not the complete 3D model. For the facades, photos were taken in the real Schwabacher Strasse, which were then projected onto the respective buildings in *Google SketchUp*. *Adobe Photoshop* was used to remove unwanted artifacts like passersby, parked vehicles, and other first-floor objects at a level in the photographs. On individual facade areas, where taking photographs was impossible, freely available building textures from *Google SketchUp* were used, blending into Schwabacher Strasse's overall image. Other 3D objects, such as trees, street signs, traffic signal poles, or benches, were downloaded from the *Sketchfab* platform or the *Unity Asset Store* and inserted into the virtual model to provide a holistic and photorealistic representation.

3.3.3. Dynamic objects: close to reality traffic simulation

The traffic model was built using the microscopic simulation program *Vissim* from *PTV Group* and based on real-world data (i.e., trajectories and traffic loads). As in the previous section, the real site plans were used for the static models and the road traffic routing of dynamic objects. The city and traffic models were superimposed so that the scale and road routing matched (see Fig. 2). To record real-world traffic loads, traffic counts were carried out in cooperation with the traffic planning department of the city of Fuerth at each intersection between Karolinenstrasse and Herrnstrasse. Traffic counting devices of *Miovision* were used, mounted on signposts or lampposts, so that the entire intersection with all its approaches was visible. The devices recorded the number and direction of motor vehicle, bicycle, and pedestrian traffic for 24 h. Subsequently, the traffic peak hour from 4 to 5 p.m. was evaluated, and the traffic volume measured was implemented into the traffic model. The traffic routing was adopted in the actual situation for the so-called zero cases 1, 2, and 3. The type of bicycle traffic guidance is a parameter for the study described below, which is why in addition to the zero case 1 there is also a zero case 2 and a zero case 3. These have a modified bicycle traffic routing, the aspects of which are discussed in detail in Section 3.4.1. In zero case 1, there is no cycling infrastructure on both sides of the model. Cycling traffic flows with motor vehicle traffic in mixed traffic on the roadway. Parked motor vehicle traffic is only present in the direction into town (marked in gray). In the opposite direction, no parked vehicles were modeled in the zero case, as this is already a parameter to be studied. Since the participants were asked to cycle out of town, only this direction was relevant. Fig. 4 shows the cross-section in zero case 1. While the lane strip widths along the real section vary from 2.00 to 4.00 m (see marked black data), the sidewalk width is 1.85 m throughout. The numbers marked in red were used for modeling because uniform lane widths simplified the parallel setup of static and dynamic models.

The width of the lanes varies in German regulations between 2.75 m and 3.75 m, depending on the traffic volume, the maximum permitted speed and the available space. If bicycle traffic is routed on the roadway, correspondingly wider lanes are recommended to ensure a safety distance of 1.50 m to the cyclist when overtaking (RASt, 2006). Thus, from the authors' point of view, the modeled lane widths represent a representative cross-section of an inner-city four-lane main road in Germany. The extent to which these widths can also be transferred to other countries is to be examined in further studies.

For a realistic representation of the traffic flow, the traffic signal programs of all intersections along the study section were provided to the authors by the city of Fuerth. These were also implemented in the microscopic simulation. Except for two intersections (Salzstrasse and Holzstrasse), fixed-time controls are present in reality. For the two traffic-dependent controls, a request button for pedestrians is present, permanent green was set in the main traffic direction in the model for simplicity, and pedestrian cross-traffic was prevented. This decision was made according to very low pedestrian traffic volumes.

3.3.4. Pretests and calibration

Before running the user study, several simulator parameters had to be calibrated. First, an average driving speed of 20 km/h (Kipke & Ullmann, 2021) was taken as a basis. The virtual speed could be calculated and adjusted based on the route length (distance from starting point to destination) and the required travel time. In addition, the wheel circumference and the associated distance cycled during one wheel rotation were determined and transferred to the VR simulation so that one real meter (according to the bike's rear wheel) matched one virtual meter

Second, at the beginning of the route to be driven by the participants, there is a slight incline of approximately 5%, which is to be stimulated by resistance during pedaling due to the roller trainer's flywheel. As soon as a participant enters the incline area, the flywheel's resistance is increased, making pedaling more strenuous.

Third, as mentioned in Section 2.2, the real and visual steering input should match as realistically as possible. In contrast to real cornering, which is initiated by a weight shift lateral tilt, a VR tracker attached to the front wheel determines (see Fig. 3) the virtual cornering radius while the bike remains stationary. Thus, the tracker reads the steering

Fig. 3. Tracker at the front wheel (left) and Hall sensor at the rear wheel (right).

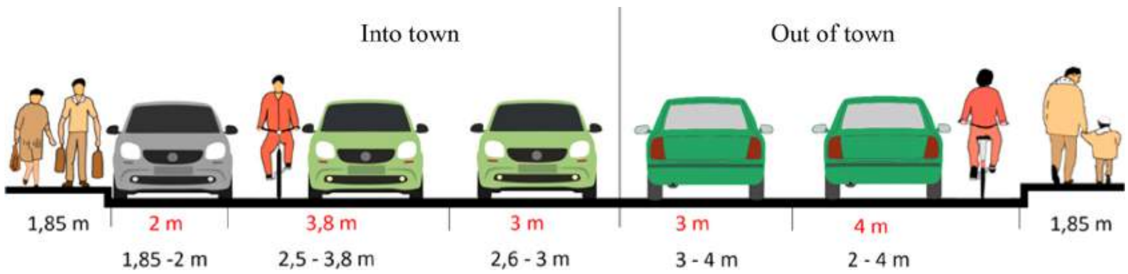

Fig. 4. Cross-section in zero case 1 (black data: Lane widths at the real cross-section; red data: Modeled lane widths).

angle of the handlebar. This entails that the virtual cornering is done by steering alone, not leaning sideways. This is a counterintuitive motion which at first requires some practice. Several pretests with an HMD revealed that a static bike's steering behavior often leads to motion sickness - especially in people without VR experience. Even small deviations between visual (i.e., the image seen through the HMD) and physical feedback (i.e., driving dynamics on the bike simulator) lead to kinetosis and nausea making it impossible to continue in VR. Cornering turned out to be particularly difficult in this case, as a weight shift when steering (leaning into the curve) is not physically possible nor transferred to the visual view. Furthermore, in VR, there are no references for the eye to orient itself to and provide some safety during the simulation. These issues were the reasons for not using an HMD to visualize the driving route. The fixed screen mentioned above was set up in front of the bike (see Fig. 5). Thus, the participants could still regulate their speed (accelerate / brake) and steer. The real-world laboratory environment peripheral around the screen gave the participants the necessary safety so that no more problems with dizziness occurred and no test ride had to be aborted. The simulation also displayed the handlebar for increased immersion, which rotates accordingly during steering movements. To overcome the VR tracker's sensitive detection of rotations potentially leading to unsafe and shaky test drives, the authors defined a dead zone of $+/-2^{\circ}$ in which the actual movement is not transferred to the virtual one. If more than 2° is steered, this steering angle is also divided by 2.5. This steering ratio offered the participants the greatest safety and comfort while representing the best compromise between a precise and easy-to-use steering.

3.4. User study

3.4.1. Design

Independent variables: Traffic planning and urban design parameters in three forms of traffic guidance

Possible cycling influencing factors (i.e., independent variables) to be analyzed were selected based on the relevant literature; see Section 2.1 for corresponding literature. For this purpose, field studies and online surveys that investigated the subjective safety of pedestrians and cyclists were used and divided into traffic planning and urban design influencing factors, see Table 2. These factors comprise, according to the literature, facilitating and hindering influencing aspects. The state of knowledge is not always unambiguous; for example, some studies determined a positive effect of green spaces on the willingness to ride a bike (Wahlgren & Schantz, 2012; Wendel-Vos et al., 2004), and others found no provable connection (Moudon et al., 2005; Winters et al., 2010b).

Fig. 5. Simulator Setup.

A decisive factor in the perception and the associated safety and attractiveness rating of cycling is the form of guidance. Different factors can result in different effects depending on whether bicycle traffic is guided on the roadway side in mixed traffic (i.e., zero case 1), on a marked bicycle lane (i.e., zero case 2), or on a structurally separated cycle path in the side space (i.e., zero case 3). For example, it has been shown that the subjective perception of safety in connection with vehicles parked at the roadside is lower when the bicycle traffic is guided to the left of stationary motor vehicle traffic (on the roadway) than when it

Table 2
Examined forms of bicycle traffic guidance with different traffic planning (blue) and urban design (red) parameters (left) and classification of the participants into groups by a randomized combination of the parameters (right).

		Group 1A	Group 1B	Group 1C
No bicycle infrastructure (**riding on the roadway**)	**Zero case 1**	x	x	x
	Reduced traffic volume (by 30%)			x
	Vehicle speed (limit 30 km/h)		x	
	Parking (on the roadside)	x		
	Greenery (trees next to the roadway)	x		x
	Bar areas (next to the roadway)		x	
		Group 2A	Group 2B	Group 2C
Marked **bicycle lane**	**Zero case 2**	x	x	x
	Reduced traffic volume (by 30%)		x	
	Vehicle speed (limit 30 km/h)	x		
	Parking (on the roadside)		x	
	Greenery (trees next to the roadway)	x		
	Bar areas (next to the roadway)			x
	Red coloring of the bicycle lane			x
		Group 3A	Group 3B	Group 3C
Structurally separated **cycle path** next to the sidewalk	**Zero case 3**	x	x	x
	Reduced traffic volume (by 30%)		x	
	Vehicle speed (limit 30 km/h)	x		
	Parking (on the roadside)		x	
	Greenery (trees next to the roadway)	x		
	Bar areas (next to the roadway)			x
	Joint sidewalk and cycle path without guidelines			x

Fig. 6. The three forms of bicycle traffic guidance in the zero cases 1, 2, and 3 (for visualization purposes without moving traffic).

is guided to the right (in the side space) (FixMyCity, 2020). To consider this, each parameter was examined for each possible form of guidance (i.e., riding in mixed traffic on the roadway, on a marked bicycle lane, and on a structurally separated cycle path), see Fig. 6. As an urban design factor, the effect of a modified pavement marking was only determined for the bicycle lane and cycle path, as there is no marking for bike traffic on the roadway due to the lack of infrastructure. For this purpose, the bicycle lane was marked in red, and the guidance form of the cycle path was changed from a separate sidewalk and cycle path to a joint sidewalk and cycle path without "guidelines". Pedestrian traffic is guided exclusively by a sidewalk, so no differences were made in the guidance form compared to bicycle traffic. Thus, a total of 20 different scenarios were created with three forms of bicycle traffic guidance (i.e., zero cases 1, 2, and 3), in each of which one parameter (i.e., traffic planning or urban design) was changed, see Table 2 summarizing all scenarios.

As explained in the previous section, the current situation in reality concerning the bicycle infrastructure is referred to as zero case 1. In zero case 2 (bicycle lane) and zero case 3 (structurally separated cycle path), a separate infrastructure is designated for bicycle traffic. Traffic (marked in blue in Table 2) and urban design (marked in red) parameters apply in all three cases. Fig. 7 illustrates how the corresponding scenarios appear to the participants given the cycling infrastructure in zero case 1.

Dependent variable and evaluation metrics

As described initially, subjective safety and attractiveness are two important factors in promoting cycling to be evaluated. Also, the willingness for active mobility increases if the infrastructure is perceived as safe (Booth et al., 2000; Rad, 2021), and the attractiveness of the urban environment plays an essential role in promoting active mobility (Ball et al., 2001; Rad, 2021). An attractive environment increases physical activity (Gao et al., 2021), and people are more willing to move slower through an urban space, affecting the time and distance perception in more attractive environments (Knoflacher, 2013). Therefore, the following perception-specific data were collected: Noticing changes in the environment, subjective rating of safety, attractiveness, and willingness to cycle, as well as the time and distance estimation; see the questionnaire in the following section for details.

A between-subjects study is used, in which the participants test each of the overall 20 scenarios (i.e., three zero cases with each five or six parameters, see Table 2). To provide a sufficient sample size and to prevent fatigue effects, each scenario is evaluated by at least ten persons, and each person drives through three scenarios. The first ride was always the zero case of the respective cycling infrastructure (i.e., riding on the roadway, bicycle lane, or cycle path, so zero cases 1, 2, or 3) so that the change made in the two subsequent scenarios could be evaluated on this baseline. Thus, the participants were divided into six groups (i.e., three groups for each type of traffic guidance, see Table 2).

Based on the current state of research presented in Section 2.1, the following hypotheses were derived regarding the effect of the defined traffic planning and urban design parameters in three different cycling infrastructures; see Table 3.

3.4.2. Procedure

The course of the user study can be separated into three steps: First, each participant was welcomed and led into the laboratory area, where the setup of the bicycle simulator was explained. Steering and braking, in particular, were addressed. A monochrome 3D printed city model of Schwabacher Strasse on a scale of 1:30,000 was used to show where the participants start their ride, where they should ride along, and where the finish line is. This visualization aims to ease the driving task in terms of orientation and focus on the perception of the urban environment. Furthermore, it was explained that the route section shown was to be driven through three times and that the configuration changed based on

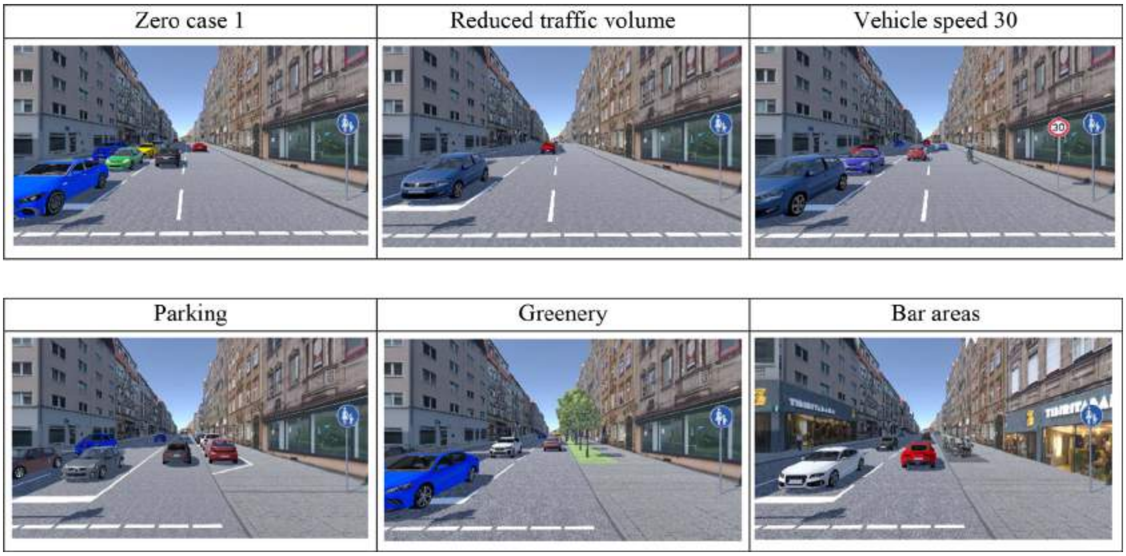

Fig. 7. Different scenarios regarding zero case 1 from the user's perspective.

Table 3
Derived hypotheses to be tested.

1	Bike infrastructure	Structurally separated bicycle facilities increase the subjective safety of cyclists.
2	Traffic volume	Lower motor vehicle traffic volume leads to higher subjective safety for cyclists, especially when riding on the roadway without bike infrastructure.
3	Vehicle speed	A lower speed limit for motor vehicle traffic increases subjective safety for cyclists.
4	Parking	Vehicles parked at the roadside result in marginally lower subjective safety for cyclists when guided on the roadway side.
5	Greenery	Greenery on streets increases the attractiveness of cycling.
6	First-floor use	First-floor uses that invite people to linger, such as bar areas, increase the attractiveness of cycling.
7	Ground marking	Red coloring of bicycle lanes and clear zoning in the form of guidelines for cycle paths increase subjective safety for cyclists.

Fig. 8. Training section for each participant (i.e., a left and right turn around the pylons and a tree that one must drive around).

the first one. The actual changes were intentionally not communicated but were meant to be noticed and evaluated by the participants. They were further informed that they should not exclusively look for these changes but should imagine that they would cycle the specific route in reality. To maximize comfort, the saddle height was adjusted. For training purposes and comparable cycling skills, each participant was first asked to ride through a test section (see Fig. 8) until VR cycling felt physically safe.

During this first test ride, the participants developed a feeling for the steering behavior and the speed control. Afterward, the following personal data were recorded:

(1) Age
(2) Gender
(3) Preferred mode(s) of transportation in everyday life
(4) VR experience
(5) Dizziness problems in everyday life

In the second part of the user study, the participants performed the three simulator rides and evaluations. After each ride, they were asked if they felt dizzy. A questionnaire was then handed out to the participants, which they filled out while sitting on the bike or a chair next to the simulator. In the meantime, the simulation of the next scene was prepared. The questionnaire, to be completed after each of the three rides, contained the following questions about the dependent variables:

(1) Did you notice any changes? *(only after the second and third ride)*
(2) How safe did you feel while driving along the road?
(3) How attractive did you find the road and its surroundings?
(4) Would you like to cycle here?
(5) Thinking about the past virtual ride:

How many meters - estimated - did you cycle on your virtual ride?

How many minutes - estimated - did you spend moving through the virtual city model?

For the questions on the perception of safety and attractiveness, a Likert scale was chosen from 1 (very unsafe / very unattractive) to 10 (very safe / very attractive), and for the willingness to ride a bike from 1 (definitely not) to 6 (definitely). The estimates at the end of the questionnaire were asked in meters or minutes.

Finally, after the third questionnaire (for the third ride) was completed, the participants were asked if the route section looked familiar, and the participants could choose a free drink as a remuneration for their participation.

Table 4
Overview of the evaluable questionnaires. .

	Riding on roadway	Bicycle lane	Cycle path
Number of participants	31	32	30
Total		93	

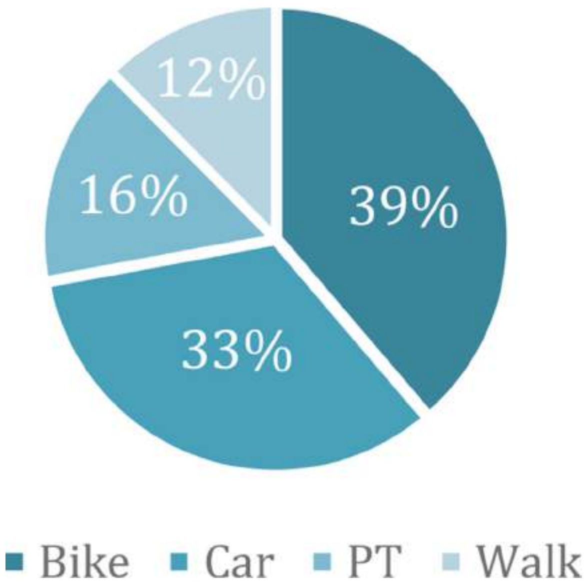

Fig. 9. Participants' everyday choice of transport.

3.4.3. Participants

A total of 93 persons participated in the user study. Of these, 45 were female, 47 were male, and one self-identified as diverse. The participants' ages ranged from 14 to 66; the average age was 37. The following Table 4 shows the classification of these participants into the three modeled guidance forms of bicycle infrastructure.

The participants' preferred choice of transport in everyday life (multiple answers were possible) can be seen in Fig. 9. The majority said they ride bicycles in everyday life (39%), closely followed by car use (33%). A few only mentioned public transport (PT) and walking. Compared to average modal split values for a city the size of Fuerth, the proportion of cyclists in the study is somewhat higher. This could be because predominantly cyclists were interested in the study's topic and thus more easily inspired to participate. To exclude the possibility that this distribution biases the results, the information provided by the participants was taken into account in the evaluation (see Section 4.5).

3.5. Statistical analysis of the data

The data obtained from the questionnaires were transferred to an *SPSS* database using anonymized participant IDs to enable statistical tests and evaluation; see Fig. 10 for a graphical overview. In addition to comparing mean values, t-tests were conducted to determine whether statistically significant differences apply to the corresponding zero case (see Table 2 and Figs. 6 and 7). More precisely, within-group (see Table 2) tests were performed for dependent and between-group tests for independent samples, respectively. The implementation of the statistical tests depended on the presence of a normal distribution of the data concerned: If no normal distribution was confirmed using the Kolmogorov-Smirnov test, a Mann-Whitney U test (for independent samples) or a Wilcoxon signed-rank test (for dependent samples) was applied. Otherwise, a *t*-test was applied correspondingly. The actual travel times and lengths were compared to each participant's estimate, so a scenario-specific underestimation or overestimation could be concluded. The user groups differed in terms of choice of transport, VR experience, kinetosis susceptibility, and location awareness. To this end, a *t*-test and a comparison of mean values were used to check whether there were significant. The following chapter will present and discuss all data and tests in-depth.

4. Results and discussion

4.1. Recognizing the changes in the environment

Before discussing subjective safety and attractiveness ratings, the participants' basic perception of the different scenarios must be considered in more detail. When looking at the results in Fig. 11, it is striking that none of the participants perceived the reduced traffic load of 30%. The reason could be that this amount of load change is too small to be perceived. Moreover, this aspect is perceived rather auditive than visually, and auditive rendering was not implemented as holistic as visual rendering. Although the traffic noise could be heard through the loudspeakers on the monitor, humans only perceive a noise change of 3 dB or more (Bundesministerium für Verkehr, 1998; Klein, 2008). This is also why traffic law measures that result in a level reduction of fewer than three decibels are often rejected (Klein, 2008); only a halving or doubling of traffic is audible (Bundesministerium für Verkehr, 1998). This

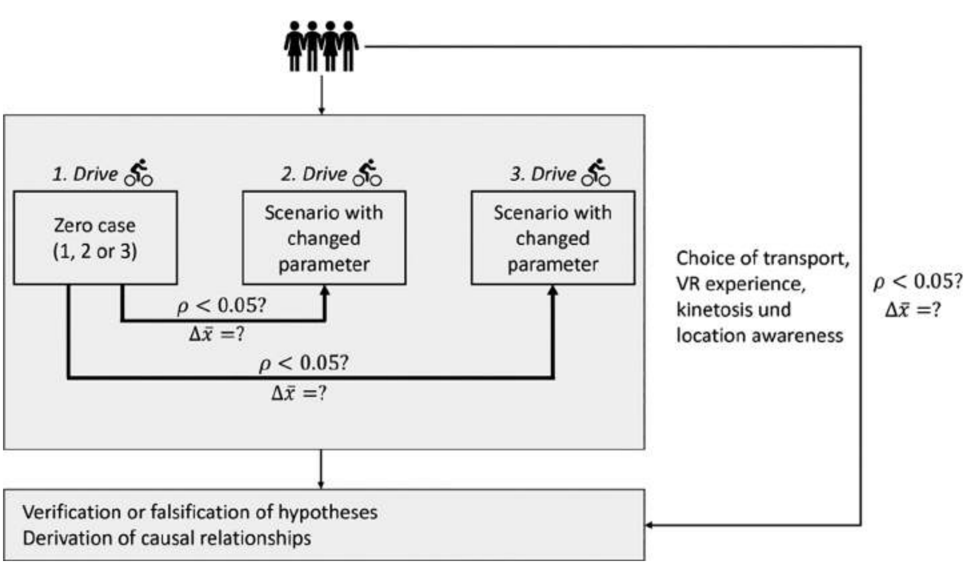

Fig. 10. Overview of statistical evaluation approach.

Fig. 11. Perception rate of the respective changes, divided into the three forms of guidance in bicycle traffic.

Table 5
Comparison of the arithmetic mean and the *t*- and p-values of the statistical evaluation for subjective safety.

Subjective Safety	Riding on roadway			Bicycle lane			Cycle path		
	$\Delta\bar{x}$	T	ρ	$\Delta\bar{x}$	T	ρ	$\Delta\bar{x}$	T	ρ
Reduced traffic volume	0.2	−0.256	0.402	0.3	−0.402	0.349	−0.5	1.246	0.122
Speed 30	1.3	−1.840	0.048	−0.1	0.143	0.445	−1.0	1.399	0.098
Parking	1.7	−1.523	0.081	0.1	−1.111	0.457	0.1	−0.128	0.451
Greenery	2.2	−3.489	0.002	0.3	−1.483	0.083	0.5	−0.711	0.248
Bar areas	1.2	−1.056	0.158	0.9	−0.987	0.175	−1.0	1.150	0.140
Red mark / Missing Mark				1.4	−4.118	0.002	−1.5	1.567	0.076

explanation is underlined by the fact that in the present study, 30% less traffic load resulted in less than 1 dB (i.e., the difference in maximum amplitude) and was not heard, not to mention seen.

When looking at the distributions in the other scenarios, it can be seen that roadway-side parameters directed at motor vehicle traffic (e.g., a 30 km/h speed limit) were also more noticeable with roadway-side guidance than side-space parameters (e.g., parking at the roadside, greenery, or the bar areas). One possible explanation for this is that the attention of cyclists, for whom there is no dedicated infrastructure and who therefore have to share the road with cars, is predominantly focused on the moving traffic to their left. Therefore, traffic regulations such as speed reduction, which impact the traffic flow and thus the cyclist's riding behavior, play a more decisive role than when the cyclist is guided on a dedicated bicycle lane or separate cycle path. Urban design elements irrelevant to this driving task are hidden and thus less perceived.

4.2. Subjective safety

Concerning the subjective perception of safety, Table 5 shows the differences in the arithmetic mean values between the respective zero case and the listed parameters and the *t*- and p-values for testing the statistical significance. All statistical tests refer to a significance level of α=0.05.

Fig. 12 shows the distribution of participants' ratings in all scenarios divided into the three forms of bicycle traffic guidance. For a better overview per guidance form, the zero cases of all three groups (A to C, cf. Table 2) were combined in one boxplot (blue). Since no significant differences were found between participants having noticed the respective changes or not, all participants' ratings in this context are presented. However, the perception results from Fig. 11 must be considered when interpreting the data. In the following, the results of subjective safety are presented concerning the hypotheses formulated in Table 3, which refer to the traffic-related parameters (i.e., hypotheses 1–4 and 7).

Hypothesis 1. Structurally separated bicycle facilities increase the subjective safety of cyclists.

When comparing the relevant three zero cases (blue), it can be seen that participants felt most unsafe riding in mixed traffic on the roadway (i.e., average safety of 4.5). The marked bicycle lane was rated with an average of 6.7, while the separated cycle path scored best with 7.7. This characteristic suggests that separated bicycle facilities increase the subjective safety of cyclists. A structural separation by a curb, for example, as in the present study, offers the highest subjective safety (p = 0.001 for zero case 1 and 2, p<0.001 for zero case 1 and 3, p = 0.045 for zero case 2 and 3). Thus, hypothesis 1 can be confirmed.

Hypothesis 2. Lower motor vehicle traffic volume leads to higher subjective safety for cyclists, especially when riding on the roadway without bike infrastructure.

Although subjective safety increased when riding on the roadway and the bicycle lane at lower traffic volumes (dark red), this change is very small and not significant (p>0.05). In contrast, subjective safety

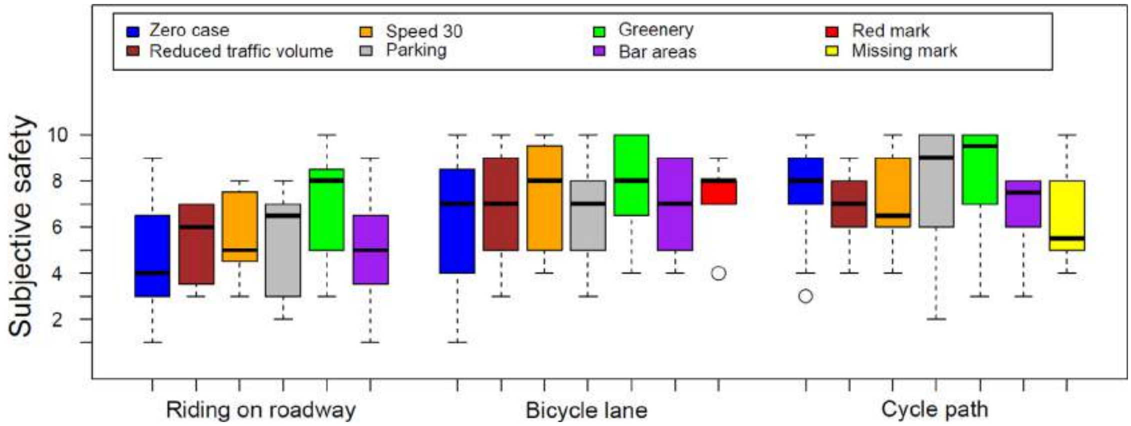

Fig. 12. Participants' subjective safety in all scenarios.

decreased for participants riding in the modeled cycle path. However, these results cannot answer the hypothesis because none of the participants had consciously perceived the change (reduced traffic volume); see Fig. 11. Thus, the rating characteristics may also result from other things the participants thought had changed. A possible rationale for this result has already been described in Section 4.1. Thus, hypothesis 2 cannot be confirmed with a reduced traffic volume of only 30%. It is recommended to reduce the traffic volume by at least 50% in further studies and examine the effects in more detail. But here, too, a distinction should be made between the different forms of bicycle traffic. Cyclists who ride off the roadway on structurally separated cycle paths generally perceive a change in traffic volume less or even less than those guided on the roadway side.

Hypothesis 3. A lower speed limit for motor vehicle traffic increases subjective safety for cyclists.

The 30 km/h (orange) speed reduction significantly increased subjective safety in mixed traffic when riding on the roadway (p = 0.048). However, these effects are not evident on the bicycle lane and the cycle path. This characteristic could be since significantly fewer participants noticed the change in these forms of guidance (see Fig. 11). When riding on the roadway, the cyclists' focus appears more on the regulations that affect motor vehicle traffic since these also directly affect them. In contrast, the specially designated infrastructure no longer requires this attention on the bicycle lane and separated cycle path. Thus, hypothesis 3 – assuming no bicycle infrastructure is designated – can be confirmed.

Hypothesis 4. Vehicles parked at the roadside result in marginally lower subjective safety for cyclists when guided on the roadway side.

In contrast to the hypothesis that vehicles parked at the roadside (gray) increase subjective safety due to the risk of dooring accidents, an increase in the perception of safety can be observed when evaluating riding on the roadway and the cycle path. Although this difference is not significant (p>0.05), it suggests that parked vehicles provide some protection for cyclists in the side space from moving traffic, which appears to be the greater hazard. This argument cannot be used when riding on the roadway, where the risk of dooring accidents is greater. However, since only 60% of the participants had perceived the vehicles parked at the roadway, the difference's validity must be questioned, and hypothesis 4 cannot be confirmed.

Hypothesis 7. Red coloring of bicycle lanes and clear zoning in the form of guidelines for cycle paths increase subjective safety for cyclists.

The red coloring of the bicycle lane (red) led to a significant increase in the perception of safety compared to the white boundary line without color (p = 0.002). The color highlighting of the infrastructure designated for bicycle traffic seems to strengthen the cyclists' position and make them feel that they are even better perceived by motorists when overtaking. Thus, this part of hypothesis 7 can be confirmed.

There was a reduced perception of safety on the separated cycle path in the absence of markings (yellow), but this difference was not significant (p = 0.076). It was noticeable here, however, that this was especially true for people who did not ride a bicycle in everyday life. In contrast, for everyday cyclists, this change had little effect on the feeling of safety. This difference could be explained by the fact that (frequent) cyclists master the roadway often without a guideline and know the situation of having to share the side space with pedestrians from practical experience. Accordingly, the second part of hypothesis 7 can be confirmed given the condition that no everyday cyclists are involved.

Another conspicuity in the subjective safety ratings is the parameter **greenery** (green) when riding on the roadway. Here, the largest significant difference compared to zero case 1 (p = 0.002) can be observed, and the average safety perception increased by 2.2 (from 4.5 to 6.7). This significant effect is not evident in the other two forms of guidance.

In the case of the **bar areas** (purple), there is a tendency toward lower subjective safety. This aspect could be explained by the fact that the change in first-floor use created more points of conflict with passersby.

4.3. Attractiveness and willingness to cycle

Regarding attractiveness, Table 6 shows the difference in the arithmetic mean values between the respective zero case and the listed parameters and the t- and p-values for testing the statistically significant differences. All statistical tests refer to a significance level of α=0.05.

In the following, the ratings of the attractiveness of the urban environment and willingness to cycle concerning hypotheses 5 and 6 are evaluated; see the boxplots in Figs. 13 and 14. As with subjective safety, it should also be noted that for a better overview per guidance form, the zero cases of all three groups (A to C, cf. Table 2) were combined in one boxplot (blue).

Hypothesis 5. Greenery on streets increases the attractiveness of cycling.

It is noticeable that greenery (green) significantly increased the attractiveness of the urban environment in all three forms of guidance (p < 0.001 in each case). Fig. 13 clearly shows the effect of the green stripe on the roadside, which the participants recognized better than any other parameter. This underlines how important green spaces are - regardless of their necessity for improved air quality and cooling effects (Wesseling et al., 2004) - for increasing the attractiveness of inner cities. To confirm the hypothesis that green spaces increase the attractiveness of the urban environment and that of cycling, the stated willingness must be included in the evaluation (see Fig. 14). Here, in the case of

Table 6
Comparison of the arithmetic mean and the *t*- and p-values of the statistical evaluation for attractiveness.

Attractiveness	Riding on roadway			Bicycle lane			Cycle path		
	$\Delta\bar{x}$	T	ρ	$\Delta\bar{x}$	T	ρ	$\Delta\bar{x}$	T	ρ
Reduced traffic volume	−0.4	0.585	0.286	0.2	−0.408	0.347	0.1	−1.000	0.159
Speed 30	0.7	−2.185	0.027	0.6	−1.541	0.076	−0.6	0.919	0.191
Parking	0.8	−1.500	0.084	−0.1	0.139	0.447	0.6	−1.203	0.130
Greenery	2.9	−4.436	0.000	2.4	−5.562	0.000	2.9	−5.749	0.000
Bar areas	1.6	−1.901	0.044	2.2	−3.498	0.004	2.0	−3.464	0.004
Red mark / Missing Mark				0.6	−1.616	0.070	0.0	0.000	0.500

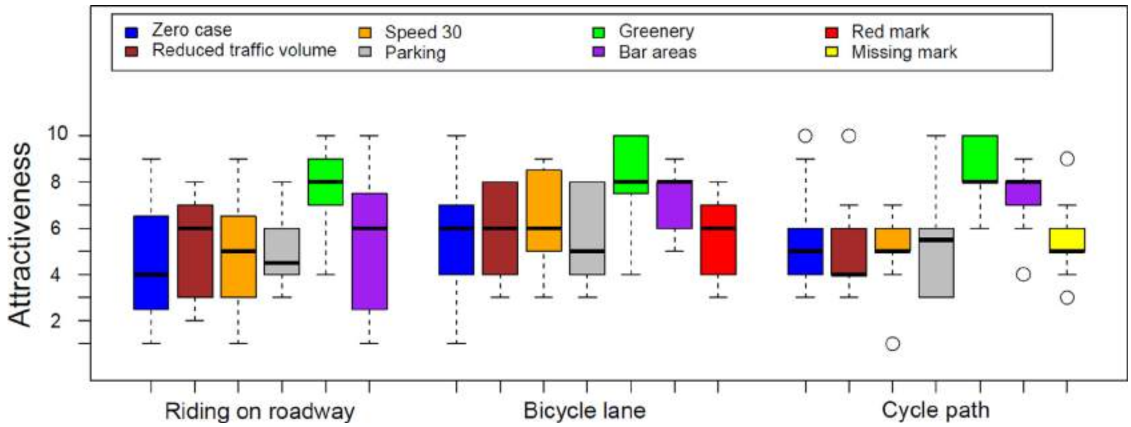

Fig. 13. Participants' attractiveness to the urban environment in all scenarios.

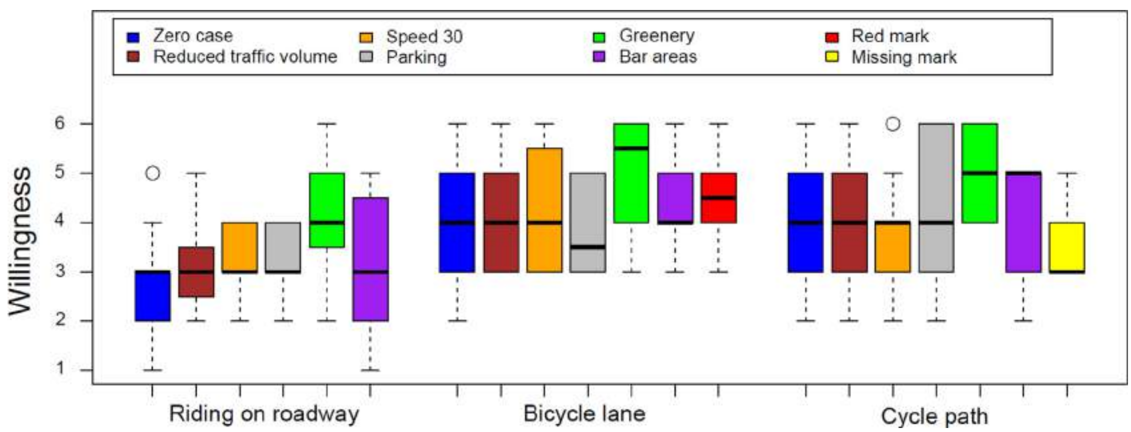

Fig. 14. Participants' willingness to cycle in all scenarios.

greenery (green), willingness increased by an average of one point on all forms of guidance ($p = 0.001$ riding on roadway, $p < 0.001$ on bicycle lane, $p = 0.002$ on cycle path). The respondents are more willing to cycle there than on roads without greenery. Thus, hypothesis 5 can be confirmed.

Hypothesis 6. First-floor uses that invite people to linger, such as bar areas, increase the attractiveness of cycling.

Bar areas (purple), associated with busier first-floor use, also increased the attractiveness of the urban environment for respondents. As with greenery, there is a significant difference for all forms of guidance ($p = 0.044$ for riding on the roadway and $p = 0.004$ each for the bicycle lane and cycle path). If one also looks at the willingness of the participants to cycle on these sections compared to the zero cases, it can be seen that there is no significant increase. Accordingly, only the statement can be made that bar areas increase the attractiveness of the urban environment, but not necessarily when cycling. Hypothesis 6 must therefore be rejected. One possible reason for this is the effect on subjective safety. Bar areas are attractive, but the increased pedestrian traffic volume and busier side space require cyclists to pay more attention and distract from the actual driving task. This additional cognitive load leads to a slight (though not significant) reduction in the perception of safety. This effect is visualized in Fig. 15, which shows the ratings of cyclists on the cycle path (duplicate ratings are not shown). A possible prerequisite for an increase in attractiveness to also apply to bicycle traffic would be a clear demarcation of the bar areas by, for example, flower pots, bollards, or similar, which prevent or at least make it more difficult for pedestrians to enter the cyclist's lane suddenly. Indeed, this concern was pointed out by many participants to justify their rating.

4.4. Distance and time estimation

At the end of each questionnaire, the participants were asked to estimate the distance covered and travel time. While no significant differences emerging from data noise were found in the distance traveled and estimated, a significant difference was found in the travel time between

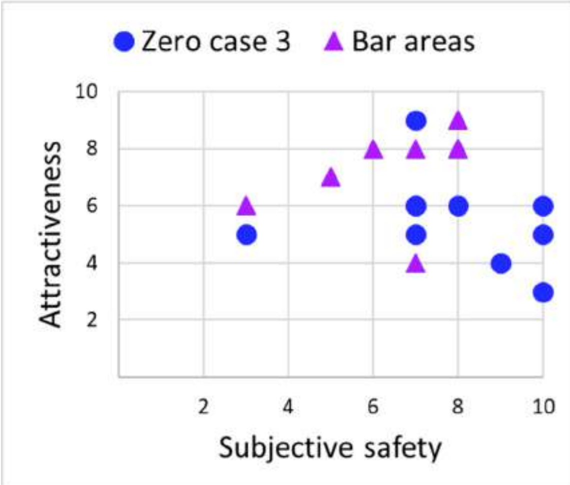

Fig. 15. Correlation between subjective safety and attractiveness on the cycle path: The zero case is assumed to be safe rather than attractive, while the opposite applies to bar areas.

the estimates in the zero cases and the scenarios with speed reduction (i.e., 30 km/h) or greenery. Figs. 16 and 17 show the deviations between estimated and actual elapsed travel time. If the deviation is above a zero value, the travel time was overestimated, and negative deviations express underestimated travel times. The estimated travel time corresponds to the actual travel time with the line drawn in the diagrams (deviation equals zero).

The mean deviation in the zero cases (blue) is 1.54 min when riding on the roadway, 1.41 on the bicycle lane, and 1.30 on the cycle path. Based on these values, it can be concluded that the safer the cyclists feel in the respective infrastructure facility, the faster the time passes or the more realistic the time estimate of the participant becomes. When comparing this time estimation with the other scenarios, significant differences in the zero cases were found in two of them: With a speed limit of 30 km/h (orange), the time seemed to pass faster for the participants than at a speed limit of 50 km/h. Since the cyclists – at least in comparison to the cars – feel faster, the time spent is possibly also perceived as shorter (p = 0.072 riding on roadway, p = 0.011 on bicycle lane, p = 0.010 on cycle path).

The same effect is seen with greenery: If the journey was accompanied by street greenery, the participants had the feeling that time passed more quickly (p = 0.005 when riding on the roadway, p = 0.041 at the bicycle lane, p = 0.006 at the cycle path). Knoflacher also came to a comparable conclusion, demonstrating in empirical studies that road users' perception of time depends on the environment of a route: "An environment perceived as beautiful stretches time less than an unattractive one" (Knoflacher, 2013). Since, in the present study, greenery was also rated as significantly more attractive than the zero cases, this statement can be confirmed.

Overall, it can also be seen that almost all deviations are above zero. This trend means that the travel time in the bicycle simulator was generally overestimated. Whether this is also the case in reality or related to the simulation must be tested in field surveys. Apart from this, the results are consistent with previous studies with similar questions and research designs (Bialkova et al., 2018; Knoflacher, 2013). Thus, VR appears as a suitable method to study the effect of traffic planning and urban design parameters, as the results are consistent with those from field surveys (Dill, 2009; Jensen et al., 2007; Krenn et al., 2014, 2015; Richter et al., 2018; van Goeverden & Godefrooij, 2011; Vera-Villarroel et al., 2016; Wahlgren & Schantz, 2012). The effects of reduced traffic volume and vehicles parked at the roadside do not provide a clear picture since different results were found in the literature (depending on the applied methodology). This issue shows that further comparative studies are necessary to define the conditions that lead to a positive or negative effect.

4.5. *Influence of choice of transport, VR experience, kinetosis, and location awareness*

Having checked the collected data of the user study for significant differences due to the previously described influencing factors, the data of the groups with specific attributes of the participants (i.e., preferred choice of transport, VR experience, susceptibility to kinetosis, location awareness) were additionally compared. Based on the results, however, no significant differences became evident, so that possible influences on the results can be prevented. Thus, it can be excluded that for example everyday cyclists rated the road section significantly better than car drivers, susceptibility to dizziness influenced the participants' rating, or location-aware participants felt safer or quicker. More specifically, 22% of the respondents indicated that they had experienced slight dizziness during the test ride, 56% declared first VR experience, and 32% stated to (at least vaguely) know the road section in reality. With regard to the generalizability of the results it can be assumed that the group of participants was heterogeneous and the road section could just as well have been a fictitious one.

5. Conclusion and future work

In this work, we investigated which traffic planning and urban design measures make cycling in urban areas subjectively safer and more attractive in order to inspire more people to cycle in the future and thus contribute to sustainable mobility and to achieving the 1.5-degree target of global warming. Using a bicycle simulator and a virtual city model,

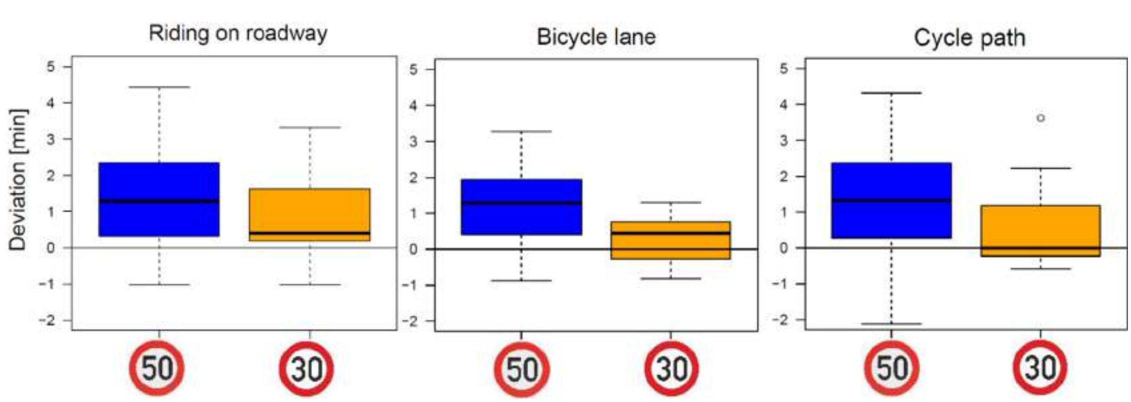

Fig. 16. Deviation between estimated and actual travel time (zero cases - speed 30).

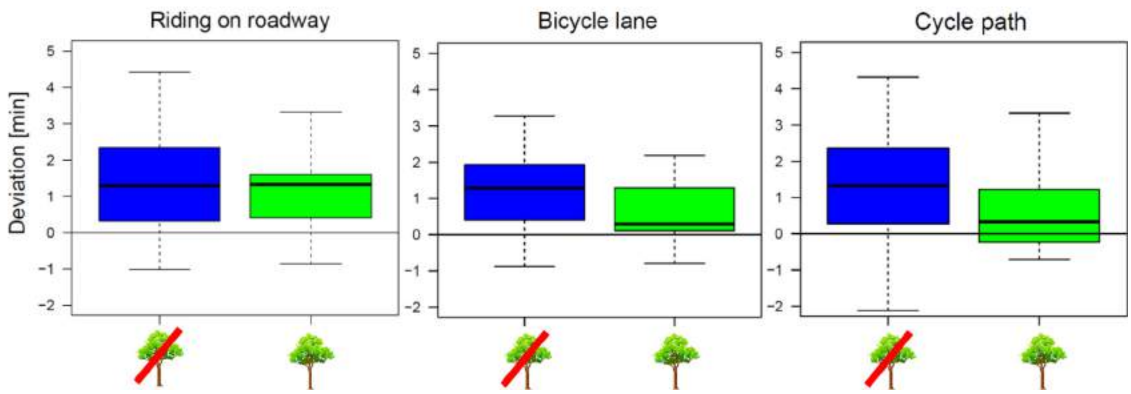

Fig. 17. Deviation between estimated and actual travel time (zero cases - greenery).

we investigated the effects of literature-derived influencing factors under laboratory conditions. The findings obtained regarding the subjective safety and attractiveness of cycling largely coincide with heterogeneous previous results from field studies, which underlines the validity of the cycling simulator as a valuable tool in cycling planning. Based on these insights, we especially recommend for planning and policy makers to use more roadside greenery in the city, in addition to traffic law measures such as reducing the speed limit or color marking of bicycle lanes since these measures were found to have the highest effectiveness regarding subjective safety, attractiveness and willingness to cycle. Furthermore, we recommend to explicitly distinguish these influencing factors in relation to the guidance form of cycling traffic, as there were significant differences in perception and evaluation. We conclude that VR technology is a suitable tool to better explore cycling and its needs, but also point out that this needs to be optimized in the future. The results give a first impression of the causal relationships in cycling and which measures can bring about significant improvements or deteriorations. They should serve as a basis, motivation and guide for future work with political leverage. More precisely, physiological optimization toward increased levels of realism and immersion is worth pursuing, which is also likely to correlate with the validity of the data collected with this virtual testbed. Especially, kinematically realistic cornering and the three-dimensional inertia of the bicycle (e.g., during acceleration or uphill and downhill riding) should be considered. Apart from the physical interaction, following work should extend the evaluation of traffic planning and urban design effects on pedestrians and car traffic (considered individually or together in an urban traffic). Based on our findings, future work could also apply advanced biophysiological evaluation approaches, e.g., EEG or eye tracking, to foster cycling as sustainable urban mobility in the long term.

6. Limitations

Concerning methodological limitations, the participants' division into groups (see Table 2) may have brought a learning effect. Even if no learning effects became evident in the evaluated data, a bias cannot be excluded due to the non-randomized order of the second and third scenarios each participant rode.

Concerning technical limitations, most important were the fixed position of the external monitor and not using an VR HMD, which possibly limited the participants' perception of the environment: The participants could not look around, but only see straight ahead to a limited field of view.

Despite the as realistic as possible roadway mapping and best possible bicycle simulator calibration, the transfer and further solidification of the findings regarding time perception to reality needs to be empirically validated. To this end, a field study on the real road section to further calibrate the spatial and in-turn temporal scale is planned.

Declaration of Competing Interest

The authors declare that they have no known competing financial and personal relationships with other people or organizations that may have inappropriately influenced the work reported in this paper.

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Ready for robots? Assessment of autonomous delivery robot operative accessibility in German cities

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Unlike autonomous car applications, the operational area of urban service autonomous robots like autonomous delivery robots (ADRs) is not clearly defined at the moment. Due to large variations in the different robot designs, specific local infrastructure and regulation, assessing the feasibility of different operational scenarios is difficult. This paper presents a prototype evaluation methodology based on Open Street Map data for the assessment of ADR deployments considering one-to-many delivery schemes. Four different robot configurations and potential operational specifications are modeled and evaluated in a sample of German cities. The bandwidth of considered robot types ranges from large ADRs operating on roadways down to small size systems operating on sidewalks. The performance of the first category is limited by the reduced accessibility in areas with higher traffic. On the contrary, small ADRs present a higher detour time but increased accessibility. The evaluated operational scenarios show very diverse performance depending on the considered metrics and cities. For all the metrics considered in the paper, sidewalk ADRs show poor performance when compared to other potential ADR deployments.

1. Introduction

1.1. Motivation

Delivery vehicles (including all types of operations, ranging from e-commerce parcel deliveries to supermarket or restaurant replenishment) are estimated to represent around 13% of the whole traffic in cities (Kummer et al., 2021). The contribution of freight last-mile transport towards air pollution is even higher, this is due to reasons such as, the vehicles used by logistics operators are older than the rest of the other road users' vehicles (Dablanc, 2007; Russo and Comi, 2012; Segura et al., 2020), the vehicel speed and more (Coulombel et al., 2018). One of the main elements that characterize most of the last-mile markets is the low efficiency of operations (Allen et al., 2018), resulting in high operation costs. In Spain, the last mile transportation can cost up to 40% of the total transportation costs of a good (Segura et al., 2020). Personnel expenses (including salary, social security) represent around 70% of the total last-mile operation costs (Generalitat de Catalunya, 2019).

The last mile is the final leg of the supply chain. Basically, it describes the logistics operations to bridge the distance from a (suburban) hub to the consignees in the urban area. More recent approaches to increase the sustainability incorporate a micro hub at which deliveries are transferred to cargo bikes, robots, light electric vehicles or similar. In this case it is often differentiated between the last mile (between the suburban hub and the micro hub) and the very last mile where the actual deliveries take place. Other common terms are tier 1 and tier 2 (Assmann and Trojahn, 2018; Katsela et al., 2022).

In this context, autonomous delivery robots (ADRs) are a very promising technology. These micro vehicles can travel in urban environments without any human intervention using sensors and artificial intelligence algorithms. The delivery process to the final customer is also done autonomously. Even if the legislation in most countries currently demands partial supervision by remote operators, it can be expected that robot operations will be fully autonomous in future years.

Manufacturers and research institutions have worked on corresponding systems in very different formats. Baum et al. (2019) listed 35 com-

Abbreviations: ADR, autonomous delivery robot; OSM, OpenStreetMap.

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(a) Nuro multi drop-off robot (Dimension 186/110/274 cm) (Nuro, 2021; Omondi, 2021)

(b) Starship robot (Starship, 2021) based delivery service (Oregon State University, 2020) (Dimension 55.4/56.9/67.8 cm, without the flagpole) (Omondi, 2021)

Fig. 1. Two different designs of ADR prototypes.

panies and 39 different designs of automated micro-vehicles. The solutions proposed in this work range from systems as big as passenger cars with a high storage capacity up to knee-high parcel robots that only transport one item and use footpaths (see Fig. 1). However, this does not reflect the entire spectrum, as there are also solutions for autonomous freight logistics and autonomous line-haul logistics (Flämig, 2016).

By reducing personnel costs in last-mile operations and improving operation optimization, ADRs are expected to cut the carriers' operations costs (Jennings and Figliozzi, 2019; 2020). A reduction in last-mile externalities emission is also anticipated (Figliozzi, 2020).

Unfortunately, as opposed to autonomous cars whose area of operation is clearly defined (mostly on streets with general traffic), ADRs operational setting raises many questions. It is not clear at the moment whether ADRs will be allowed to travel on pedestrian tracks (including sidewalks), bike lanes or residential streets, depending on their dimensions (Hoffmann and Prause, 2018).

In this discussion, it is important to keep in mind the heterogeneity of the non-road infrastructure elements: bike lane and sidewalk width are far from being homogeneous, pavement might be largely different, and the presence of stairs or urban equipment would hinder the movement of ADRs. The particular case of sidewalks and pedestrian areas is even more problematic. This urban space generates a huge competition between all usages (restaurant terraces, urban furniture, passers-by...) that has to be considered when planning sidewalk ADR operations.

As a consequence, it is not possible to make general statements about the possible use of an autonomous robot system for a specific delivery task in a specific service region. Even the fundamental question of an optimal robot size raises a multitude of imponderables and cross-relationships which are:

1. The appropriate dimensions of the robot is obviously limited by the environmental conditions (width and height restrictions) in the potential operation area. Accessibility for each actual robot configuration must be individually checked.
2. A purely geometric study would disregard particular specifications from local authorities. Regulations for autonomous driving are in the works and are currently changing very dynamically. However, these regulations mostly relate only to roads; regulations for bicycle paths and footpaths are unclear (Bundesgesetzblatt Jahrgang 2021 Teil I Nr. 48 - ausgegeben am 27.07.2021 - Seite 3108, 0000; Hoffmann and Prause, 2018). Consequently, the applicability of tracks and corresponding rule sets (speed level) include large uncertainties.
3. The acceptance of ADRs and their interaction with other road users (especially pedestrians) have not been studied in a comprehensive manner yet. Cultural differences will have an influence on the average speed of ADRs and the accepted proximity (Gnambs and Appel, 2019). Consequently, individual sets of criteria must be derived for the applicability of ADRs in international scenarios.

It is important to note that the size of the robot is only one aspect of the network of interdisciplinary configuration parameters. Fig. 2 summarizes further characteristic values of an ADR scenario and illustrates their interrelationship.

One of the main challenges that need to be addressed to maximize ADR efficiency is to find an adequate balance between the robot design, its environment and the logistical tasks (use case) it will be used for (see Fig. 2).

As a matter of illustration, if the pavement is of poor quality (which is a given environmental condition), the robot energy consumption will be higher (Ziyadi et al., 2018). This limits its maximum range of action because the total capacity of its battery is given (technological restriction) and cannot be easily increased. Overcoming obstacles (environmental conditions) also increases the energy consumption rate of the robots, limiting their range of action and impacting the way logistical tasks can be executed. The shortest route between two points may not be the most suitable one for the ADRs if it includes many steps that have to be overcome (considering the robot is able to do so, which may not be necessarily the case).

The challenges raised by the robot speed are quite more complex. On the one hand, maximizing ADR's speed (eventually limited by the inherent technical features of the robot) is fundamental for logistics operators. If the robot operation speed is high, more stops can be done in a given amount of time, i.e. increasing its efficiency. However, if the robot speed is high, the energy consumption is increased (Ziyadi et al., 2018), which limits its operation range, and eventually increases the fleet size and the operation costs. On the other hand, high speed ADRs reduce the acceptance by other road users and passers-by when the robot operates on foot and bike paths. In addition, a fast-moving robot requires more sophisticated sensors and processing units for predictive motion planning, which further increases energy requirements. This example clearly illustrates the duality between the operator's main objective of costs reduction and cities' willingness to reduce the environmental impact of last-mile logistics and prevent accidents with other road users.

The logistical tasks that are to be done essentially depend on the considered use case. The logistics patterns induced by one-to-many distribution (from a logistics hub to a set of final customers) (Ulmer and Streng, 2019) are completely different from many-to-many delivery schemes (food dispatching from a pool of restaurants to final clients) (Dai et al., 2019). Given robot designs and operation rules may be more suitable for one or the other. The size of items that are to be delivered is also a fundamental variable that needs to be considered. Smaller robots will not be able to deliver big and heavy parcels and dual distribution strategies may be required depending on the item's characteristics

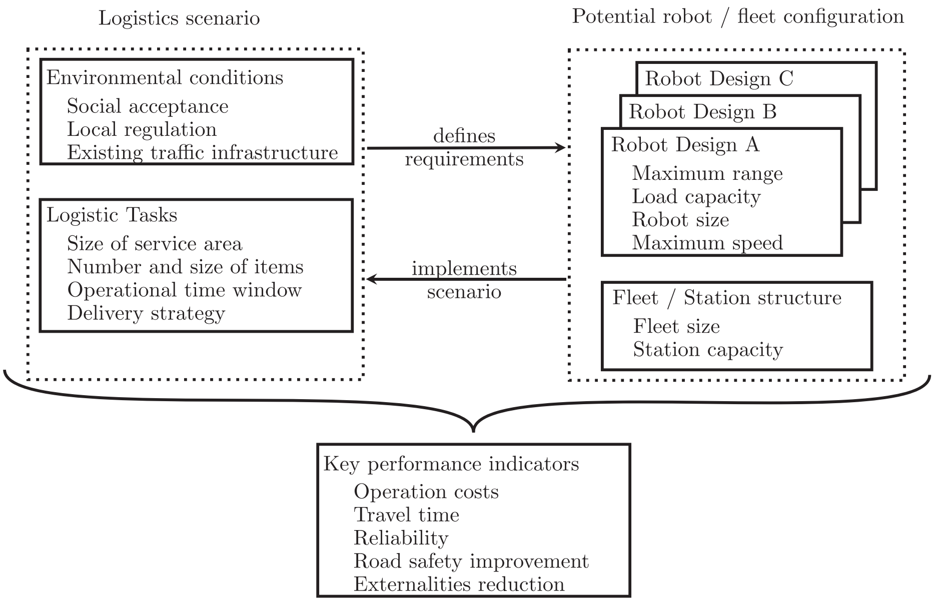


Fig. 2. Decision variables for ADR operation planning.

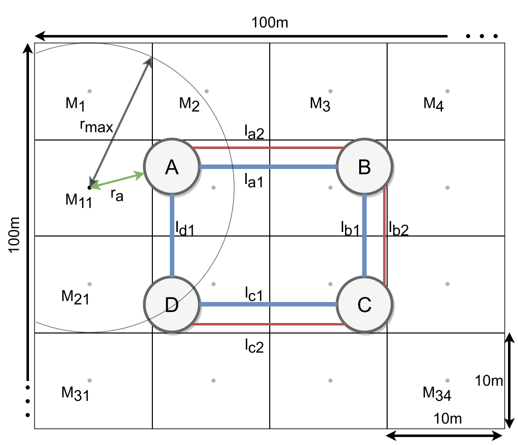


Fig. 3. Population assignment and detour computation.

(Estrada and Roca-Riu, 2017). Other important variables that have to be considered in the optimization of logistics operations are the operational time window (Figliozzi, 2007), the demand density (number of receivers that have to be served in a given area) or the size of the service region (Lemardelé et al., 2021).

The environmental conditions, the logistics tasks that are to be executed, the robot design and the interaction between these three aspects determine the value of some operation key performance indicators (KPIs). Depending on the relative importance of each KPI, the most adequate operative scenario will be selected and implemented. For logistics operators, the most relevant KPIs are, by order of importance, the operation costs, the travel time, the reliability, the road safety improvements and the reduction of externalities (Perera and Thompson, 2021).

To sum up, the robot design must be tailored to the ambient conditions with regard to the geometric dimensions, the configuration of the drive and the running time, as well as the robot volume capacity (Jaller et al., 2020). Different operation models (single vs. multiple jobs at one tour) for ADRs will achieve different performance values. Accordingly, the planning of ADR scenarios is a complex process, which has not been examined in the literature for specific use cases, but with a generic objective.

1.2. Research questions

This paper focuses on a prototypical toolchain that supports the planning of one-to-many ADR operations, including many potential use cases:

1. Food distribution from a restaurant (or cloud kitchen also known as dark kitchen), considered in this case as a logistics micro-hub, to a set of customers (Domino's Pizza Inc., 2021).
2. Grocery distribution from a supermarket to a set of customers (Korosec, 2021).
3. E-commerce parcel deliveries from a hub to final receivers (Ulmer and Streng, 2019).

To understand the purpose of this study, we think it is important to emphasize here the main hypothesis that drove us all along the research process.

As we described in the previous section, different operational scenarios can be envisioned. As a matter of illustration, let us consider large robots traveling on roadways on the first hand, and small sidewalk ADRs on the other hand. Large ADRs will undoubtedly be faster (see Table 1). Nevertheless, they may have to travel a larger distance, meaning that the detour time between the large-ADR scenario and the small-ADR one may not be so high. The lower traveling speed of small ADRs would be compensated by increased accessibility and much shorter distances, especially considering one-way streets.

Fig. 5 presents a very simple city with 4 nodes. The blue graph represents the small-ADR operation scenario whereas the red one corresponds to the roadways used by large ADRs. To go from A to D, even if the speed of large ADRs is 4 times higher (on the red edges), the detour time induced by small ADR operations may not be so high because small ADRs travel much less distance between A and D.

This balance between speed and distance in different operational scenarios and on a large-scale basis is the main aspect we wanted to investigate in this paper. We included other metrics to complete the analysis of the different operational scenarios.

The proposed methodology is evaluated in 16 different German cities on the basis of local population statistics and Open Street Map (OSM) data sets. In this way, the paper focuses on 5 main research questions:

1. Which classes of ADRs can be derived from the systems described in the literature, and which of their properties have to be considered in the planning process?

Table 1
Comparison of autonomous delivery device applications related to system configuration and operational area.

Type	Scenario	Location	Robot size	Operational parameters	Ref.
Concept	Parcel delivery		Delivery trucks + small ADRs	Hub and Spoke	(Hoffmann and Prause, 2018)
Concept	Parcel delivery		Medium robot	Sidewalks, bike lanes and roadsides 3-to-5 mile radius around a retailers location	(FedEx, 2020)
Experiment	Parcel delivery	Washington (US)	Small Size	Pedestrian tracks, accompanied by an operator	(Scott, 2019)
Experiment	Parcel delivery	California (US)	Big robots (small car)	Fair weather conditions Public roads including freeways, highways and streets	(DMV, 2018)
Regulation		San Francisco (US)		On streets with 6-feet-wide sidewalks In given areas of the city Robots must be accompanied by an operator	(Wong, 2017)
Regulation		US (regulation depends on the State)		Max speed on sidewalks = 16–19 km/h Max speed on roads = 32–40 km/h Max weight up to 250 kg but often between 36–54 kg	(LMAD, 2021) (RList, 2021)
Regulation		EU		Most advanced countries = Lithuania, the Netherlands and Germany, AVs can be tested without a driver No differentiation between autonomous cars and ADRs	(LMAD, 2021)
Productive	Food delivery	Milton Keynes (UK)	Small Size	Pedestrian tracks, maximum speed of 6 km/h Within a radius of up to 5 km, supervised by an operator at complex intersections Packages up to 10 kg	(Hoffmann and Prause, 2018) (Hern, 2020)
Productive		California (US)	Medium size (half a car)	On streets with a speed limit of 35 mph Fair weather conditions	(DMV, 2020) (DMV, 2020)

2. How to aggregate, represent and evaluate relevant information to evaluate the applicability of an ADR class for a city?
3. Which metrics are suitable for representing an abstract ADR-preparedness of a city?
4. Would it be possible to use OSM data to plan a large-scale deployment of ADRs in German cities considering one-to-many delivery patterns?
5. Is an operational scenario more suitable to improve given logistics operators' KPIs?

The work is structured as follows: the next chapter describes the state of the art related to existing delivery services based on autonomous robots, assessing concepts for ADR operations and accessibility metrics. Section 3 describes the methodology of the approach and explains the implementation. The last two chapters include an investigation of the applicability of ADR scenarios in different German cities and a discussion of the results. In particular, the limitations of the quality of the underlying OSM dataset are addressed.

2. Literature review

2.1. Autonomous delivery services

Pani et al. (2020) identified the most relevant socio-demographic determinants that condition the acceptance of ADR services by end-users. Willingness-to-pay (WTP) for ADR deliveries is higher in urban areas and for customers located between 0.5 (around 10 min walking) and 2 miles from the closest shopping stores, indicating that the ADR ”optimal range of action” is between 0.5 and 2 miles.

Kapser and Abdelrahman (2020) found that the most important factors for ADR acceptance by end-users are the price of the delivery, and the performance expectancy (mainly the time between the order and the delivery). These two variables are also a top priority for logistics operators (Perera and Thompson, 2021). German customers seem to be quite neutral and adopt a utilitarian approach, i.e. they will ask for autonomous deliveries if they are cheaper and faster than conventional solutions (Romanjuk, 2020).

Unfortunately, the work done by Kapser and Abdelrahman (2020) and Pani et al. (2020) was not based on an actual pilot of an autonomous delivery service; the interviewed persons were to imagine fictitious ADR use cases. On the contrary, the work done by Romanjuk (2020) is based on an existing autonomous delivery service operating in the city of Tallin. This data is very valuable because it deals with an ex-post analysis of an existing service. Unfortunately, these types of studies are mostly unavailable to the research community. Some autonomous delivery services are already being piloted (see Table 1) but no analysis of their operations and the perception of users is available. Sharing this data is strategic for private companies (Hoffmann and Prause, 2018) and only some press articles provide a very partial overview of the different operational scenarios (see Table 1).

Acceptance of ADRs by pedestrians and other road users (Wong, 2017), data privacy issues, the obstruction of sidewalks by robots and safety challenges are topics that are also investigated at the moment (Marks, 2019).

2.2. Assessing ADR operations

ADR operations assessment currently generates a great activity within the research community. Because ADRs are most of the time electric vehicles with a limited range of action, carriers' distribution channels have to be adapted to this restriction and promising collaborative delivery schemes are emerging. Boysen et al. (2018), Chen et al. (2021a), Chen et al. (2021b) and Yu et al. (2020) analyzed ADR cooperation with "mothership" delivery trucks that behave as mobile depots. The van stops at given locations and deploy some ADRs to perform the final deliveries to customers. Operation costs reduction seems quite promising in this type of model (Jennings and Figliozzi, 2019). Other schemes using pickup stations and ADRs were also studied (Ulmer and Streng, 2019).

When considering ADR-related literature, two main types of modeling strategies appear. On the one hand, continuous approximation (CA) formulations are used to get a first overview of the robot fleet optimal development (Figliozzi, 2020; Jennings and Figliozzi, 2019; 2020). From this type of modeling approach are derived compact and easy-to-interpret equations in which the most important decision variables can be rapidly identified (Daganzo et al., 2012).

On the other hand, ADR operations can also be analyzed using numerical optimization algorithms (Boysen et al., 2018; Chen et al., 2021b; Simoni et al., 2020; Ulmer and Streng, 2019; Yu et al., 2020). In most cases, these approaches aim at determining optimal solutions of the traveling salesman problem (TSP) or vehicle routing problem (VRP) particular instances. Given a set of final customers' locations (that need to be visited) and a set of restrictions, the logistics service provider optimizes the tours of its vehicles to minimize a certain objective function (operation costs in many cases).

Unfortunately, in this second category of operation-oriented studies, actual ADR operating conditions in "real-life" environments are almost never considered. The instances that are generated to evaluate the developed numerical methods do not consider the actual grid that the ADRs would have to use (Boysen et al., 2018; Chen et al., 2021a; 2021b; Simoni et al., 2020) and the different key performance indicators of the system are computed using an L2 metrics. Even if some sensitivity analyses are most of the time performed (Chen et al., 2021a; 2021b; Yu et al., 2020), these aspects remain quite marginal. To the best of our knowledge, only Ulmer and Streng (2019) used the road grid data from the city of Braunschweig (Germany) to perform their simulation.

These operational conditions are key aspects that need to be assessed to evaluate ADR delivery patterns. The distinction between sidewalk ADRs (Figliozzi, 2020; Jennings and Figliozzi, 2019) and road ADRs (Jennings and Figliozzi, 2020) seems to be structuring the work within the research community. Clearly defining ADR allowed pathways, maximum speeds (on each kind of pathway), as well as the maximum size of the robots, will be fundamental elements of future regulation to avoid conflicts with other stakeholders (de Groot, 2019; Hoffmann and Prause, 2018). This set of rules that may be defined by an ISO standard in future years (Harmonize Mobility, 2021) will greatly affect the operations of ADRs because it conditions the accessibility of a given neighborhood and the delivery level of service. A previous work by Bashkanov et al. (2019) already aimed at comparing different speed and movement profiles of ADRs. However, only one type of robot and one scenario were examined and only the average speed was adjusted. Interesting in this context was the question of crossing situations, which was also investigated. In one of the cases, exceeding the speed limit was only allowed if there were traffic lights or a zebra crossing.

2.3. Accessibility analysis

Analyzing the structure of cities can be done in different ways. One approach is to analyze the underlying network (Crucitti et al., 2006). In this case, ADRs with different restrictions would generate different networks for the same city. City networks are a specific class of complex networks that are embedded in real space (Albert and Barabási, 2002; Boccaletti et al., 2006; Crucitti et al., 2006; Newman, 2003). As a consequence, only nodes that are spatially close may be connected and the number of edges connected to a single node is limited. Methods to analyze the structure of such graphs have been proposed by Buhl et al. (2004).

A metric that is commonly used to analyze these networks is the average shortest path length (APL) (Albert and Barabási, 2002; Boccaletti et al., 2006) which describes the average shortest path possible considering all pairs of nodes present in the graph.

Another commonly used metric is the centrality measure (Bavelas, 1948; Boccaletti et al., 2006; Crucitti et al., 2006). Crucitti et al. (2006) showed that different centrality measurements - closeness, betweenness, straightness and information - can be used to derive insight into the structure of a given city.

A third commonly used metric is the reachable population considering a given time window (van Eck and de Jong, 1999; Ford et al., 2015; Liu and Zhu, 2004), also known as the accessibility index. Depending on the starting point, different parts of a city can be accessible and thus the value of the reachable population changes based on density and accessibility.

These concepts are established and used for various vehicles. A accessibility analysis specifically for robots was not found.

3. Methodology

ADR applications are directly related to operational conditions, logistical tasks and robot configurations. Hence, the quantitative assessment of autonomous delivery robotic scenarios requires:

1. A classification scheme of different robotic systems for logistic purposes
2. An aggregation strategy for a graph-based analysis of the operational area
3. Metrics for the evaluation of the results

This section discusses these prerequisites in abstract terms and definitions. These concepts are then applied to a practical example with specific parameter sets in the next section. The goal here is not to evaluate a particular type of robot class or a particular distribution system. The point is to provide a measure of how prepared a city is for ADR in general. If possible, objective criteria should be found to quantify an area's readiness for ADR.

3.1. Network-oriented scenario definition

A prerequisite for the successful use of autonomous robots is a sufficient level of acceptance by other stakeholders that will be determined by a variety of parameters depending on the context. For instance, only small systems traveling at low speeds will be tolerated by other users on sidewalks or bike lanes. Conversely, for larger robots, a minimum speed will be necessary to operate together with other vehicles on roadways. The existing literature on human-machine interaction focuses strongly on autonomous vehicles (Rasouli and Tsotsos, 2020) but these results (aggressive or friendly design of passenger cars, see Dey et al. 2017) cannot be transferred to smaller robots in proximity to passers-by. To fill this gap, we designed an abstract classification scheme for road types and robot configurations for defining trafficability and average speed.

Infrastructure categories

For the description of differently configured urban operation areas, the following street classification, based on the work done by Eppell et al. (2001), is adopted:

Collector roadways. They give connection to residential streets with traffic carrying roads (Eppell et al., 2001) and are the support for public transport. They are affected by local cycle movements. The maximum allowed speed is usually set to 50 km/h.

Local roadways. This network refers to residential neighborhoods and low-capacity streets. It provides direct access to the property (Eppell et al., 2001). The maximum allowed speed on this secondary road network is mostly 20 or 30 km/h.

Table 2
Infrastructure category definition.

OSM Tag	highway	others
Collector streets	`primary`, `secondary`	
Local streets	`tertiary`, `service`, `living_street`, `residential`, `unclassified`	
Bike lanes	`cycleway`, `path`, `service`, `track`	`cycleway = *`, `bicylce = *`, `:(left & right & both) = *`, `cyclestreet = yes`
Sidewalks, pedestrian areas	`Pedestrian areas`, `pedestrian`, `footway`, `path`, `living_street`	`sidewalk = *`, `foot = * :(left & right & both) = *`, `footway = sidewalk`, `crossing`, `path = sidewalk`, `sidepath`

Table 3
Operative scenario definition.

Scenario	Collector	Local	Bike lanes	Pedestrian tracks
O1	40 km/h	20 km/h	15 km/h	5 km/h
L1	40 km/h	20 km/h	NO	NO
M1	NO	20 km/h	15 km/h	5 km/h
M2	NO	NO	15 km/h	5 km/h
S1	NO	NO	NO	5 km/h

Bicycle lanes. Usually, bicycle lanes are physically separated from the street and provide protection to the user. The usage by pedestrians depends on specific local restrictions.

Sidewalks and pedestrian areas. They are primarily used by pedestrians but could support small vehicles.

Highways are excluded from our study.

Scenario definition We cluster the ADRs described in Section 2 into 4 groups, each of them representing a certain size and speed category. The combination of a given robot design and operational area generates an operational scenario. For each specific operational scenario, the allowed speed level has to be assigned to each street type (see Table 3 in Section 4).

Scenario L1 - Large ADRs. These ADRs are equivalent to small passenger cars (in terms of volume capacity) and use collector and local roadways only. Examples of those robots are the *NuroR2* and the *Robomart* (Nuro, 2021; Robomart, 2021).

Scenario M1 - Medium ADRs. These robots are smaller than large ADRs but big enough to travel on local roadways without being an obstacle for general traffic. They are small enough to travel on bike lanes as well. An example robot system for this category is the *teleretail* (TeleRetail, 2021).

Scenario M2 - Medium restricted ADRs. Unlike in scenario M1, these medium ADRs are not allowed to travel on local roadways because of local traffic regulations. They are allowed to travel on bike lanes as well as sidewalks at a low speed. The *Roxo* system belongs to this category (FedEx, 2020).

Scenario S1 - Small ADRs. These knee-high robots are only allowed to travel on sidewalks and pedestrian tracks at a low speed. A typical robot for this category is the robots of Starship Technologies (Starship, 2021).

Scenario O1 - Optimal ADRs. This is a hypothetical scenario in which the ADR is allowed to travel on each type of street and track at the maximum speed. This is the reference scenario for our study.

3.2. Graph-based analysis and evaluation metrics

In the following, we consider directed weighted graphs $G = (V, E)$ that are derived from OSM data. Edges from E that are not tagged according to the given operational scenario (`living_street`, `cycleway`, `pedestrian`, etc.) are removed. This process is repeated for every scenario i we defined, resulting in operational graphs $G_i = (V, E_i)$ where $E_i \subset E$. Some metrics will be normalized by the amount of nodes $|V|$ in G to make the results comparable between city-graphs with different sizes.

Several metrics are considered to evaluate the performance of ADRs in the different operational scenarios:

1. The degree count. The amount of nodes with degree $d(v) > 0$.
2. The average number of reachable nodes.
3. The average detour time.
4. The maximum and average coverage of a graph component.
5. The operational graph total component count.
6. The maximum and average reachable population.

Filtered node count Let $\mathcal{D}_i$ be the set of nodes in V_i with degree greater than 0.

$$\mathcal{D}_i = \{v, \forall v \in V_i \mid d(v) > 0\} \tag{1}$$

The filtered node count f_i of graph G_i is then defined as

$$f_i = \frac{|\mathcal{D}_i|}{|V|} \tag{2}$$

Average number of reachable nodes

A node $v \in V_i$ is counted as *reachable* from a node $u \in V_i$ when there is a *path* $p(u, v)$ from u to v. The shortest path is denoted $d_{G,w}(u, v)$ where w are the weights of the edges and $w(p)$ is the sum of the weights of the edges of $p(u, v)$ (Brandes, 2005). w will be dropped from the notation because the edge weights do not change. In the following, the edge weights are the travel time t along that edge. The travel time along a path is thus $t_G(u, v)$. If there is no path from u to v the length and thus the travel time shall be infinite. The set $\mathcal{R}_u$ of reachable nodes in G_i from $u \in V_i$ in the operational graph G_i is defined as

$$\mathcal{R}_u(G_i, h) = \left\{ \forall v \in V_i \;\middle|\; t_{G_i}(u, v) < h \right\} \tag{3}$$

where h is the maximum travel time allowed. When $h = \infty$ all connected nodes are reachable. If not stated otherwise $h = \infty$ is applied. The percentage of nodes that can be reached from u is thus

$$\frac{\mathcal{R}_u(G_i)}{|V|} \tag{4}$$

As a consequence, the average percentage number of reachable nodes $\mathcal{R}_{avg}$ for the operational graph G_i is

$$\mathcal{R}_{avg}(G_i, h) = \frac{1}{|V|} \sum_{u \in V} \frac{\mathcal{R}_u(G_i, h)}{|V|} \tag{5}$$

The total number of shortest paths $|p_i|$ in G_i is:

$$|p_i| = \sum_{u \in V_i} |\mathcal{R}_u(G_i)| \tag{6}$$

Average detour time The detour time $\Delta T_{G_i}(u,v)$ shall be the time difference between $t_{G_i}(u,v)$ and $t_{G_{opt}}(u,v)$ (see Fig. 5).

$$\Delta T_{G_i}(u,v) = \frac{t_{G_i}(u,v)}{t_{G_{opt}}(u,v)} \tag{7}$$

Considering every possible combination of nodes, the average detour time $\Delta T(G_i)$ in an operational graph G_i can be calculated as:

$$\Delta T(G_i) = \frac{1}{|V|^2} \sum_{u\in V} \sum_{v\in V} \Delta T_{G_i}(u,v) \tag{8}$$

Logically, if there is no path $p(u,v)$ from node u to node v considering the set of edges E_i, it is impossible to have a detour time $\Delta T_{G_i}(u,v)$. As a consequence $t_{G_{opt}}(u,v)=\infty$ and thus $t_{G_i}(u,v)=\infty$ shall not be considered in the calculation of the average detour time in graph G_i. The cases where $u=v$ can also be ignored because the shortest path is 0 either way. Because of these restriction Eq. (8) can be written as

$$\Delta T(G_i) = \frac{1}{|p_i|} \sum_{u\in V} \sum_{v\in \mathcal{R}_u(G_i)} \Delta T_{G_i}(u,v) \tag{9}$$

Component count and maximum component coverage A component is a maximum sub-graph of G such as there is a path for each pair of nodes. A component is weakly-connected if there is at least one path of $p(u,v)$ or $p(v,u)$ (Brandes, 2005). Let C_i be the set of weakly-connected components of G_i. $|C_i|$ is then the total number of (weakly-connected) components in G_i. The normalized component count $c(G_i)$ is defined as follows

$$c(G_i) = \frac{|C_i|}{|V|} \tag{10}$$

The percentage coverage $k(c_j)$ of a component $c_j=(V_j,E_j)\in C_i$ with $V_j\subset V$ and $E_j\subset E$ is

$$k(c_j) = \frac{|V_j|}{|V|} \tag{11}$$

The largest component $c_{\max}$ in the operational graph G_i is:

$$c_{max} = \max_{c_j=(V_j,E_j)\in C_i}(V_j) \tag{12}$$

Reachable population

Let $G=(V,E)$ be a weighted, directed graph as described above. Nodes are weighted with a population count which is determined as described in Section 3.3.

The total reachable population in scenario i $\mathcal{P}_t(G_i)$ is defined as

$$\mathcal{P}_t(G_i) = \sum_{v\in V,\ d(v)>0} w(v) \tag{13}$$

The reachable population $\mathcal{P}_u(G_i,h)$ from node u in time h is defined as

$$\mathcal{P}_u(G_i,h) = \sum_{v\in \mathcal{R}_u(G_i,h)} w(v) \tag{14}$$

The average reachable population in G_i within the time window h is:

$$\mathcal{P}_{avg}(G_i,h) = \frac{1}{|V|} \sum_{u\in V} \mathcal{P}_u(G_i,h) \tag{15}$$

The maximum reachable population $\mathcal{P}_{\max}(G_i,\infty)$ is defined as

$$\mathcal{P}_{max}(G_i,\infty) = \max_{u\in V}(\mathcal{P}_u(G_i,\infty)) \tag{16}$$

It corresponds to the population that can be reached from the ”best” node considering an infinite time window.

3.3. Application and implementation

For the aggregation of the graph-based representation of the operational scenarios, OSM data is analyzed. The entire processing chain for the aggregation of the OSM data set, i.e. filtering, assignment of maximum speed and population information and the evaluation of the success criteria is shown in Fig. 4. The explanations reference the abbreviations `({a-e}{1--4})` assigned to the components in the flow chart for better comprehensibility. 'i' are the Inputs. 'a' are all the intermediate results. 'c' are all steps related to the shortest path calculations and 'd' are all the steps related to the population calculations. Variables such as the width or condition of the road were not considered because data limitations would have overshadowed any results. For more details on this topic, see Section 5.

Network generation

In the first step, a defined area is queried from the OSM database (i1) and an OSM graph (a1) is built using the OSMnx framework (Boeing, 2017)[1]. OSM is an open-source database which works through community consensus, i.e. the variety of tags characterizing the different objects is high (Taginfo, 2021), which can be a problem to make use of this data (Vandecasteele and Devillers, 2015). To tackle this issue, we investigated the distribution of tags for German maps. Obviously, the codification of bike lanes and sidewalks or pedestrian areas is much more heterogeneous and less standardized than roads used by cars. The resulting assignment of tags and requests on track types in collected in Table 2. The ":" marker defines subtags in OSM and applies to the tag listed in a row before it. i.e. "cycleway:both". The '*' marker is representative of all values that are positive for this primary key. The primary key "cycleway" has currently 18 commonly-used values, which all indicate that it is present, for instance cycleway: "yes, both, right,..."

The definition of the allowed pathways in each operational scenario is done in the filtering step (c1) of the general OSM-Map (only queried and downloaded once). This filtering process results in an operational graph (G_i) which is different for each ADR scenario (a2).

Speed level assignment Each edge of the obtained operational graphs is then weighted by the traveling time on this particular edge (c2), which depends on the allowed traveling speed of each robot design (see Table 3).

Average shortest travel time calculation Considering these weighted graphs, the shortest travel times (a4) between all the pairs of nodes are calculated (c3). As stated in Section 3.2 The obtained average shortest travel times are compared (c4) between the different scenarios and used to compute the reachable population (d4) (see Eq. (9) and Fig. 5). For routing the python library `igraph` was used (Csardi and Nepusz, 2006).

Population assignment To assign a number of inhabitants to each node present in an operational graph G_i, population data from the 2011 German Census (i3) (Statistischen mter des Bundes und der Lnder, vertreten durch den Prsidenten des Statistischen Bundesamtes, 0000) is used. In this data set, population is given in a 100 m x 100 m grid with coordinates in the European Grid (EPSG: 3035) system which is converted (d1) into the WGS84 format to be usable in the OSM tool chain.

To increase the granularity of the population data, the 100 m x 100 m grid is divided into a 10 m x 10 m one (d1), assuming a uniform population density within each cell of the original 100 m x 100 m grid (see Fig. 5). As for the 10 m x 10 m cells, we assume that the population resides in the center points M1 to M100 (see Fig. 5).

Even if other approaches exist (Pajares et al., 2021), we assume this subdivision into 10-meter squares is sufficient for a first analysis. For each center point, the nearest node of G_i is determined (d3) by finding the distance r_i of the surrounding nodes to the center point. The population of this grid cell is then considered reachable from this node and the population is assigned to this node for further processing. The maximum distance $r_{\max}$ at which population gets assigned to a node is 85 m, which approximately corresponds to 1 min walking at 5 km/h. The population assignment process is a topic that should be investigated in future works. The population is only assigned to nodes that have a degree $d(v)>0$. This way close nodes that satisfy the filter parameters

[1] Similar results can be achieved with other tools like Osmosis or JOSM

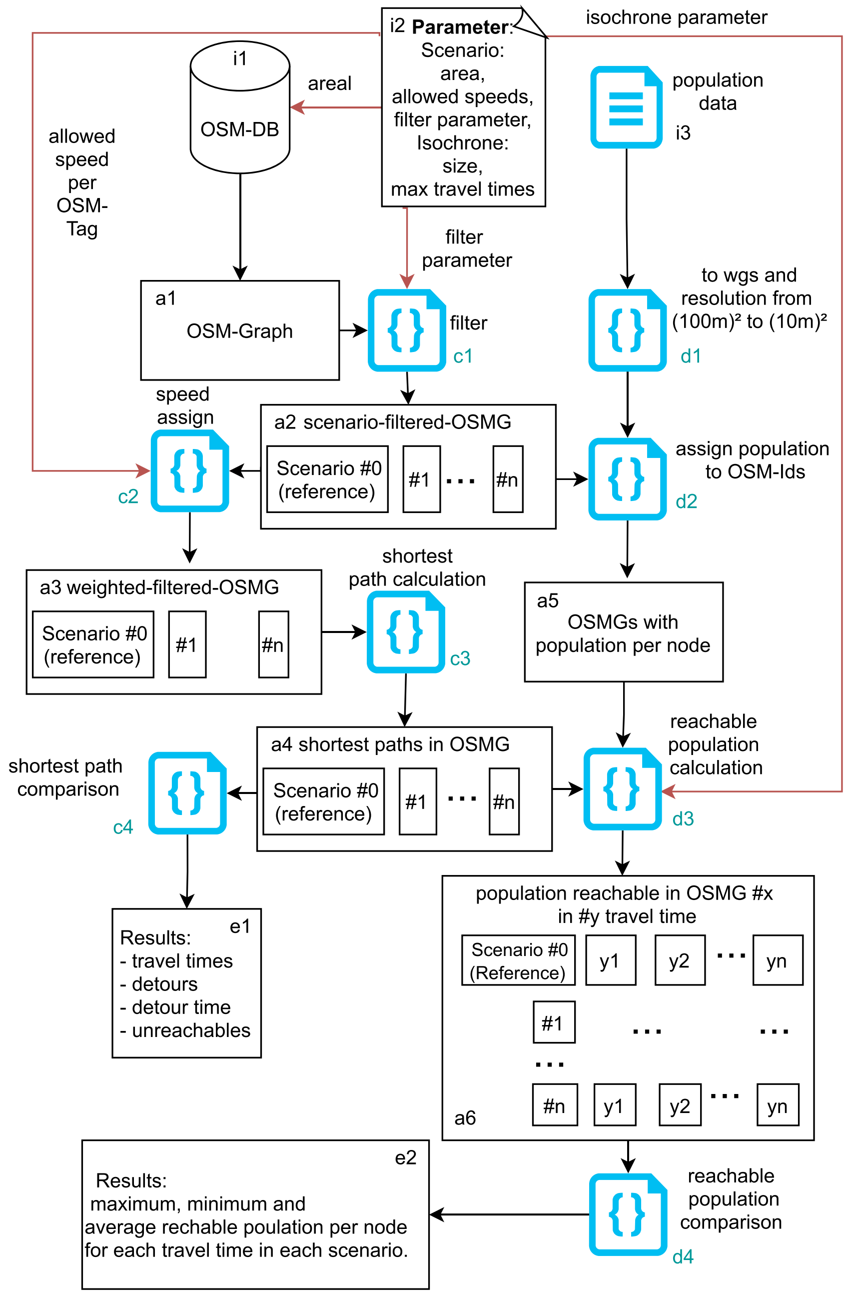


Fig. 4. Workflow chart. The index ‘i’ refers to the inputs, ‘a’ are all the intermediate results, ‘c’ the steps related to the shortest path calculations, and ‘d’ all the steps related to the reachable population calculations.

are preferred to make the comparison fairer and account for the errors stated above.

Reachable population calculation To compute the average reachable population, the shortest travel times between all pairs of nodes previously defined and calculated are used. We consider different time frames (i2) to compute the average reachable population (O’Sullivan et al., 2000; Street, 2006). For the different time frames h the $\mathcal{P}_{avg}(G_i, h)$ from Eq. (15) is calculated (d3). The reachable population per node is different in each scenario and for each time frame (a6). The analysis (d4) of these results leads to the evaluation (e2) of the scenario.

4. Results and interpretation

To evaluate the defined parameters and metrics, we applied the toolchain to real scenarios in cities of different sizes located in Germany (see Table 4).

The list of 16 cities includes major, medium and small cities. The first choice is the city of Freiberg, for which the results were easier to verify by observation. We included in the sample two big cities close to Freiberg, Dresden and Chemnitz, to analyze a similar developed area, in this case the region of Saxony (Germany). The remaining cities were taken from lists of bicycle-friendly cities (Allgemeiner Deutscher Fahrrad-Club (ADFC), 2021; Copenhagenize, 2019; Coya, 2019), since the basic assumption was that favorable infrastructure conditions may exist for scenario S1 (small sidewalk ADRs). Our selection was also made to ensure a variety of city sizes and topology.

A NVIDIA DGX-2 executed the graph based evaluation of the cities. It includes 16 NVIDIA Tesla V100 GPUs and has a GPU Memory of 512GB total. According to the listed calculation efforts in the last column, the investigation of larger cities cannot be realized without a high performance computer.

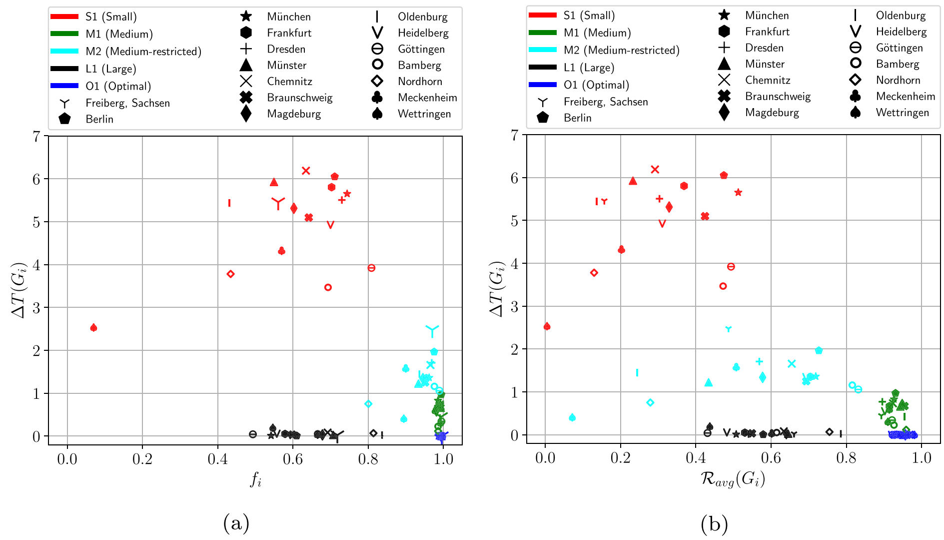


Fig. 5. Distribution of the detour time $\Delta T(G_i)$ over (a) filtered node count f_i and (b) the average percentage of reachable nodes $\mathcal{R}_{avg}(G_i)$.

Table 4
Selected cities for further evaluation. RCT is the relative calculation time taken compared to Freiberg. The RCT gives an overview of the calculation effort and is taken from the computation times observed by our DGX-2. Unfortunately, we do not have exclusive access to the system. Entries marked by an asterisk illustrate the occurrence of other calculations in parallel. For absolute comparison, Freiberg calculations took between 2 and 3 min.

City name	Edges	Nodes	Area (km^2)	Inhabitants	RCT
Berlin	753.648	283.497	890	3.318.592	625*
München	381.977	141.812	311	1.369.045	184*
Frankfurt	165.872	64.487	248	681.917	64
Dresden	199.927	78.015	328	523.631	64*
Münster	116.457	45.955	303	290.124	36
Braunschweig	111.846	41.345	193	243.496	40*
Magdeburg	106.072	40.145	201	228.281	36
Chemnitz	92.011	36.377	221	243.751	32*
Oldenburg	60.284	24.933	103	162.723	32
Heidelberg	52.765	20.128	109	152.935	10
Göttingen	91.470	36.894	117	116.098	12
Bamberg	27.235	10.331	55	72.877	2
Nordhorn	17.668	6.471	150	52.592	1
Freiberg	21.731	8.453	48	40.708	1
Meckenheim	13.897	5.333	35	24.157	0.8
Wettringen	894	359	21	1.041	0.4

4.1. Network-oriented metrics

Fig. 5 shows the filtered node count f_i as well as the average percentage number of reachable nodes $\mathcal{R}_{avg}(G_i)$ over the normalized average detour time $\Delta T(G_i)$ for the considered operation scenarios and cities.

In Freiberg (Y), in scenario S1 (red), 56% of the nodes have at least one connected edge. However, only 16% of nodes are reachable on average and the detour time is 546% of normal time, on average. A large robot (scenario L1, black) in Freiberg is able to use a graph where 72% of nodes have at least one edge and the average reachablility is 66%.

When considering the node count f_i, a scenario hierarchy appears across cities. scenario O1 shows the highest values for every city followed by M1 and M2, except in Nordhorn where scenario L1 has a higher value than M2. scenario L1 shows higher values than scenario S1 in approximately 1/2 of the considered cities. It is remarkable, that O1 never has a node count equal to 1. Even in the optimal definition, we cannot access every node present in the unfiltered graph. This may be due to the presence of islands in the city graph or because unknown OSM tags were used, which truncates nodes in the graph. The best value for O1 was 99.7% and the worst 98.6%. We will discuss these issues later on.

The second parameter, the average detour time $\Delta T(G_i)$, shows a complex pattern across the scenarios too. In Freiberg, $\Delta T(G_i)$ is 545% for S1, 45% for M1, 247% for M2, and 2% for L1 (see Table 6 in Appendix). A hierarchy of operational scenarios across cities can be seen again. L1 shows the lowest detour time, followed by M1, M2 and S1. This is true for every examined city. O1 obviously has no detour because it corresponds to our reference graph.

The combination of the two metrics shows corresponding clusters per scenario. This indicates that the operation scenarios have similar characteristics in different cities. Nevertheless, there are some disparities within each cluster, Hence it is not possible to make a general statement about the superiority of one of the scenarios. The effectiveness in terms of accessibility and detours must be evaluated individually.

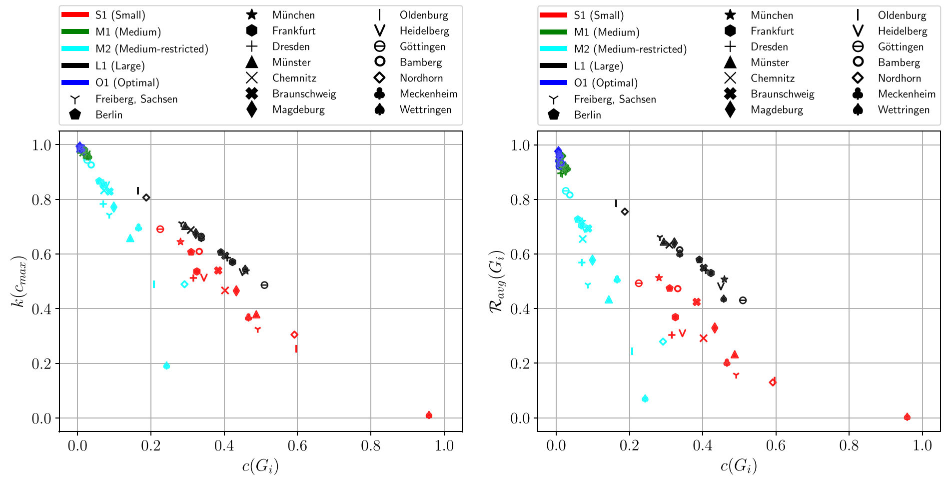
The comparison of the detour time $\Delta T(G_i)$ over the average percentage number of reachable nodes $\mathcal{R}_{avg}(G_i)$ is shown in Fig. 5b. It presents a similar clustering as the results in Fig. 5a. However, considering scenario M2, it can be seen that having a good amount of nodes with connected edges does not mean the graph is well connected. Removing the streets from the operational graph in M2 has major influence on the average reachable nodes for every city. On the other hand, allowing operations exclusively on collector streets as in scenario L1 is also sub-optimal. In L1, $\mathcal{R}_{avg}(G_i)$ is between 43 and 78% and for M2 between 7 and 83%. For S1, the values are between 0.4 and 51%. Because S1 is a subset of M1 it will always be the worse choice. The comparison between L1, S1 and M1 depends on the considered city. Close to optimal is M1 for every city, meaning that using a mix of sidewalks, bicycle lanes and local roadways is the best option.

The detour duration reflects the speed levels of the scenario and the increased path lengths that result from the allowed routes. Based on the speeds of the scenarios, however, conclusions can also be drawn about the distances traveled. An operational graph G_i may contain the same edges as the optimal graph G_{opt} but with a different allowed speed. This is because an edge in OSM can have multiple tags at once. If that edge could be driven on with the maximum speed for each scenario there would be a travel time difference. Thus even if a path uses the same edges, it does not necessarily have the same length.

The maximum speed ratios in each operational scenario are

$$\frac{v_{O1}}{v_{L1}} = \frac{40}{40} = 1; \quad \frac{v_{O1}}{v_{M1}} = \frac{40}{20} = 2; \quad \frac{v_{O1}}{v_{M2}} = \frac{40}{15} \approx 2.7; \quad \frac{v_{O1}}{v_{S1}} = \frac{40}{5} = 8 \qquad (17)$$

If a path exists in G_{opt} from node $u \in V$ to $v \in V$ for which each robot could travel at its maximum allowed speed, the detour time would only be due to the difference in travel speeds. Nevertheless, the detour time $\Delta T(G_i)$ is usually lower than the maximum speed ratios presented in



(a) (b)

Fig. 6. Distribution of (a) biggest component coverage $k(c_{\max})$ and (b) average percentage number of reachable nodes $\mathcal{R}_{avg}(G_i)$ over normalized component count $c(G_i)$.

Eq. (17) (see Fig. 5a). This indicates that, even in the optimal scenario, the robot is not traveling at its top speed.

This concept can be extended to the differences between the other scenarios. As a matter of illustration, $v_{L1}/v_{M2} \approx 2.7$. However, the mean detour time between scenarios L1 and M2 is lower than this value. Hence, routes in scenario M2 (sidewalks and bicycle lanes) must be shorter than in scenario L1, but the robot drives more slowly.

To conclude with Fig. 5, a compromise has to be made. Either a small proportion of the city is quickly accessible or more parts of the city are accessible, but at a lower speed. For instance, the detour induced in the scenario that is only able to use major roads (L1) is very low, however between 20% and 50% of the city are not accessible at all. The scenario that is able to use smaller streets as well as bike lanes and pedestrian ways (M1) seems to offer the best compromise. It is true that the detour is higher than in the first case (L1) but almost all the city can be accessed. The restriction to only pedestrian tracks (S1) presents the lowest performance overall.

Biggest component It was also investigated if the average percentage number of reachable nodes R_{avg} can be determined by either the component count $c(G_i)$ or the coverage of the biggest component $k(c_{\max})$ (see Fig. 6a and 6b). We observed more connectivity at the center of a city graph (Fig. 9). Looking at the largest component is thus similar to excluding border areas of the city. If there were a correlation between largest component and average percentage of reachable nodes the calculation time could be minimized.

At first glance, Fig. 6a and 6b look very similar and so do Figs. 7a and 5b. Nevertheless, this similarity does not withstand close inspection. The biggest component coverage cannot accurately predict the average reachability in the operational graph but may be sufficient as a first estimation.

Fig. 7b presents the relation between the biggest component coverage $k(c_{\max})$ and the average percentage number of reachable nodes $\mathcal{R}_{avg}(G_i)$. $k(c_{\max})$ usually over predicts $\mathcal{R}_{avg}(G_i)$ yet the exact amount is unclear and different per city.

The relation between the component count $c(G_i)$ and the average percentage number of reachable nodes $\mathcal{R}_{avg}(G_i)$ (see Fig. 6b) seems to have a relation per scenario which can be explained by the relation of $k(C_{\max})$ and $c(G_i)$.

4.2. Population reachability

As stated in Section 3.2 we also looked at the average reachable population $\mathcal{P}_{avg}(G_i, h)$ as a function of the time window h.

For the population reachability we identified four different measurements that can be of interest (see Section 3.2). The results are shown in Fig. 8a and 8b.

For Freiberg, there is a clear hierarchy of scenarios when considering the metrics of the average reachable population $\mathcal{P}_{avg}(G_i, h)$. O1 is the best over all time frames, closely followed by M1 then L1 and M2 with S1 being the worst.

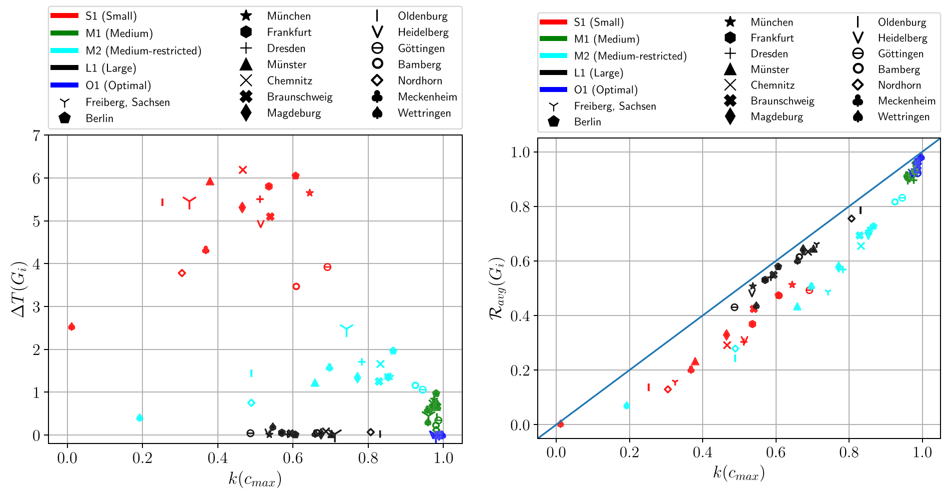
The results can look different even for a city of the same size. For instance in Bamberg, different results are obtained (see Fig. 8b). For $\mathcal{P}_{avg}(G_i, h)$ O1 is best over all, but M1 is very close. L1 is better for smaller time frames but as the time window increases, more population can be reached in M2 than in L1. S1 still presents the lowest values of average reachable population. This means that in the case of Bamberg the M2 scenario is to be preferred for a maximum travel time around 1260s or 21 min.

The results concerning the maximum average reachable population are in line with the findings about the average percentage number of reachable nodes $\mathcal{R}_{avg}(G_i)$ This confirms that considering one starting point a trade-off must be made between either reaching a small proportion of the city quickly or more parts of the city but at a lower speed. Another option would be to build more hubs to have an overall good accessibility. Nevertheless it can also be seen that operating only on sidewalks (scenario S1) is highly sub-optimal.

Fig. 9 depicts the networks that can be used by the scenarios in the city of Freiberg as well as the reachable population within 20 min for each node of the operational graphs. In Freiberg, L1 would be able to reach around 20.000 inhabitants within 20 min, on average (see Fig. 8a). M1 would be able to reach around 10.000 inhabitants within 20 min. This figure decreases to 2.000 approximately for S1 (see Fig. 8a).

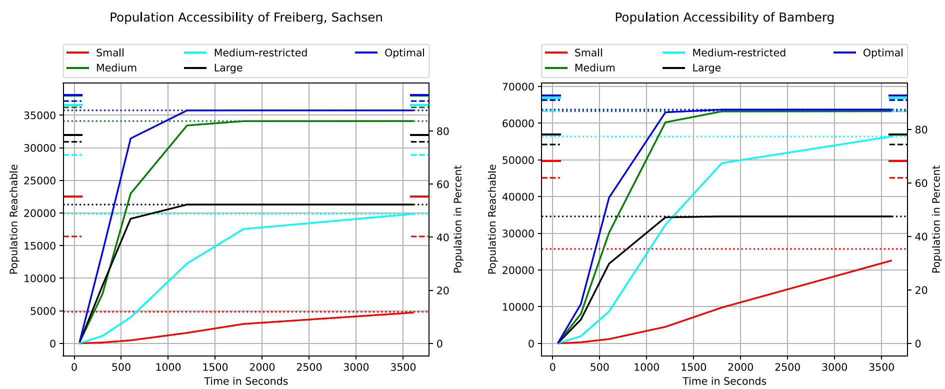
In O1 almost all nodes are reachable within 20 min. The accessibility in S1 is concentrated on the city center, while the outer districts are poorly accessible or not accessible at all. In M1 the outer regions of the graph are accessible, but parts of the city are cut off. L1 shows a good coverage over all, but some areas outside the city center are not accessible.

To sum up, the defined scenarios show different characteristics for all examined values. The categorization of which is the best excluding O1, cannot be generalized but depends on the considered metrics. It is also not possible to generalize over all scenarios because they perform differently in different cities. The underlying network is of integral importance. A good balance of local roadways, sidewalks and bicycle lanes in M1 performs the best as it would have been expected. Neither “just roadways” in L1 nor “just sidewalks and bicycle lanes” in M2 are ideal. L1 is to be preferred if a small portion of the graph should be reached



(a) (b)

Fig. 7. Distribution of (a) the detour time $\Delta T(G_i)$ and (b) the average percentage number of reachable nodes $\mathcal{R}_{avg}(G_i)$ over the biggest component coverage $k(c_{\max})$.



(a) (b)

Fig. 8. Average reachable population $\mathcal{P}_{avg}(G_i, h)$ as a function of the time window h in (a) Freiberg and (b) Bamberg. The maximum reachable population $max(\mathcal{P}_u(G_i, \infty))$ (from the "best node") is displayed as the short dashed line at the y axis. The total population present in the graph $\mathcal{P}_i(G_i)$ is displayed as the solid line at the y axis.

quickly. M2 is to be preferred if a larger portion of the graph should be reached and the associated time window is not as restrictive. As a consequence, it was not possible to get a single value as a "ready for robots" rating, instead $\mathcal{R}_{avg}(G_i)$ and $\Delta T(G_i)$ can be examined to make an informed case-by-case decision.

5. Discussion and further research

The following subsections address the elements of the research methodology that need improvement, as well as the future development potential of the study.

5.1. Scenario specification

We identified some weaknesses in the operational scenarios specifications:

1. *Street usage rules* - The current implementation of the analysis tools is based on a simple mapping of speed specifications to given path types. However, it is assumed that the legislator will describe additional regulations for small robot applications in public space. These include, for example, the question of the conditions under which a small robot may cross a road - this can be limited to crossings with traffic lights or zebra crossings, for example. Therefore, the potentially complex regulations must be integrated into the tool-chain by a configurable machine-readable rule set.
2. *Robot types* - The specification of robot use is based on a classification of existing autonomous systems. We assume that in connection with general rules for robots, there are also specifications for their technical configuration. As soon as specifications on the maximum size, interaction possibilities with passers-by, operating times, etc., impact the use of roads and paths, the possible area of operation must be re-evaluated.

5.2. OSM Database and graph representation

OSM data is based on the collection activities of volunteers who are not trained to systematically collect geographical data. In addition, the number of contributors varies locally, leading to different levels of detail in the representation and different sets of errors (Bashkanov et al., 2019; Mondzech and Sester, 2011), which may affect:

1. *OSM network connectivity* - For the assessment of an area, a graph-based environment model, is required. This network may have gaps, especially when filtering by different road types. This means that the transition from one OSM element to another, which is possible in the real world, is not implemented in the graph. In Fig. 10, the accessible roads for the S1 scenario are marked in red. Due to small discontinuities in the data, parts of the graph get cut off. The upper left gap is due to the tag stating specifically that there is no sidewalk on this part of the Philosophenweg (OSM ID 524044727). The gap in the bottom right corner at the Albert-Ueberle-Straße (OSM ID 362593646) is due to a street without a proper tag, disconnecting

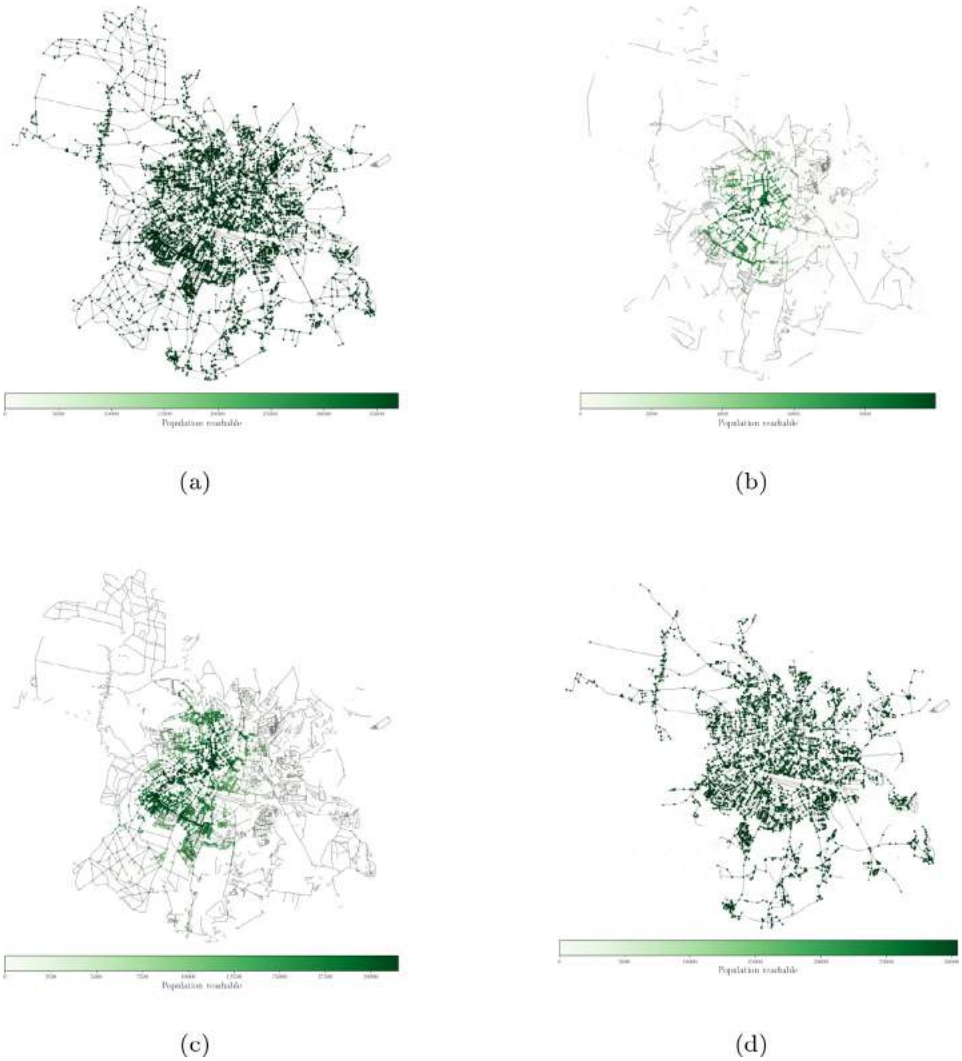


Fig. 9. Freiberg accessible edges and reachable population within 20 min in the (a) optimal, (b) small, (c) medium-restricted, and (d) large scenarios.

Fig. 10. Heidelberg map.

two valid ways. In some cases, concepts and methods are available to identify obvious gaps (Basiri et al., 2016).

2. *OSM attributes* - While the first error category addresses the missing linking of the OSM elements, the second addresses the missing or incorrect entries of the associated attributes. Different constellations are possible:
   (a) missing or wrong attributes describing the type of a track or
   (b) missing or wrong attributes specifying properties of a track.

   In the first case, a faulty graph is created, roads with faulty or misleading assignments are not taken into account, or supposed edges are integrated that cannot be used for a scenario at all. The mere existence of a track is not sufficient for scenario planning. A detailed analysis would have to consider many more restrictions, i.e. excluding stairs, ramps, certain types of surface, streets with a limited width, and so on. Unfortunately, these data are only available to a limited extent (see Table 5). A potential solution to this challenge is the automated collection of attributes. Various solutions have been presented for this, such as analyzing aerial photographs Kaiser et al. (2017) or bicycle data[2].
3. *OSM objects* - The current study ignores obstacles such as polders, rubbish bins, or other structural barriers. One reason for this is the

[2] https://www.bmvi.de/SharedDocs/DE/Artikel/DG/mfund-projekte/akhoch2.html

lack of completeness in the recording in OSM. However, possible solutions are offered by research initiatives that aim to automatically record and classify these objects and embed them in OSM.

5.3. Graph representation and analysis

Finally, two aspects in the graph-based representation of the operational scenarios must be further investigated:

1. *Constant velocity levels* - The current implementation of the analysis tool uses the assumption of a constant speed. However, this is unrealistic for real-life robot scenarios, in crowded places for instance. Accordingly, more complex models are necessary to predict the travel time, which covers time-varying influencing variables. In this context the topic of intersections and available crossing options should be studied as well.
2. *Inhabitants aggregation and assignment* - The population assignment could also be improved. Currently, each part of the population (10m x 10m square, see Section 3) can only be reached by one node. In reality, however, a house can possibly be reached from several points.

5.4. Summary of research questions

Finally, to close this discussion, we would like to give an answer to the research questions previously defined in the paper. For a more comprehensive answer, please refer to the appropriate chapters.

1. Which classes of ADRs can be derived from the systems described in the literature, and which of their properties have to be considered in the planning process?

Based on a review of the literature, it appears that ADRs are typically categorized based on a specific attributes such as size or speed. We have proposed a different classification of ADRs which is not based on the specifics of each vehicle but on a set of (circulation) rules (see Section 3.1). A robot may be able to satisfy the constraints of multiple scenarios simultaneously. The identification of the most relevant properties for the planning process is not easy. If a constraint prohibits the passing of an ADR, it should be considered. However, critical data is not always available. The most important data that should be included depends on each particular use case (see Fig. 2).

2. How to aggregate, represent and evaluate relevant information to evaluate the applicability of an ADR class for a city?

We have shown that OSM can be used to aggregate, represent, and evaluate relevant information to assess the applicability of an ADR class for a city. Nevertheless, there are some limitations. In particular, data availability has proven to be a problem (see Section 5.2). There is no reason to believe that other services providing the same data could not be used. However, this is only true for planning such operations; the data is not sufficient for performing the actual trips.

3. Which metrics are suitable for representing an abstract ADR-preparedness of a city?

Each of the metrics looked at in this paper provided insight into the state and preparedness of a city for ADR operations. It was not possible to provide a single metric. A combination of $\Delta T(G_i)$, $\mathcal{R}_{avg}(G_i)$ and $\mathcal{P}_{avg}(G_i, h)$ present opportunities for decision-making.

4. Would it be possible to use OSM data to plan a large-scale deployment of ADRs in German cities considering one-to-many delivery patterns?

That depends on how much uncertainty can be tolerated. In principle, it is possible. But if a scenario or robot requires a minimum width, for example, OSM is currently not a suitable source. However, it would be possible to add the required data to OSM to improve its representativeness.

5. Is an operational scenario more suitable to improve given logistics operators' KPIs?

It appears so, but which one it is depends on the city and the criteria (e.g. maximum population reachable or short travel times) that the logistics entrepreneur places more emphasis on.

6. Conclusion

The paper describes a prototypical implementation of data aggregation and evaluation for assessing the operational domain of mobile robotic systems. For this purpose, we defined several operational scenarios, and designed evaluation metrics to validate their performance in one-to-many delivery patterns considering the particular examples of different German cities.

In the case of large autonomous delivery devices (ADRs) traveling on collector and local roadways, almost no detour time (when compared to the reference optimal operational scenario) would be observed. Nevertheless, the operational graph of large ADRs has, on average 35% less nodes than in the optimal case, which seems to indicate that some parts of the cities would remain inaccessible to these large ADRs.

For medium ADRs, we considered two distinct operational scenarios. In the first one, the robots are allowed to travel on local roadways, bike lanes and sidewalks whereas they are allowed to travel only on bike lanes and sidewalks in the second one ("medium restricted"). In both cases the operational graph node count reduction is inferior to 10%, meaning that most of the city can be covered by the robot. The situation is quite different concerning the detour time. If ADRs are allowed to travel on local roadways, the average detour time is comprised between 20 and 100%, which is reasonable. On the contrary, if ADRs are not allowed to travel on local roadways, the average detour time is superior to 100%. Being able to access the local network of a city seems to be a key element to increase the efficiency of ADR operations.

Moreover, in the case of using small sidewalk ADRs, operations seem to be much less efficient. On the first hand, considering the current available OSM data, the operational graph would be highly fragmented (many subgraphs) and the operational area very limited (the operational graph node count reduction is high). In addition, the detour time is in most cities superior to 500% when compared to the optimal situation. However, it is worth noting that passing from the "small ADR" operational scenario to the "medium restricted" one generates a 400% reduction in the average detour time. Allowing small ADRs to travel on bike lanes would be very beneficial to increase their efficiency.

Finally, it seems quite complicated to assess a large-scale development of ADRs given the current OSM data availability and quality. For instance, the average number of unreachable nodes in the small ADR seems too high, especially in European cities that are reputed to have a quite good walking accessibility.

The result shows a heterogeneous outcome for the individual robot classes in different cities. While in some cities, small and medium robots can access most inhabitants with little detour, other cities showed large gaps in coverage. For the final evaluation of a city or a neighborhood, a differentiated investigation is necessary that combines the road/path network with a robot rule set. This data-intensive process cannot be shortened by using alternative parameters (node/edge count, component count, largest component size, density of people in the neighborhood) as indicators for the determination of robot readiness.

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Appendix

Table 5
Completeness of OSM attributes for different pedestrian tracks.

		intercity	local	sidewalk	bicycle
Freiberg	surface	99.52	58.68	66.39	51.61
	width	0.00	3.55	2.09	2.21
	smoothness	10.04	8.06	6.97	4.27
München	surface	97.53	55.22	63.62	56.31
	width	2.20	1.45	5.28	5.14
	smoothness	23.75	13.73	16.23	21.68
Berlin	surface	97.63	50.06	57.87	41.47
	width	0.82	2.63	6.41	7.50
	smoothness	13.22	10.07	10.01	10.80
Amsterdam	surface	56.62	24.31	30.19	41.42
	width	3.75	8.34	14.62	28.61
	smoothness	13.09	11.88	10.83	31.98
New York	surface	31.43	11.17	17.37	13.55
	width	0.14	0.01	0.35	0.45
	smoothness	0.41	0.10	0.16	0.15

Table 6
Node count f_i average reachable Nodes $\mathcal{R}_{avg}$ here short $\mathcal{R}$ and average detour times $\Delta T(G_i)$ here short ΔT. $\Delta T(G_i)$ is zero for O.

	S1			L1			M2			M1			O	
	f_i	$\mathcal{R}$	ΔT	f_i	$\mathcal{R}$	ΔT	f_i	$\mathcal{R}$	ΔT	f_i	$\mathcal{R}$	ΔT	f_i	$\mathcal{R}$
Freiberg	56	16	5.5	99	89	0.4	97	49	2.5	72	66	0.0	100	93
Berlin	71	47	6.0	99	93	1.0	98	73	2.0	61	58	0.0	99	94
München	74	51	5.7	99	93	0.8	96	72	1.4	54	51	0.0	99	93
Frankfurt	70	37	5.8	99	91	0.7	95	70	1.4	58	53	0.1	99	93
Dresden	73	30	5.5	99	90	0.8	97	57	1.7	59	54	0.0	99	92
Münster	55	23	5.9	99	94	0.7	93	43	1.2	71	65	0.0	99	95
Chemnitz	63	29	6.2	99	92	0.7	97	65	1.7	69	63	0.1	99	95
Braunschw.	64	42	5.1	99	95	0.7	95	69	1.3	60	55	0.0	99	96
Magdeburg	60	33	5.3	99	95	0.7	95	58	1.3	68	64	0.0	99	96
Oldenburg	43	14	5.4	99	95	0.4	94	24	1.4	84	79	0.0	99	97
Heidelberg	70	31	4.9	98	90	0.6	95	69	1.3	56	48	0.1	99	92
Göttingen	81	49	3.9	99	92	0.3	99	83	1.1	49	43	0.0	99	92
Bamberg	69	47	3.5	98	93	0.2	97	81	1.1	66	61	0.0	99	93
Nordhorn	43	13	3.8	99	96	0.1	80	28	0.8	81	75	0.1	100	98
Meckenheim	57	20	4.3	98	91	0.6	90	51	1.6	67	60	0.0	99	96
Wettringen	7	0	2.5	99	91	0.3	89	7	0.4	55	44	0.2	100	98

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Re-shaping urban mobility – Key to Europe´s green transition

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A R T I C L E I N F O

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A B S T R A C T

This paper outlines the vision of EIT Urban Mobility towards sustainable urban mobility. EIT Urban Mobility is an initiative of the European Institute for Innovation and Technology (EIT), a body of the European Union. EIT Urban Mobility's ecosystem counts more than 260 organisations from cities, research & academia, and industry working to enable people and goods to move affordable, fast, comfortably, safely, and cleanly.

In the context of climate emergency and extreme weather events that an increasing number of European cities are already facing, it is of utmost importance to develop, and scale decarbonised urban mobility solutions. Such solutions must address acute challenges faced by cities and their inhabitants, linking urban and mobility planning, while actively engaging with citizens at all stages of transformation processes, from design to implementation.

Our vision aims to facilitate this process by channelling public and private efforts towards priority areas of transformation, which are technological and behavioural pathways leading to more sustainable urban mobility spanning from street experiments to connected and shared on-demand mobility. The paper also identifies structural enablers of change, which are key technological and regulatory innovations required to turn our vision into an everyday reality.

1. Introduction

Transforming urban mobility is a fundamental precondition for the European Union to deliver on its Green Deal objectives, and to respond to city challenges with sustainable and inclusive solutions.

1.1. Urban mobility at the heart of the green transition

The EU's decarbonisation objectives cannot be realised without a sustainable urban mobility transition. The carbon neutrality objectives by mid-century laid out in the European Green Deal (European Commission 2019) and the strengthening of the EU's climate ambition to achieve a 55% reduction in greenhouse gas (GHG) emissions by 2030 compared with 1990 levels requires societal adaptation. These goals are especially significant for cities, which currently account for around 70% of these emissions worldwide, while generating about 80% of all economic growth (European Commission 2021). The European Green Deal expresses the vision to make transportation fit for a climate-neutral society by 2050, including a 90% reduction in transport-related GHG emissions by 2050 compared with 1990 levels. To deliver on this ambition, urban mobility must quickly decarbonise, while larger transport CO2 emitters, such as aviation and the maritime sector, also do their parts. It is therefore crucial that any future urban mobility solutions contribute to more sustainable, more silent, and less polluted cities. These challenges are acute since urban mobility accounts for 40% of all CO_2 emissions from road transport and up to 70% of other pollutants from transport (European Commission 2021).

1.2. Shaping the future we want starts today

At EIT Urban Mobility (EIT Urban Mobility 2021), our vision of future mobility systems revolves around cities' and citizens' needs and aspirations. EIT Urban Mobility ecosystem counts more than 260 organisations gathered around the core concept of accelerating urban mobility innovation by integrating the knowledge triangle (research centres – universities – companies) and cities. We work to enable people and goods to move affordable, fast, comfortably, safely, and cleanly. At the same time, cities need to reclaim public space from cars, creating more space for people to work, meet, be active and play.

Multimodality is the driving force at the heart of the urban mobility transition. Providing multiple travel options across all modes, encouraging the uptake of walking and cycling as healthier mobility habits, drives resilience of transport systems, supports a competitive economy and a balanced regional development. Future urban mobility systems will move from fossil fuels dependence to renewable energy, limiting pollutant emissions and energy waste to a minimum while minimizing the impact on land use and noise generation and. A robust public transport network will remain the backbone of cities' transport systems that will provide basic access to services and places, catering for people's and

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businesses' needs, and respecting citizen rights to clean air, safe and inclusive mobility, while promoting equity within and across generations.

To shape an urban mobility future that will improve quality of life in cities, mitigate climate change, and create jobs to strengthen the European mobility sector requires a new form of cooperation between private and public organisations, across regional boundaries and involving citizens locally.

If we want to accelerate the transition to sustainable mobility and liveable urban space, municipalities and regions, industry, start-ups, universities, and citizens need to jointly co-create new solutions from idea to market scale. Several enablers and key areas of transformation are key to deliver our vision.

1.3. Purpose of the paper

In this vision statement, we make the case for a citizen-centred approach to mobility in cities, aligned with the EU's sustainability goals and EIT Urban Mobility's core objective to create more liveable spaces.

Laying out our vision for the future of mobility in cities, we want to inspire change locally and accelerate urban mobility transformations across Europe. We draw on best practices and learnings from the EIT Urban Mobility community to identify key areas of improvement in urban mobility and derive recommendations from experience and insights gathered by our ecosystem.

The current paper focuses on how EIT Urban Mobility's vision for the future can be realized and implemented by practitioners, researchers, and decision-makers. It lays out pathways for more sustainable mobility that can inspire small, medium, and large cities alike. The paper distinguishes between:

- Priority areas of transformation, where behaviour and technological innovations can have the greatest impact on citizens' mobility and quality of life
- Structural enablers of change, mainly pertaining to regulatory and innovation ecosystems.

2. Delivering our vision

To deliver a sustainable urban mobility future, practitioners from the private and public sectors must focus their joint efforts on key areas of transformation and structural enablers.

2.1. Priority transformation areas

2.1.1. Repurposed urban spaces

Future urban spaces will no longer be dominated by roads and streets designed primarily for traditional types of vehicles. Today still, in many cities, more than 50% of public urban space is taken up by roads and parking (Le Monde, 2021) at the expense of space available for citizens for other uses such as work, trade, play, leisure, or social interaction.

It is crucial to start repurposing streets now to better accommodate new mobility solutions and community activities, active mobility modes, recharging facilities, green spaces, and commercial activities. Some cities are already starting to implement initiatives that are repurposing public spaces and streets: cities such as Milan ("Piazze Aperte" and "Strade Aperte", open squares and open street), London ("Healthy Streets") are adopting bold street design principles to integrate health consideration into public realm design and turn streets into places for people's everyday activities, with more green areas and space for active mobility. In parallel, the multiplication of green spaces induced by urban redesign has the potential to create more liveable neighbourhoods, encouraging interactions between people in calmer, quieter environments. In that vein, Barcelona announced its intention to expand the Superblock concept to create 21 pedestrian plazas at intersections in the Eixample district, with work starting in 2022 (City of Barcelona, 2021). Repurposing places also requires a new relationship between the built environment and green spaces. As illustrated by the ambition of Paris to "green" the Champs Elysées avenue with a mix of trees and traffic calming measures, future cities will seek to integrate natural elements in the urban environment (Bloomberg City Lab, 2021). Such strategies contribute to decreasing mobility's carbon footprint in cities and the overarching objective of reducing GHG emissions.

Improving the quality of places thanks to more liveable neighbourhoods has a direct positive impact on people's physical and mental wellbeing (Barcelona Institute for Global Health, 2018). Likewise, promoting active mobility supports the prevention of physical and mental health problems. Its uptake also means less air and noise pollution caused by motorised traffic. This is of particular importance in Europe, where the European Environment Agency estimates that poor air quality causes 400 000 premature deaths per year, mostly because of heart disease and strokes (European Environment Agency, 2020). Innovation in the field of emissions monitoring helps tackle this challenge: the CAROLINA project, supported by EIT Urban Mobility in 2020, empowers cities to take more informed decisions to reduce air pollution by deploying a hybrid air quality monitoring system, which includes vehicles from shared fleets, taxis, or public transport equipped with sensors (Urban Mobility, 2021).

Repurposing urban spaces to favour active mobility and social interactions will also directly contribute to the European Commission's "vision zero" objective, that no deaths and serious injuries take place on European roads by 2050 (European Commission, 2021).

Targeted projects and replication of small-scale changes through local initiatives projects help communities to support this vision and enact change towards it, while highlighting the importance of street design and infrastructure to spread more sustainable mobility behaviours. Few success factors have been identified during pilot experiments, mainly the importance to analyse and adapt to the local context, proper means to engage with citizens, and a "trial and error" mindset (CLEAR project, 2021).

Experience has shown that putting emphasis on short, walkable distances and traffic-calmed streets is an effective way to shape an environment where active mobility is easy, attractive, and cheaper than motorised individual mobility. To give inhabitants more creative ownership of their streets, local authorities and cities can deploy planning strategies aimed at reducing speed or limiting through traffic across lively neighbourhoods. This was recently illustrated by the city of Brussels who introduced a speed limit of 30 km/h across the Brussels Capital region, except only major axes (City of Brussels 2021).

The multi-faceted impacts of urban redesign and infrastructure deployment for walking and cycling show that repurposing places can not only drive the shift to sustainable modes of transport, but that it also contributes to reduced congestion and pollution, while stimulating healthier ways of life.

2.1.2. Positive attitudes toward sustainable behaviours

The future of urban mobility will be co-created, building upon bottom-up processes to shape cities and streets in line with citizens' and other stakeholders' ideas and expectations. Ultimately, the uptake of multimodal urban mobility depends on people´s behaviours and willingness to adopt more sustainable and urban-friendly transport modes. Therefore, moving away from the car-orientated status-quo requires close engagement with citizens and stakeholders to rethink cities together. To identify aspirations as well as acute problems faced by communities, cities and public authorities can work with dedicated (digital) citizen engagement platforms allowing a more tailored development of solutions focusing on citizen and stakeholder needs. This is a key step in shifting to a more user-orientated approach, increasing innovation's contribution to societal goals in urban mobility.

In parallel, building public acceptance, developing a relationship of trust amongst users in the public transport system, and attractive alternatives to private car use will facilitate the success of new forms of mobility. In 2020, the MOBY project contributed to this objective in producing an in-depth review of research and statistics used to illustrate how e-micromobility has become an integral part of urban mobility systems. The project provides examples of e-micromobility best practices from European cities, as well as examples of the problems and complaints that e-micromobility has been met with. Focussing on lessons learnt, the MOBY project offers a toolkit for regulations, policies, and best practices that will help release the potential of micromobility as a vital part of sustainable, intermodal urban transport (EIT Urban Mobility, 2021).

Living labs serve as catalysts for co-creation processes and place citizens or any other kind of end-user at the centre of innovation. Involving stakeholders through first-hand trial activities provides the opportunity to receive real-time feedback and adapt new solutions accordingly. Co-creation in user-centred and open-innovation ecosystems opens new avenues for communities and stakeholders to shape their mobility environment. Living labs are levers for change and enablers of the deployment of more sustainable transport systems by helping to address some of the barriers facing cities, for example encouraging political acceptance and support for novel solutions; promoting public acceptance of new technologies; fostering improved relationships between stakeholders; identifying viable business models; and stimulating innovation uptake. The Copenhagen Street Lab (Copenhagen Street Lab 2021), the city's testbed for smart city solutions, and the Amsterdam Marineterrein (Marineterrein Amsterdam 2021), which provides a real-world test area for innovations such as self-driving vehicles, offer strong illustrations of testing and deploying new solutions in urban areas.

The transition to future sustainable urban mobility will also be unlocked with the generation-triggered change in values and mobility choices. While for many millennials having access to a car is still important, fixation on car ownership is declining. This opens new opportunities to accelerate shift towards shared, on-demand, and more sustainable mobility options. A 2018 study for the UK Department of Transport found that "between 1995 and 99 and 2010–14 there was a 36% drop in the number of car driver trips per person made by people aged 17–29" (Chatterjee et al., 2018). This unfolding trend will help enable our vision of future urban mobility, progressively lifting the resistance from traditional car advocate groups. It also means the different actors of the mobility ecosystem need to factor in the expectations of upcoming generations to provide relevant services to a broad enough user base.

Reinforcing positive attitudes towards sustainable urban mobility requires targeted communication with citizens and local businesses through timely and personalised content. Innovators and mobility practitioners need to get the right tone in communicating on specific initiatives. Recently, mobility innovations aimed at managing the impact of Covid-19 on cities showed the effectiveness of communicating a sense of urgency with citizens and stakeholders to gain sufficient media attention and traction. This was the case, notably, with the rapid roll-out of pop-up bike lanes across cities worldwide, from Bogota to Berlin, which were quickly understood to safeguard sustainable mobility during the pandemic (ADFC, 2021). Replicating such a sense of urgency on climate change issues, similar to what Fridays for Future has initiated, could act as an accelerator of change towards zero emission urban mobility.

2.1.3. More locally based neighbourhoods

One major benefit of living in a city is having access to a diverse range of goods and services. However, the design of cities based on cars has led to urban sprawl, segregation of different functions withing the city like living, learning, shopping and hence the need to travel farther and more often to access everyday goods and services.

We envision a future where new forms of mobility, densification, and integration foster polycentric development and create neighbourhoods, both in the inner-city and outside the city, where people can live, work, shop, even grow food, and access other services in the vicinity, while also maintaining good connection between neighbourhoods and cities. Future neighbourhoods focus on accessibility, diversity, and density, while enhancing green space, individual character, and regional connectivity. Locally based neighbourhoods reduce the need to travel to access essential services and leisure, and as such strengthen local communities while encouraging active mobility.

Even if there is still a long way to go to fully transition to more locally based neighbourhoods, steps have been made in that direction during the Covid-19 pandemic. Confinements during the pandemic have encouraged citizens to take advantage of neighbourhood life and to consume differently, focusing spending on essentials while cutting back on other categories (McKinsey 2020). Cities such as Paris (15-Minute City concept) or Stockholm (the one-minute city concept) are developing strategic initiatives to increase local value creation and improve well-being within the community. While Paris focuses on providing access to essential amenities at neighbourhood level, in the case of Stockholm the planning scale is "hyperlocal" and focused on street level. Both examples are living experiments of what cities can look like when walking and cycling are prioritised over driving. Shortly after its first tests, the city of Stockholm saw a 400% increase of neighbours on the streets of redesigned blocks, with the majority being either happy or very happy about the changes (FastCompany 2021).

An increasing number of people teleworking because of the Covid-19 pandemic has been a huge stimulus to animate life in neighbourhoods through more mixed use of places. A survey by Eurofound shows that more than a third of European employees worked solely from home in the month of July 2020, while less than five percent of employees reported working in this way regularly in 2018 (Eurofound 2020). This significant change in daily behaviours can support the transition towards innovative neighbourhood design and more sustainable urban mobility. Forward-looking urban mobility planning will need to take these evolutions into account, considering that many employees will still be working from home at least a few days a week even once the Covid-19 pandemic is over.

2.1.4. Increased availability of sustainable mobility solutions

The future of urban mobility will be characterised by multimodal offerings of active, clean, shared, and partially automated modes (including public transport). These offerings will complement the public transport network, which should remain the backbone of cities' transport systems, mutually reinforcing the attractiveness of both types of services. The increased availability of a wide range of mobility options will mean urbanites will not need to own cars but will be able to access the right transport mode according to their needs. In parallel, enhanced design of walking and cycling routes and improved traffic and parking management are also important flanking measures to nudge users towards the use of low carbon, sustainable modes.

Shared mobility which includes new types of micro, mini and maxi mobility are expected according to McKinsey to expand in coming years at an annual growth rate of over 20% through 2030 (McKinsey 2021). New solutions for car and bicycle pools and rentals, and Mobility as a Service (MaaS) apps are providing inspiration for mobility services that offer point to point transportation in a convenient and easy to use way, in combination with public transport as the backbone of the system. More electric bicycles, scooters, and small vehicles plus the flexibility of on-demand booking for flexible solutions, such as a cargo bikes, are providing means for reducing traditional fossil-fuelled car trips and ownership. Recent initiatives such as Cityrestarts, a project supported in 2020 as part of the EIT Urban Mobility COVID-19 response calls, aim to address challenges for shared mobility that have arisen from the pandemic. This project deployed in Milan is the first large scale public taxi sharing in Europe, allowing citizens to book shared taxi rides over the phone or through an app that automatically assigns the most suitable taxi and optimizes driver routing. The project aims to provide first and last mile extensions to the public transport network, which will be a success factor for future multimodal mobility systems.

Increasing the attractiveness of shared transport solutions, including public transport, are essential to offer suitable alternatives to the private car. This requires high frequency of service, enhanced reliability, and greater availability close to home and work. To achieve this, comprehensive mobility data analysis is a pre-requisite for cities aiming to optimise their mobility systems and tailor their mobility offers to citizens' needs. Partnerships on data collection and management across the knowledge triangle and cities will be instrumental to the provision of reliable and seamless mobility services. Similarly, there is a need to address remaining sustainability challenges of some new mobility vehicles, as well as aspects related to business model definition. New models should be self-sustaining and focused on the transfer of car trips to other mode shares. Solutions should be locally adapted but have universal applicability across cities. As an example, InclusiveEbike, a project funded under EIT Urban Mobility´s special COVID-19 response initiative. designed innovative rickshaw-like vehicles with a 300 kg load capacity to be used not only for the transportation of people but also as a zero-emission alternative for last-mile delivery of goods in urban areas. Two version of the e-bike are currently being developed: one for carrying people in a wheelchair, and one for last mile delivery. A prototype has already been delivered and will be tested as a pilot in the city of Bilbao, Spain.

Meanwhile, vehicle electrification is supporting the transition to more sustainable mobility, helping cities reduce their greenhouse gases, pollutants, and noise emissions. In 2020, for the first time in European history, registrations of electrified vehicles overtook those of diesel vehicles (JATO, 2020). Sales of electric vehicles in the EU and EFTA countries, including the UK, accounted for 10,2% of total vehicle sales in 2020 (EV-volumes, 2021) and are expected to grow to 32% of market share by 2030, according to recent estimates by Deloitte (Deloitte, 2020). Similar trends can be observed in the European electric bicycle market, that grew by 23% in 2020 compared to 2019 levels (Forbes, 2020).

Progress made in vehicle automation constitute a change of similar magnitude with significant opportunity to increase road safety while optimising traffic flows. It is expected that by 2040, autonomous vehicles (SAE level 4 and above) will account for about 66% of total passenger kilometres worldwide (McKinsey, 2019). For practitioners from both the public and private sectors, this revolution calls for the deployment of proper infrastructure and standards to enable communication between vehicles and infrastructure. Combined with connected on-demand mobility packages, shared autonomous vehicles – for example in the form of robotaxis – have the potential to improve connections with low-density areas, further increasing the attractiveness of shared mobility overall, and to free up a significant amount of public space that today is allocated to car use.

2.1.5. Innovative and efficient solutions for goods and logistics

Less road space for traditional heavy vehicles, like trucks and lorries will pose a challenge for municipal authorities and freight companies. In the future, when less urban space will be dedicated to car roads it will be more difficult for deliveries of goods and services, municipal services like waste collection and emergency service, and various other logistic services, to navigate in the urban environment.

The challenge will be amplified by the rise of e-commerce and on-demand delivery services. According to the OECD, online orders in Europe surged by 50% during the first quarter of 2020 (OECD, 2020). The rapid increase in parcel and meal deliveries in a relatively short time frame has spurred a range of innovations aimed at optimising city logistics and reducing related congestion and pollution. Some of them, such as night deliveries, rail deliveries, logistic hubs, new vehicle types that are electric and autonomous, have great potential to make delivery and logistic services more efficient. Spanish start-up Vonzu has developed a flexible logistics management software-as-a-service (SaaS) that integrates retailers and logistics operators to digitalise and automate last mile delivery processes. In 2020, Vonzu provided its services to 12 logistics operators and digitised more than 300,000 deliveries. Likewise, centralised package delivery systems, with appropriate large infrastructure close to major transport nodes and city depots in urban areas, are efficient solutions to reduce traffic caused by home deliveries.

Further innovations such as improved management of loading/unloading bays to reduce the impact of deliveries on traffic will optimise deliveries in dense urban environment. Where feasible, the use of waterways should be the focus of future logistics concepts. In recent years, an increasing number of cities have rediscovered the potential of waterways for urban logistics and waste management. For instance, the city of Paris' 2030 climate objectives foresees a tripling of the freight volumes currently delivered on the Seine, equivalent to an estimated 2 million avoided lorry trips, to reduce both inner city congestion and air pollution (Agence parisienne du climat, 2021). Looking ahead, the use of drones for parcel or medicine deliveries will offer further opportunities to diversify and further optimise urban logistics, with both industry leaders and start-ups already developing advanced concepts for drone delivery services.

2.2. Structural enablers of urban mobility transformations

2.2.1. Innovation-orientated legal and policy frameworks

In view of upcoming vast transformation in the field of urban mobility local communities and administrations need support, to make legal and regulatory frameworks more flexible and adaptable to new mobility solutions. A common challenge for many projects across Europe is working within legal frameworks that support traditional planning methods and are not adapted to innovations in technology and urban planning. Laws and regulations restricting the deployment of autonomous vehicles, electric vehicles, new market solutions, data management, building codes, and even parking, can make it difficult to implement new projects in urban environments. Even if there is political support, it can take extensive periods of time to adjust the municipal and national legal and regulatory frameworks to implement projects.

Uptake of future mobility innovations requires more flexible and adaptable local administrations, who act as drivers and enablers of future mobility. Working in the EIT Urban Mobility Community, we have identified some key structural enablers to future mobility concepts:

- Innovation deployment depends on the right conditions being in place - for instance living labs and large-scale demonstrations that help raise political support for sustainable mobility, and to secure investments in sustainable mobility measures. This needs to be complemented by lean procedures to facilitate the approval and deployment of urban mobility innovations, granting permits and exceptions through regulatory sandboxes where relevant.
- Political decisions and participation of the public and key stakeholders is crucial to raise awareness about sustainable mobility, accelerate the uptake of Sustainable Urban Mobility Plans (SUMP) (Eltis 2019) and long-term mobility strategies as well as roll out smart transport solutions. Coherent long-term mobility plans help to align all stakeholders on a common vision and roadmap towards future mobility.
- Clear governance and adequate policy frameworks are necessary to drive and regulate innovation. Regulations should provide clarity to all stakeholders regarding requirements and expectations from public authorities and communities towards innovative mobility solutions. At European level, a common approach to issues that are central to innovation could, for instance, facilitate the EU-wide roll-out of safer and more sustainable mobility solutions such as autonomous vehicles and MaaS applications.
- Pilot projects, short-term projects that test individual solutions in isolated locations or neighbourhoods, serve as a safe way to try various solutions in different locations. Well-designed pilots create new solutions for real-world mobility issues. However, these must scale beyond project stage if they are to bring substantial, systemic change to the wider mobility landscape, transforming short-term success into long-term impact.
- Access to the right funding solutions is an important enabler for innovators to test and roll out new products and services and facilitate

the scaling-up of innovative companies. (Capgemini, 2019). Plans and funding instruments for the recovery of cities from the pandemic need to focus on innovation as the engine of productivity and of competitiveness. For the recovery to be green, digital, and resilient, funds must enable close-to-market solutions to scale and boost sustainable urban mobility.

2.2.2. Improved real data and technological ecosystems

Unlocking future mobility will require a modern toolbox of solutions for collecting, managing, and sharing data. City officials need to improve their understanding of how people and goods move through the city, to help implement the right solutions in the right places for the right target groups.

To make the most of the data available and create better visibility of how goods and people move throughout the city, mobility practitioners need to look at the whole ecosystem of technology for data collection. In the GEMMS project to relieve congestion in the Bulgarian capital Sofia, excessive street load was explored in terms of traffic and parking through combined geo-spatial and thermo mapping. The data was translated into an Open Innovation challenge for sourcing solutions with the engagement of experts in the urban mobility and planning sector and citizens. The activity resulted in generation of innovative solutions for offloading public spaces and will allow Sofia Municipality to deploy these towards giving back space to citizens and turning the urban environment into liveable spaces fostering active and alternative modes of transport.

More accurate data also helps measure the effects of implemented solutions, creating a feedback loop. Developing a toolbox of solutions for collecting, managing, and sharing data would enable better, more effective project designs. With the digitalisation of almost all industries, it will be easier and more accurate to track how people and goods and services move. Digitalisation and new survey methods also allow to build a more accurate picture of how specific social or demographic groups travel. This requires a technology ecosystem that supports data collection with the proper compiling, managing, understanding, and analysis of data.

Open access to data, data quality and availability are paramount to support decision making, inform good plans and strategies, measure impact and monitor indicators. Traffic data is a key enabler for future mobility, for example to optimise the operations of the estimated 350 million connected cars worldwide by 2023 (Capgemini, 2019), as well as enable a seamless user experience with on-demand mobility services. Data has great potential to improve mobility from public transport and multimodal journey planning (e.g., real-time information), transport infrastructure and planning (e.g., walking and cycling movements, and health economic impact of increased active mobility, cost-benefit analysis for sustainable urban transport measures), C-ITS and connected and cooperative autonomous mobility, Mobility as a Service, ticketing, etc. In the case of MaaS, open access to specific data sets is crucial. The European project UMOS (Urban Mobility Operating System), aims to tackle the challenge of MaaS provider fragmentation by developing a service platform that lifts the barriers between different mobility solutions and ecosystems. The goal of this currently ongoing project is to set up a universal, open, GDPR compliant service platform for optimized, customised, and seamless mobility. As a mobile and web application it will be a one-stop platform, integrating various mobility services to provide real-time service data (EIT Urban Mobility, 2021).

Further innovations in the digital infrastructure include setting up and running IoT systems, and public databases that allow cities' digital twins to be modelled. Based on real-time data, these simulations allow cities to monitor traffic, environmental conditions, and energy consumption, and to develop digital scenarios, thus supporting decision-making processes. Experiments with digital twins are multiplying in Europe, with, for instance, a recent government-backed cross-city project starting in the cities of Hamburg, Leipzig, and Munich (City of Hamburg, 2021).

3. Conclusion

Together, we need to translate our vision of the future of urban mobility into a coherent strategy that delivers both short-term and long-term results.

3.1. From vision to strategy

It is the conviction of EIT Urban Mobility that achieving the vision as laid out in this article will contribute to mitigating climate change, improving quality of life, creating jobs, and strengthening the economics of European cities – in line with the EU sustainability objectives. The creation of more liveable urban spaces – which is at the heart of EIT Urban Mobility's mission - will improve citizens' quality of life and accommodate urban growth while strengthening cities resilience. The move away from car-orientated urban planning to a people-centred planning approach will be supported by the uptake of more efficient, clean, and shared mobility options. Facilitating the exchange of best practices will accelerate the local implementation of change experiments. Similarly, urban transitions will be accelerated by promoting the ability to innovate through education and training across Europe.

To boost the swift deployment of green, user-centric, integrated mobility solutions for people and goods, private and public stakeholders need to ensure that novel mobility solutions are designed around people's needs and offer all citizens access to a new generation of clean, safe, affordable, and equitable travel options while reducing private car use and boosting the use of alternative modes of transport, especially active mobility. The climate urgency combined with the numerous air and noise quality challenges faced by cities compels us to act now so that by the end of the decade, our envisioned co-created urban mobility systems become tangible realities for all European citizens.

Generating a favourable environment for innovative start-ups, SMEs and industry leaders will be key to the successful implementation of the changes our cities need. Knowledge and best practice exchange as well as stakeholder cooperation across borders will stimulate the entrepreneurial ecosystem to unlock new business ideas, models, and players. The creation of such a technologically and socially innovative ecosystem will lead to new jobs, products, and services. Finally, the concretisation of our vision into a coherent strategy will require effective policies and behavioural change to increase citizen awareness of sustainable mobility solutions and to create a regulatory environment that allows the most sustainable mobility solutions to be competitive in terms of price, accessibility, and comfort.

3.2. From strategy to impact

With its network of local governments, leaders from industry and academia, EIT Urban Mobility drives local transformations through targeted innovations, that are contributing to:

- Strengthening intermodal mobility to connect people to jobs, education, and leisure, and expanding equitable access to mobility.
  Example: In 2020, EIT Urban Mobility supported projects aiming to improve seamless shared mobility integration with public transport, as well as initiatives to restore confidence in bus and metro (x30Futuremob, 2021), and taxi services in the middle of the COVID-19 pandemic (EIT Urban Mobility, 2021).
- Expanding clean and efficient city logistics for goods deliveries for businesses and people.
  Example: Development of shared micro depots for logistics parcels in the cities of Helsinki, Munich, and Helmond, testing real-world solutions to optimise urban logistics and reduce motorised trips linked to city deliveries (EIT Urban Mobility 2021).
- Enhancing a mobility system that protects and fosters people's health and wellbeing, engaging citizens and communities.
  Example: local experiments of local placemaking and urban design tactics that changed the use of public space in Milan, Munich,

and Amsterdam (CLEAR project, 2021). Similar activities were conducted during the pandemic, based on the objective to digitally fabricate and deploy urban elements for the purpose of adapting temporary public spaces to ensure social distancing in the public realm (Furnish, 2021).

All of the above will facilitate fast piloting and scaling of innovations, knowledge, and experiences across cities to accelerate positive change and enable Europe´s urban mobility sector to be a global leader for sustainable urban mobility transformation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Self-Attention based encoder-Decoder for multistep human density prediction☆

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ABSTRACT

Multistep Human Density Prediction (MHDP) is an emerging challenge in urban mobility with lots of applications in several domains such as Smart Cities, Edge Computing and Epidemiology Modeling. The basic goal is to estimate the density of people gathered in a set of urban Regions of Interests (ROIs) or Points of Interests (POIs) in a forecast horizon of different granularities. Accordingly, this paper aims to contribute and go beyond the existing literature on human density prediction by proposing an innovative time series Deep Learning (DL) model and a geospatial feature preprocessing technique. Specifically, our research aim is to develop a highly-accurate MHDP model leveraging jointly the temporal and spatial components of mobility data. In the beginning, we compare 29 baseline and state-of-the-art methods grouped into six categories and we find that the statistical time series and Deep Learning Encoders-Decoders (ED) that we propose are highly accurate outperforming the other models based on a real and a synthetic mobility dataset. Our model achieves an average of 28.88 Mean Absolute Error (MAE) and 87.58 Root Mean Squared Error (RMSE) with 200,000 pedestrians per day distributed in multiple regions of interest in a 30 minutes time-window at different granularities. In addition, the geospatial feature transformation increases 4% further the RMSE of the proposed model compared to the state of the art solutions. Hence, this work provides an efficient and at the same time general applicable MHDP model that can benefit the planning and decision-making of many major urban mobility applications.

1. Introduction

The modeling and prediction of human mobility is a topic of increasing interest due to its applications in multiple domains of urban mobility, such as personalised recommender systems (Zheng et al., 2018), urban planning (Du et al., 2020) and the design of smart cities (Chen et al., 2019), just to mention a few. In particular, human mobility refers to the movement of human beings (individuals as well as groups) in urban areas in time periods that span from a few minutes to a few hours (Barbosa et al., 2018). It is evident that modeling the human mobility, urban and transport planners can identify movement behavior patterns and suggest corrective actions to improve the livable urban spaces.

This generates an important opportunity for urban mobility and planning stakeholders by leveraging smart mobility data and analytics to not only analyze how existing infrastructures facilitate the life of community members but also how to create a sustainable environment based on the forecasted human mobility. Obviously, the core of the smart mobility data analytic tools is the data related to the movement of the users in an urban environment. Fortunately, nowadays humans, transport infrastructures, and even entire cities are equipped with sensors included in mobile devices, GPS tracking tools and social media geotagging systems that generate continuously mobility data that reflect the every-day activities of citizens.

Following, these data should be carefully analyzed to extract the appropriate knowledge that will make relevant applications more efficient and more intelligent at the same time. To this end, the key theme of this

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paper is to design a data driven and machine learning model that processes the mobility data in order to provide timely and accurate insight for an optimal decision making and what-if (Arman et al., 2019) analysis in the context of urban mobility. Specifically, the problem we address is the Multistep Human Density Prediction (MHDP). This problem is defined as the real time prediction of the distribution of moving entities into multiple Regions of Interest (ROIs) or Points of Interest (POI) through different temporal granularities. In this context, moving entities are individuals or human groups moving in an urban area, whereas ROIs are locations which the moving entities frequently visit. The involved prediction can be in a next-step or a multi-step granularity, according to how far in the future the prediction should be made.

Most of the current models are designed to provide single next-step predictions. However, there are many contemporary applications that require predictions with different time granularities. For instance, three major application categories that require multi-step ahead forecasting of the amount of people gathered in multiple ROIs are the following: (a.) The epidemic spreading modeling (Balcan et al., 2010) which defines the crowded ROIs and the time duration they will remain crowded. (b.) The wireless networks (Kapoor et al., 2017), especially in the context of smart cities, where multiple users and sensor devices try to connect in an access point creating network planning bottlenecks. (c.) Edge Computing task offloading mechanisms (Saeik et al., 2021) in which user devices, e.g. Augmented Reality (AR) glasses in touristic attractions, offload their computational intensive workloads in nearby processing nodes at the edge of the network. By leveraging the sequential density of users in different ROIs this can lead to a better planning of these applications both in a short and in a long-term time window.

The above applications are only few of a vast range of applications that an MHDP can be used. Nonetheless, what is import to understand is that to reap the benefits of the MHDP we need first to understand the people's behavior. The mobility and the density of people/application-users into ROIs is characterised by the properties of periodicity and self-similarity making a model that analyzes and forecasts time series a rational approach, since data are usually collected within equal time intervals. These data must include spatial and temporal information of the mobility. Additionally, based on different use cases the models can be enriched with exogenous information like the weather, the terrain characteristics, and various events that affect the mobility decisions of people. Nonetheless, in the particular research we focus only in the spatio-temporal data represented by timestamps and geo-locations feature vectors, which are structured in a time-series dataset (e.g. a person's position every 30 minutes).

For many years, the main approach for time series problems, such as the problem at hand, was the statistical modeling and forecasting. Later, Machine Learning (ML) methods have been proposed as alternatives to the statistical ones. Although, ML models are based on more complicated and advanced mathematical models, their accuracy is criticized to be often below than their statistical counterparts (Makridakis et al., 2018). For this reason, lately, the hype in forecasting prediction is around other types of Artificial Intelligence (AI) techniques such as the Deep Learning (DL) and specifically the gated variations of Recurrent Neural Networks (RNN).

The above techniques are not always performing the same for different types of applications (De Saa and Ranathunga, 2020; Yamak et al., 2019), signifying that there is a strong connection between the use-case and the most appropriate prediction model to be used. Accordingly, in this paper, one of our research aims is to find the best prediction model for any urban mobility use-case that can benefit from the MHDP mechanism. More precisely, our research is trying to answer which model should be incorporated into a MHDP mechanism in order to provide a high prediction accuracy for multiple ROIs in a sequence of time-steps. Hence, this motivated us to make extended experiments among statistical, machine learning and deep learning models in a real dataset and a synthetic human mobility simulator in order to find which has the best performance for the multi-step forecasting of the human density. Our research reveals, that a technique of deep learning, the attention-based Encoder-Decoder (ED) architecture, provides the best accuracy for the mobility prediction.

Towards our path to design the most accurate predictive model for the urban density prediction we have identified the four following major research contributions:

- We discuss how a data-driven methodology applies for the multi-step forecasting of the number of people gathered in ROIs.
- We make an extended experimental comparison in statistical, machine learning and deep learning time series approaches in order to find the best performance model.
- We propose the self-attention based Encoder-Decoders architecture which surpasses the accuracy of the other methods in the literature.
- We propose a geospatial feature transformation that scales the density of people in a ROI based on the density of its neighborhood ROIs weighted by the lengths of their borders. This data transformation improves further the performance of the multi-step predictions.

The rest of the paper is structured as follows: Section 2 provides a short overview of the MHDP in three popular use cases. Section 3 highlights the related work in multi-step forecasting of human density. Section 4 explains how the mobility prediction can be modeled with self-attention based ED architecture and the geospatial feature transformation. Section 5 describes the experimental setup and the evaluation results of our proposed methods. Finally, Section 6 concludes the paper and suggests future directions.

2. Applications of multistep human density prediction

Multistep human density prediction has applications in multiple domains such as smart cities, edge computing, wireless networks and epidemiology modeling. The density prediction in a future time-window give us a comprehensive understanding of the moving entities in a spatio-temporal framework. Doing so, the dynamicity of the moving entities can be reflected in the component of time and the component of space taking into consideration their correlation. The aggregation of the predictions in next location and also the crowd flow prediction miss the depth in the component of time while, the trajectory prediction of single entities misses their relations on the component of space.

2.1. Smart cities

The domain of smart cities includes multiple fields of the information and communication technology in order to improve the quality of human life, wellbeing, economic development and optimise the utility of different resources and services. Mobility data in smart cities are acquired by mobile devices, vehicles equipped with global positioning system devices, smart cards (bank cards and transport cards), and embedded sensors. These data monitored by intelligent systems for traffic management, traffic lighting control, tourism recommendation systems, civil protection experts, intelligent transportation and many more services. Decisions can be real-time based on the dynamic changes of the human density. Every service has its own requirements in the time-steps granularity. For instance, traffic lighting systems need time steps of one minute while intelligent transportation systems of ten minutes or more. Even in these examples the time requirements change based on the scale of geospatial regions and the context of the use cases. Specific use cases in which the multistep density prediction can be leveraged by urban and transport planning are the transportation demand analysis over time (Verma et al., 2021), the sustainable mobility planning (Singh et al., 2022) and the bike-sharing services (Arias-Molinares et al., 2021)

2.2. Edge computing

Edge Computing is another emerging technology where mobility can play a vital role. Edge computing refers to adding the necessary computational and communication resources closer to the end-user at the edge of the network. This approach can allow fast data processing and real-time decision for mission critical applications. Accordingly, new and future internet technologies, such as Internet of Things (IoT) and 5G and beyond are and will be largely based on the Edge Computing concept. An inherent part of these technologies is mobility. Hence, the adequate prediction of user mobility can facilitate the resource allocation at the edge, and the proactive planning of a relatively limited infrastructure. Additionally, Edge computing is quite dynamic and distributed in its nature due to the type of the applications it supports (Dechouniotis et al., 2020). Specifically, when the application supports mobility, the computational resources allocated to a user should follow its direction by traversing the edge infrastructure close to the ROIs. At the same time, the requirements of ultra reliable and low latency communications that these applications impose, make a necessity the high accurate prediction of mobility models with different granularity of time-windows.

2.3. Epidemiology modeling

Epidemic spreads depend on the human density as there is a significant positive correlation of the likelihood of infection with the close humans interactions. The temporal and spatial dynamics of disease transmission within a population can be modeled by a sequence of multiple time-steps of human density in ROIs. This provides a useful tool to decision-makers who use non-pharmaceutical interventions policies (Ilin et al., 2021), such as quarantines, perimeter closures and social distancing. Specifically, infectious disease epidemiologists use models based on population size, population density, and travel distance. The gravity and radiation models are the most commonly used (Sallah et al., 2017). The gravity model is based on the assumption that the mobility between two locations has a positive correlation with the population size and a negative with the distance, whereas the radiation model assumes that the mobility depends on the population density.

3. Related work

In this paper we address the human density prediction problem in multiple RoIs and multi-steps with a time-series dataset. Accordingly, in this Section we first review and categorize pertinent prediction mechanisms proposed in the literature that could be used and adapted for the human density prediction. Secondly, we present relevant works that have used mobility prediction mechanisms. Finally, we investigate the research gaps of each of the prediction mechanism categories and we reason the need of the proposed novel Self-attention based Encoder-Decoder equipped with the geospatial density transformation mechanism, that tackles the problem of human density prediction.

3.1. Time-series prediction mechanism

1. Statistical methods (Faghih et al., 2020) are based on the assumption that the data are stationary, They may use one polynomial for the Autoregression (AR), which regresses the variable on its own past values, and the Moving Average (MA) polynomial which is a linear combination of error terms occurring contemporaneously and at various times in the past. The sum of these two polynomials gives the ARMA model. In case the data are not stationary then ARIMA model can be used. ARIMA is based on ARMA but also includes the integration part which is a number of differences in the sequences of data observations.
2. Linear Regression (LR) (Fernández-Delgado et al., 2019) is based on the assumption that the output of the model is a linear function of the input variables. Lasso, Ridge and Elastic Net (EN) are variations that also assign a regularization penalty. Huber regression is a variation robust in outliers, whereas Passive Aggressive Regression (PAR) is an online regression approach. We also experiment with the Stochastic Gradient Descent Regression (SGDR) which is an extension of the stochastic gradient descent classification to the regression case. Finally, Least-Angle Regression (LARS), the Random Sample Consensus (RANSAC) and the Lasso model fit with the Least Angle Regression (LLARS).
3. Machine Learning (ML) (Xie et al., 2020) is a broad field, spanning an entire family of different techniques. However, all these techniques have the common principle that they automate the model building from data without being explicitly programmed. From this category we first examine the Support Vector Regression (SVMR), which is based on drawing the maximum margin hyperplane in an n-dimensional feature space. Following, we study the Regression Trees (Extra, CART), which is based on tree structures combined with decision rules. Finally, we evaluate the K-Nearest Neighbors (KNN) algorithm, which is based on the average of the values of K Nearest Neighbors of the testing instance.
4. Ensemble ML (Raj S. and M., 2021) are models that include multiple weak predictors and aggregate their individual outputs in order to improve their performance. They are mostly divided in the bagging methods that decrease the variance error, such as Bagged Decision Trees (Bag) and Random Forest (RF), and the Boosting methods that mostly decrease the bias error, such as Adaboost and Gradient Boosting Machines (GBM). The Bagging methods include homogeneous weak predictors that learn independently and in parallel while the predictors of the Boosting methods learn sequentially and adaptively.
5. Deep Learning (DL) (Luca et al., 2021) is a prominent subfield in ML that includes Artificial Neural Networks (ANN) with different types of hierarchical layers. In mobility modeling and prediction the Feed-forward, Long Short-Term Memory (LSTM), Convolutional layers (CNN) and many variations and combinations of them have been used successfully. Each of them captures the spatio-temporal dependencies of the mobile entities through different representation formulations.
6. Encoder-Decoders (ED) (Luca et al., 2021) are DL topologies with one ANN that compress the input feature vector in a latent space and one ANN to decode the latent vector to the output feature vector. Various types of DL models have been used in the literature for the encoder and decoder such as simple LSTM for both of them (LSTM-ED), bidirectional and simple LSTM (BD-LSTM-ED), unidirectional and bidirectional LSTM (Uni-BD LSTM ED, also named HB ED) and CNN encoder and LSTM decoder (CNN-LSTM ED). Special emphasis has been given to the ED that also include an attention mechanism which mimics cognitive attention and solves the bottleneck problem focusing on the most significant parts of the mobility features. A specific architecture of ED topology is the transformer (TRNF) with significant results in sequence to sequence problems which also lately adapted in mobility challenges.

3.2. Prediction mechanisms for mobility

Regarding the use of some of the above techniques specifically for the mobility prediction problem, only a few studies exist. For example, a work that compares statistical time series with DL methods for multi-step crowd distribution (Cecaj et al., 2020) has shown that generally statistical time series methods have better performance than simple DL models. But, an ED with a CNN for encoder and an LSTM for decoder outperforms the other DL models and it has similar performance to that of ARIMA. Comparing ED CNN-LSTM with ARIMA, we see that both approaches have advantages and limitations. The ARIMA has slightly better performance in the mean error metrics for most time-steps. In contrast, DL approaches reduce the maximum errors and they are more robust to spikes and sudden changes in the sequential values. Other important conclusions from this work are that there is a steady increase in the forecasting errors when going from a few steps forecast to more steps in the future. In addition, when the data sample size grows, DL methods significantly improve their predictive performance. This work presents experimentally that the ED has the potential to be the state-of-the-art approach for multi-step density prediction using only an off-the-shelf ED. Our work goes a step beyond by trying to understand theoretically how the ED topologies can be adapted to the mobility characteristics. Furthermore, we conduct research with different ED topologies that also include the attention mechanism.

Our work is also related to the WiFiMod (Trivedi et al., 2021) model which uses an off-the-shelf TRNF taking into consideration long term mobility dependencies and multiple spatial scales. Even though this study also makes density prediction, it differentiates from our work because it focuses only on indoor modeling. The authors explain that the indoor mobility modeling has major differences from outdoor mobility because in a finer spatial scale, the mobility becomes more frequent, the prediction space expands and there is a more complex sequential periodicity.

Two important advances in time series forecasting that worth to be investigated by the mobility researchers but do not match with our work are the AR-NET (Triebe et al., 2019) and the DeepAR (Salinas et al., 2020). The AR-NET combines the best of traditional statistical models and neural networks using the stochastic gradient descent for the estimation of the AR weights. AR-NET can deal efficiently with long-range dependencies with fine granularity data. Nonetheless, as the authors mention, AR-NET currently has been designed for one-step forecasting while they leave multi-cast forcasting as future work. The DeepAR is based on an autoregressive recurrent neural network model and has the ability to learn a global model from multiple related historical time series. Its main advantage is that it provides probabilistic forecasts which is a characteristic we do not require in density prediction.

Recently, an Encoder-Decoder with Attention mechanism has been used in mobility prediction but for different challenges, such as the trajectory prediction (Zhou et al., 2019) and the prediction of users next PoI (Gao et al., 2019). In addition, it is important to mention that the Attention mechanism has different variations such as the (a.) Multi-dimensional Attention, (b.) Hierarchical Attention, (c.) Self Attention, and (d.) Memory-based Attention (Hu, 2020) just to mention the most popular. These variations can be used in different ways and have a different role in the DL ED topologies.

3.3. Comparison of related works

In all of the aforementioned works, related to mobility prediction, only a subset of the possible solutions from the 6 categories were used. This paves the way for a research investigation and for an analysis opportunity to examine which solution is the most appropriate for the MHDP. To the best of our knowledge, this is the first research endeavor of such a holistic analysis that tries to expose the limitations and advantages of the six categories in the context of urban mobility.

Some of these limitations can be extracted by analyzing the main functional blocks of each method. For instance, the methods of the categories from 1 to 5 have the limitation that they are not designed to provide predictions jointly in the spatial and temporal component. In addition to that, the statistical methods (category 1) are based on the stationarity assumption, which does not always characterise mobility data. LR models (category 2) include simplistic methods based on the assumption that the data have linear dependencies and can be represented using a linear model. Unfortunately, this assumption does not always characterise mobility data. The ML, ensemble methods and DL (categories 3, 4 and 5) can work with no-stationary and non-linear dependent data. However, their multi-output outcomes are limited to only one single step for the multiple ROIs or multi-step predictions for one single ROI. ED models (category 6) can provide sufficiently multiple output predictions in a forecasting time window but they are intrinsically designed to process natural language data. From a first look, it seems that the ED models may be a promising solution for the MHDP, yet they have not been designed for the particular problem. In other words, this means that there is a research gap since the current ED models have the structure to provide multi-step predictions but they have not been tailored for urban mobility data.

Thus, the key theme of this paper is to address the Multistep Human Density Prediction problem, by comparing and evaluating the related machine learning methodologies, while in the end proposing an innovative Self-attention based Encoder-Decoder and a geospatial density transformation mechanism. The latter, is a secondary problem that we address, namely, how to design an ED model to process efficiently urban mobility data in order to provide accurate density multi-step and multi RoIs predictions. It should be noted, however, that the novelty of this approach is not just the reuse of a state-of-the-art model in the urban mobility context but the optimization of the particular model through the design of an innovative Attention based ED that leverages the spatial and temporal properties of urban mobility data. This proposed model, as we will see in the experimental evaluation, surpasses the accuracy of all other methods.

4. Attention based encoder-decoder

A geospatial area, in which people move, can be separated in a set of POIs or ROIs (Kuo et al., 2018). A POI is defined as a specific physical location that people find useful or interesting and visit with high frequency. A ROI in the geospatial domain is defined as a polygonal selection in a 2D map that is important to be examined. The two terms, for the purpose of our research, can be used interchangeably since in both of them a high density of people concentration can be noticed.

Accordingly, in every POI/ROI people are concentrated and their density is changing over time. The POIs/ROIs are characterized by geospatial properties which affect the mobility and the flow of people among them. These factors make us to design a prediction model that should leverage: (a.) the geospatial properties among the POIs/ROIs, (b.) the number of people grouped in every POI/ROI and (c.) the time that is a key factor that shows how people density changes. Regarding the factor (a.), we propose a geospatial density value transformation that scales the number of people grouped in a POI/ROI, the number of people grouped in its neighborhood POIs/ROIs and the length of the borders between the ROIs. For the factor (b.), we empirically know that the density of people has a self similarity property with temporal dependencies (Trivedi et al., 2021) and can be predicted through a time series approach. Lastly, the time component (c.) can be leveraged through a sequence to sequence approach that takes as input a look back window of n previous values and provides m sequential predictions in a future time window.

As an example, Fig. 1 depicts an urban-area of interest, that we will also examine later in the experimental evaluation. We see that different regions are characterized by polygonal borders and a representative centroid. The density of people change over time and it is illustrated with different colors, according to the depicted heat bar. For each ROI we predict the density of people given the number of people it has in the n previous steps and the number of people in its neighboring regions. The predictions are multistep meaning that the models provide forecasts for the density in a sequence of m steps.

In the next subsections, we will firstly present the overview of the model and then we will focus on the technical details of our proposed model.

4.1. Model overview

The strong part of our proposed model is the mapping ability between the input and output sequences. The relationships and the prediction between the sequences is enhanced by the self-attention mechanism, as explained later, that focuses on the most significant parts of the temporal density dependencies. The attention mechanism learns which patterns in the input sequences should be considered as relevant and which as background noise in order to predict the sequential density

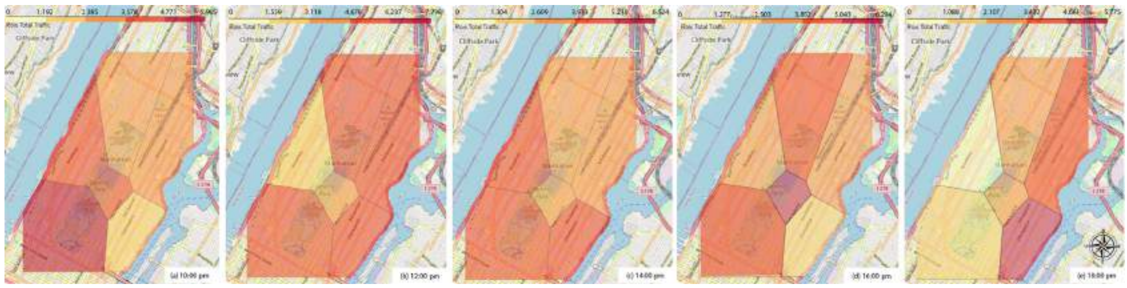

Fig. 1. Human density evolution over time.

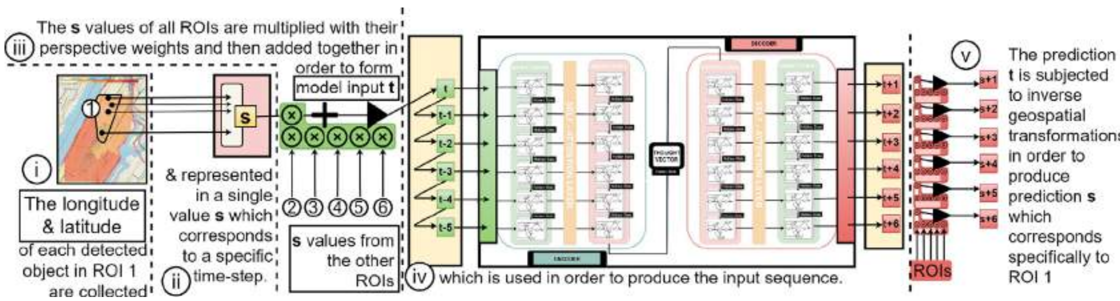

Fig. 2. The pipeline of human density prediction.

values. However, first and foremost, we need to understand which are the inputs and the outputs of our prediction model.

In more detail, we use an end-to-end mobility prediction model that begins from the sensoring of the geolocation data in constant intervals and ends up in the prediction of the human density distribution in a set of POIs/ROIs as it is depicted in the Fig. 2. The sensored mobility data, in its simplest form, are sequences of timestamps, latitude and longitude. The mobile entities that they represent can be physical entities or mobile devices. The output of the human density can be expressed either as a scalar number declaring the percentage of people in each POI or the real amount of people.

Furthermore, an additional characteristic of our model is that we assign the users to the nearest ROI and aggregate them in a single value s that represents them. The processing of aggregated values of people's density has three benefits compared to the processing and prediction of batches with individual geolocations. Firstly, it outputs smaller errors because it does not aggregate the errors of all the individual predictions. Secondly, it is more computationally lightweight because it makes less calculations. Finally, it preserves the privacy of individuals according to the General Data Protection Regulation (EU 2016/679 (GDPR))- the EU regulation law on data protection and privacy.

After the sensoring step (i) and representation step (ii) of individuals geolocations, which are also depicted in the Fig. 2, the time series are constructed by the ordered transformed density values of POIs/ROIs step (iii). Each POI/ROI has its own version of time series based on its own spatial properties (i.e. centroid distances and borders sizes) and the temporal users' mobility behaviors step (iv). As an example, users may have different mobility behaviors in regions with museums than regions with open-air concerts. Each POI/ROI has its own univariate prediction model with a self-attention based ED. As we will discuss in the experimental evaluation, the univariate models with the geospatial preprocessing have better performance than the multivariate models. At the last step (v) we apply the inverse geospatial transformation in the ED outputs to take the real predicted density values.

4.2. Geospatial feature engineering

As stated above, our input data are generated by sensoring devices, such as GPS tracking tools, which provide raw features of timestamps, longitudes and latitudes. These raw mobility data contain latent knowledge regarding the density of people. A feature engineering technique using geospatial domain knowledge can transform the raw data into a more suitable representation for the input of the ED model. The geospatial feature representation (Geo) leverages the length of the region borders and the contextual human density information.

In particular, we combine the representations of the various regions in a single variable which can be digested by the univariate proposed model. Given that the current density state of a region could affect the future states of other regions, two main points should be properly considered. The first point is to decide which of the other regions are affected by considering (a.) the data based on the activity of people, (b.) the actual size of the regions formulated and (c.) the established time-steps. Additionally, it is safe to assume that during each time-step an individual can traverse two regions at most. Thus, the state of a region can only be affected by the states of its neighboring regions within the time-frame which is currently being examined. The second point is the extent at which the states of the neighboring regions are affected. The next state of a region depends on the current states of its neighboring regions in accordance with the length of the borders they share. A longer common border between two regions means that it is statistically more likely for people to cross it.

In order to extract this inter-regional correlation it is essential to incorporate two additional mechanisms. The first mechanism is in charge of the formulation of the variables in an $Input\_Matrix$, which contains information regarding the states of all the regions. The backbone of this mechanism is the implementation of the $r \times r$ weight matrix named $Weight\_Matrix$ which contains representations of the r regions, normalized in a $0 - 0.5$ zone. For instance, the first row of the $Weight\_Matrix$ will contain information regarding the borders that the region i forms with the other regions. In the case of not neighboring regions between two ROIs, it will take the value 0. The declared border that a region forms with its own is equal to the sum of the borders which are formulated with the rest of the regions. In this way, the sum of the weights of each row will be equal to 1, the elements of the main diagonal will be equal to 0.5 and the rest of the weights of each row will have a sum which is equal to 0.5. Following, the states of all regions for each one of the m specified time-steps are collected, thus creating a $r \times m$ $Weight\_Matrix$. The two matrices are then multiplied with each other.

Out of the r rows of the resulting matrix only the one which corresponds to our area of interest is going to be selected. The following equation describes the formulation of our model input.

$$Model\_Input[i][j] = \sum_{l=1}^{r} (Input\_Sequence\_Matrix[i][l] \cdot Weight\_Matrix[j] \cdot k) \quad (1)$$

where i is the index of the input sequence, j is the index of the area of interest, and k is an additional weight vector which was introduced to enhance the efficiency of the model. In more detail, to guarantee the generality of the Eq. (1) and to estimate the optimal significance between different ROIs and their neighbors, we multiply the resulting vector with the k vector, which is the updated weighted matrix. This updated matrix entails weights that correspond to the significance of each region in accordance to our area of interest. Much like before, the elements of the k should have a sum which is equal to 1. The values of this vector can be formulated via processes such as Grid Searching. The final product is named $Model\_Input$ (Eq. 1) and it is consumed by the proposed Self-attention based ED.

The second mechanism is responsible for transforming the produced prediction sequence back into a form which corresponds to only one specified region. In order to achieve this functionality every prediction output is subjected to the transformation which is described in the Eq. (2).

$$Prediction\_Specific[i][j] = \frac{1}{k} \cdot (Prediction[i][j] + Input\_Matrix[i][j] \cdot k - \sum_{l=1}^{r} (Input\_Sequence\_Matrix[i][l] \cdot Weight\_Matrix[j])) \quad (2)$$

The Eqs. 1 and 2 are derived by the geometrical properties of the ROIs based on the assumption that more people can move between two ROIs through a longer border than a shorter one.

4.3. Sequence to sequence prediction

As mentioned before, we treat the MHDP problem as a time series problem. For our study, the look-back window of a time series forms a sequence of previous human density values. The multi-step-ahead prediction also constitutes a sequence of density values. This intrinsic structure of the input and output data, makes us to use a sequence to sequence (seq2seq) approach.

Hence, we resort to Encoders-Decoders (ED) models that their structures allow us to follow this seq2seq approach. Specifically, (ED) with RNN is a prominent DL model that maps the input sequence to the output sequence. RNNs neurons send feedback signals to each other through hidden states and keep prior inputs in memory while they process the current inputs and outputs. The training of long sequences in simple RNNs has the vanishing gradient problem, which can be addressed by the gates of LSTM units. The gates regulate what information of the time series the model should learn, forget or remember.

Fig. 3 illustrates the form of the encoder, which processes the sequential input values and encapsulates the temporal and spatial information into the context vector, also named thought vector. The encoder utilizes a bidirectional and a unidirectional LSTM layer. The bidirectional layer provides one hidden state output for each time-step in an n-dimensional space form which is then utilized as input by the unidirectional layer. The synergy between the heterogeneous layers is capable of exploiting the temporal correlations in the look back-window leveraging past and both past and future information. This structural symmetry enables the decoder later on, to capture the sequential patterns in both directions.

The context vector is the last hidden state of the Encoder and the input of the Decoder. It is calculated by the hidden and cell states of the LSTM units. Its main role is to summarize the information of the input sequence in a fixed-length representation. This representation captures the similarity relations among the sequential density values and it can work as the compressed information that the decoder will unfold in order to predict the density values in the next steps of a POI/ROI.

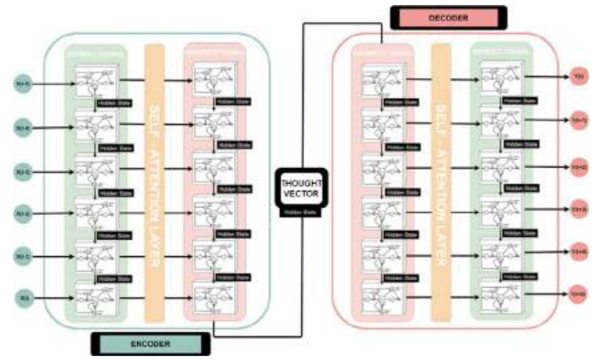

Fig. 3. Self-attention encoder decoder.

In addition, as it will be described in the next subsection we enhance the information of the context vector using a self-attention mechanism. This mechanism, focuses on the most informative patterns between the uni-directional and the bidirectional layers.

Regarding the decoder, it interprets the context vector and generates sequentially the output values. The decoder is also implemented by utilizing a unidirectional and a bidirectional LSTM layer with the self-attention mechanism. In addition, there is an interpretation layer and an output layer. The purpose of the fully connected interpretation layer is to interpret each time-step in the decoder output sequence and send the product to the output layer. We also wrap both the interpretation and the output layers inside a time-distributed wrapper. By doing so, the output provided by the decoder will be processed by the same fully-connected and output layer. This results at enabling the wrapped layers to be used for each time-step by the decoder.

4.4. Innovative encoder-decoder with attention mechanism

In this part of the section, we present the final model of our proposed mechanism, which is the Hybrid Encoder-Decoder (HB ED) model. The Encoder and the Decoder parts of the HB ED consist of Unidirectional and Bidirectional layers. In this particular architecture, we also utilized two Self-Attention (SATT) based layers alongside the recurrence-based ones. The first one, which is present at the encoder, receives as input the output of the bidirectional layer and its output will be utilized as input by the unidirectional layer. The second one, which is present at the decoder, receives as input the output of the unidirectional layer and its output will be utilized as input by the Bidirectional layer.

This final architecture, which is named SATT-HB-ED, is differentiated from the existing ones because the Attention mechanism is incorporated inside the encoder and the decoder parts respectively. The de facto use of the Attention mechanism is that it enables the decoder to examine the various states of the encoder and to provide an output by selectively focusing on specific elements from the sequence. At the same time, in this particular architecture, the Attention layer is utilized in a manner which aims to enhance the ability of the Hybrid bidirectional-unidirectional structures to encapsulate temporal dependencies. This enhancement manifests in the form of more robust encoding / decoding capabilities when compared to various alternative options.

In more details, the purpose of the incorporation of the Attention mechanism in the Encoding / Decoding process is to encourage the formation of homogeneous representations. The level of similarity to its counterparts each of the intermediate products of the encoding / decoding process holds, shall determine its impact on the overall encoding / decoding process. Since the Weight Vectors of the Attention mechanism are trained alongside the rest of the network and not in an independent manner, the same logical process is applicable in the opposite direction as well. Therefore, the elements of the input sequence which are more significant (in regards to affecting the output of the model) are more likely to be conceptually represented via the Encoding / Decoding process in a similar way. This process enables the important elements of each input sequence to be represented in a more stable manner.

The Self-Attention mechanism, which is used in this particular architecture, is a variation of the Additive Attention mechanism (Cheng et al., 2016). The Additive Attention mechanism was introduced in order to provide more efficient sequence-to-sequence modeling by aligning the decoder with the relevant input elements. The variation which is used in this architecture implements the following process. The first recurrence-based layer produces the hidden states for each element of the input sequence. Following, the Alignment Scores between each element's hidden state and the rest of the hidden states are calculated. Each Alignment score corresponds to a specific element and is indicative of the similarity between the Hidden State of this specific element i and the Hidden States of the other elements j of the input. The Alignment Score for each pair is calculated using the Eq. (3).

$$scorealignment(i, j) = W_t \cdot tanh(W_i \cdot H_i + W_i \cdot H_j) \quad (3)$$

where H represents the Hidden State and W the Trainable Weight Vectors.

In the above equation, the $W_i \cdot H_j$ vector consists of N times as many columns as the $W_i \cdot H_i$ vector, since it is derived by the Hidden States of N elements of the input. Thus, the latter is added to each column of the former. The resulted vector is then passed through a tanh activation function and multiplied with another trainable vector. This process enables the Alignment Scores to be combined and represented in a single vector. The Attention Scores are then produced by passing the Alignment Scores through a softmax layer. The softmax layer will force the vector values to sum up to 1. By doing so, the importance of each timestep is properly encapsulated. Finally, the hidden states of the input are combined with their perspective Attention Scores in order to produce the Context Vector. The Context Vector is ultimately consumed by the second recurrence-based layer.

The proposed SATT-HB-ED is trained with the preprocessed data using the Adam optimizer, the backpropagation technique for the ED and also the Teacher Forcing technique for the Decoder. The Adam optimizer (Kingma and Ba, 2017) involves a combination of Momentum and Root Mean Square Propagation (RMSP), where both the exponentially weighted average and the exponential moving average of the past gradients are taken into consideration. The backpropagation technique (Hecht-nielsen, 1992) is used to minimize the cost function which evaluates the performance of the model by adjusting the network's weights and biases. The Teacher Forcing (Williams and Zipser, 1989) technique is a method that uses the ground truth from a prior time step as input, instead of model output from a prior time step. This is used to achieve faster and more efficient training for recurrent neural network models.

5. Experimental evaluation

The proposed methodology has been implemented and experimentally evaluated in the Python 3 programming language using the libraries NumPy, pandas, Scikit-learn, SciPy, GeoPy, TensorFlow 2 and its higher-level API Keras. The environment we used for the experiments is a Jupyter notebook of the Google Colaboratory. In order to help other scholars to replicate the same approach we provide the experiments' source code for any kind of reproduction in the second author's GitHub repository (Theodoros, 2021). Our research includes experiments for multiple time steps and ROIs with the twenty nine different methods described in Section 3 and the Attention based Encoder-Decoder presented in Section 4. In this part of the paper, we provide the figures and tables that summarize the most important outcomes. However, we have also uploaded the more detailed experimental outcomes in the GitHub repository.

For the evaluation of the proposed model we used two datasets. At first, we evaluated the performance of the SATT-HB-ED in a single-POI without using the geospatial transformation. Doing so, we focus our experiments on the ability of the SATT-HB-ED for sequence to sequence prediction. Next, we carried out extended experiments using a mobility simulator in an area of multiple ROIs/POIs. In this case we took into consideration the geospatial and crowd flow characteristics of the examined area and the human mobility behavior respectively. In the second set of experiments, we also used the proposed Geospatial transformation (Geo). In the Table. 1 we provide the data requirements for both data sets.

To evaluate the performance of our approach we use the Mean Absolute Error (MAE) and Root Mean Squared Error (RMSE) metrics, since they are the most popular metrics to be used in time series forecasting and ML regression models (Adhikari and Agrawal, 2013). MAE measures the average absolute deviation of forecasted values from original ones and it shows the magnitude of overall error, which occurred due to forecasting. The RMSE penalizes extreme errors occurring while forecasting. This emphasizes on the fact that the total forecast error is much more affected by large individual errors (i.e. large errors are much more expensive than small errors). For a good forecast, the obtained MAE and RMSE should be as small as possible.

5.1. Single-POI prediction outcomes and discussion

For the comparison and evaluation in a Single-POI task, we used the real-world dataset Crowdedness at the Campus Gym (Du et al., 2019). This dataset includes measurements of the number of people located in the campus gym of UC Berkeley. The measurements are taken every 10 minutes over more than one year and consists of more than 26,000 people counts. The reason we have selected this dataset is because going to a gym is a daily life activity for many people in urban areas. Additionally, with the current situation of the pandemic we have observed that many Covid-19 outbreaks were associated with the attendance of people at a gym. In particular, the visitors can stay in the POI of the gym for a significant amount of time, often more than one hour and there is a fluctuated flow of people during the parts of the day. The MHDP can provide the number of people crowded in the gym letting know the athletes and the coaches when they should go.

Many human out-of-home activities are characterized as stationary processes or can be transformed into stationary process by a difference transformation. Stationary means that the statistical properties of a time series do not change over time and it is the main assumption to guarantee the soundness of the model fit. We applied the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test (Kwiatkowski et al., 1992) in the initial data values and it showed that the sequence values are not stationary. The non-stationarity is also visual perceived in Fig. 4, where we can see the density mean value to change in different parts of time. We continued with the differencing of the time series in order to eliminate the trend and seasonality. The new transformed time series was stabilized and the test showed that it is stationary.

In this first experiment, we have applied the ARIMA, linear regression (LR), and KNNR models. Additionally, we examined the three types of ED, namely, the LSTM ED, the Hybrid ED (HB ED) and the self-attention based Hybrid ED (SATT-HB-ED), which were described in Sections 2 and 4 respectively. The experimental outcomes are summarized in Table 2. The time-step was ten minutes and we predicted six steps ahead in a time window of one hour. Making experiments with different time granularities and number of steps in the look back window and look ahead window we derived the same conclusions regarding the applicability and performance of the methods. The multistep prediction in the ARIMA, LR, and KNNR took place with the recursive strategy while, in the ED with the direct strategy (Bontempi et al., 2013). The ED models have the intrinsic characteristic to provide multiple predictions directly by the output layer while the vanilla statistical, linear regression and machine learning models need multiple versions of the same model, one for each output. The latter approach increases the computational workload and we did not select it. For the sake of completeness, we mention that there are time series models that provide multi-outputs directly. This is the vector autoregression (Schimbinschi et al., 2017)

Table 1
Data requirements.

	Duration(days)	Time-step (min)	Regions (number)	People Counts
Campus Gym	430	10	1	26,000
Central Park	7	5	6	1,554,778

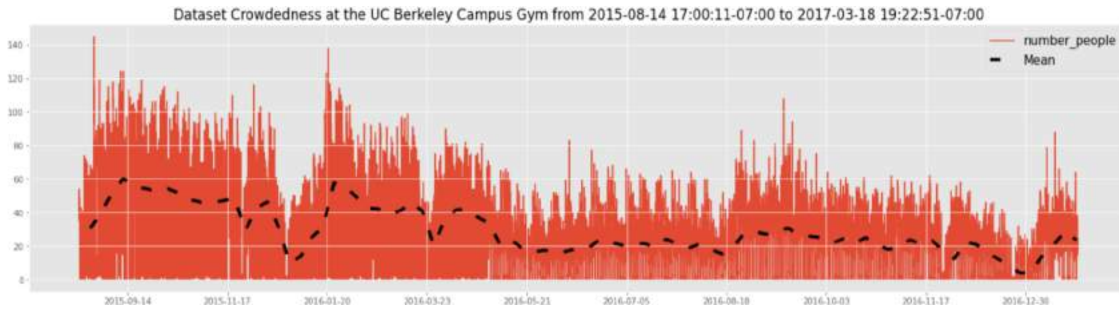

Fig. 4. Timeplot and vizual checking of stationarity. Different time periods have different statistical properties.

Table 2
Single POI Evaluation in the Dataset Crowdedness at the UC Berkeley Campus Gym.

	ARIMA	LR	KNNR	LSTM ED	HB ED	SATT-HB-ED
MAE	**4.008**	4.821	5.858	4.149	4.986	4.127
RMSE	6.225	6.647	8.640	6.096	7.11	**6.019**

model, but as we will see in the last experimental setup we selected the univariate because they had better performance.

From the Table 2 we see that in terms of RMSE the SATT-HB-ED has the best performance and in terms of MAE it has the second best performance. The ARIMA model has been optimized selecting the (p,d,q) values based on KPSS and Canova-Hansen tests (Canova and Hansen, 1995). The ED parameters have been learnt with the Adam optimizer but we didn't select the hyper-parameters i.e. number of layers, neurons, activation functions, etc. with a tuner such as Bayesian optimization or Hyperband. We just selected an ED topology based on our experience of previous time series tasks. This means that the ED performance can be further improved using a hyper-parameter optimization process.

The ED models seem promising even if they have not been hypertuned. The outcomes confirm that the ED approaches can achieve good performance in human density prediction. The RMSE metrics show that the SATT-HB-ED has the best performance in high-variability observations and when the sequential data have anomalous behaviors. Last but not least, it is obvious from the comparison of HB ED with SATT-HB-ED that the self-attention mechanism in the encoder and in the decoder improves the performance.

The above results corroborate that SATT-HB-ED has the following advantages in MHDP modeling compared to the others methods: i) It efficiently captures long-range dependencies and complex interactions. ii) It detects and focuses on the most relevant previous time steps against the target time-step. iii) It jointly leverages temporal dimensions (different time steps of a sequence), spatial dimensions (different regions of space) and different feature values. These characteristics are also present in the multi-ROIs experiments that follow. Specifically, in the following section, we will compare the performance of all the 6 categories mentioned in Section 2 and we will also apply the geospatial transformation.

5.2. Multi-ROIs prediction outcomes and discussion

For the evaluation and comparison of Geo SATT-HB-ED in multiple ROIs, we run a mobility simulation for seven days in the area of Central Park of New York. In every day of the simulation we examined approximately 200,000 to 230,000 pedestrians that roam around or stay in the same location. We partitioned the Central Park into six ROIs. We adopted a time step of five minutes, a look-back window of six steps and a look-ahead window also with six steps. We split the dataset into the training part with the first four days and the evaluation part with the last three days.

The Central Park covers a rectangular area of $3.41 km^2$ with sides that are $4 km$ in length and $0.8 km$ width. In our simulation we also took into consideration many building blocks that surround it. The Central park has geospatial and smart city characteristics such as multiple attractions, every day activities, events, concerts, tours, the Central Park Zoo, the 21 official playgrounds and 8 lakes and ponds. All these make it an ideal area for study and experiment of mobility models. The visitors stay or walk through the central park, they remain, come in or go out in the different ROIs. The route of the visitors is affected by the geospatial characteristics of the terrain and the park attractions making some areas with low or zero concentration like the areas of lakes and some others with a high concentration like the Conservatory garden and the Rumsey Playfield. The lake of central park has also rowboats and gondolas but we limited this research only to pedestrians.

The area is partitioned into ROIs based on the Voronoi diagram and the k centroids generated by the k-means clustering algorithm (Du et al., 1999). Firstly, the k-means algorithm is applied in the training dataset in order to cluster all the recorded pedestrian geolocations. The clusters are created with the objective to minimize the intra-cluster distances of the pedestrians' geolocations and maximize the inter-cluster distance of the clusters centroids. Doing so, we have centroids with latitude and longitude being shaped coherently and by well separating the groups of pedestrians. Following, using the geolocations of the centroids and the Euclidean distance we draw the borders of the Voronoi diagrams as illustrated in Fig. 1. Each Voronoi cell defines the region of the corresponding ROI. The reason we follow this approach in order to select the ROIs instead of using predefined ROIs, is that the new Edge computing and wireless network infrastructures cover areas with this type of geospatial and number of connected users criteria (Chowdhury and De, 2021).

The trajectories of the pedestrians are generated with the software package named Simulation of Urban MObility (SUMO) (Lopez et al., 2018). SUMO is a highly portable, microscopic and continuous traffic simulation for handling large mobility networks. It has multiple types of transportations including pedestrians and comes with a large set of tools for different mobility scenarios creation. The simulation offers many realistic properties of the pedestrian mobility such as pedestrian-

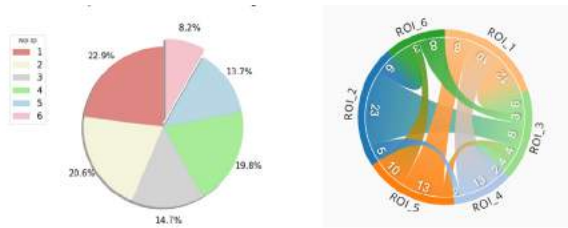

Fig. 5. Density of People (left) and mobility percentages among ROIs (right) in Central Park NYC.

pedestrian interactions when they are close, reasonable walking speeds and movement behavior.

Pedestrians interactions also include features such as the collision avoidance. In order to achieve this, the SUMO divides the lateral width of a lane into discrete stripes of fixed width, adding to the pedestrians the ability to overcome obstacles or slower pedestrians by moving to another adjacent stripe and proceeding. More complicated movement rules apply when moving on a walking area, where pedestrian paths cross in multiple directions. In that case, pedestrians follow a predetermined trajectory calculated at the beginning of the simulation. It is finally important to note that each pedestrian involves a list of rides, stops and walks. Rides are not implemented in our case, because no vehicles were included in the simulation. Stops correspond to non-traffic related activities such as working or shopping, while walks model trips taken by foot.

The ROIs cover different areas, number of people and mobility patterns. The size of the ROIs is constant in our experiments, defined by the Voronoi diagram and can be depicted in the Fig. 1. The distribution of people in the ROIs for three different timestamps is also depicted with different colors in Fig. 1. The total amount of people in the ROIs during the first four days of the simulation is depicted in the left of the Fig. 5. The chords in the right of the Fig. 5 represent the percentage of people that move from ROI-*i* to ROI-*j* during five minutes. These five minutes are selected randomly and it is obvious that the chord diagram changes over time. Every different use case and area of interest has different mobility patterns and statistical properties. Yet, this analysis is important in order to conceptually understand the challenges of the heterogeneity and dynamicity that a mobility model should tackle.

We compared the performance of the Geo SATT-HB-ED with the baseline and state-of-the-art models mentioned in the related work. We applied both the direct and recursive methods in order to develop the multistep forecasting as we did in the Section 5.1. The outcomes in terms of MAE and RMSE are summarized in Fig. 6. We see that the models are mostly grouped together based on the category they belong to. ML and linear regression models seem to have the worst performance with the highest MAE/RMSE. Next, ensemble methods and DL models follow with a significant improvement in the performance. Time series models and ED have the best performance. An unexpected outcome was the bad performance of Transformers (TRNF), since it is mentioned as the state-of-the-art method for many sequential problems. We made an error analysis and searched in the literature to reason the TRNF outcomes. The results of the error analysis can be explained by (Fan et al., 2021) who say that TRNF have inability to track long sequences, do not have access to higher level representations and cannot maintain a belief state. In contrast, SATT-HB-ED does not have these limitations. The long sequences can be tracked by the bidirectional and unidirectional LSTM layers and the belief state can be maintained in the encoder and the decoder.

Fig. 7 depicts that the Geo SATT-HB-ED has better performance compared to ARIMA in every ROI. We see that the ROI-1 and ROI-5 in both models have significantly lower accuracy than the other ROIs. This means that the historical data of the ROI-2, ROI-3, ROI-4 and ROI-6 are sufficient to train the prediction model compared to ROI-1 and ROI-5. In the error analysis, we saw the phenomenon that similar input patterns are mapped to different output sequences which also have high variability. This phenomenon was more intense in ROI-1 and ROI-5. The SATT-HB-ED can capture these mobility patterns better than ARIMA using a non-linear approach and giving the proper attention into the important parts of the long sequences.

In Fig. 6 we also see the performance of the geospatial scaling Geo SATT-HB-ED compared with not scaling SATT-HB-ED. We see a significant improvement in the RMSE and a slight deterioration in MAE. The geospatial transformation compress the information of the number of people in every ROI and the geospatial properties among the ROIs in one value. In case we disentangle these pieces of information and process them as different sequences of features we have a multivariate forecasting model. The related scientific literature contains many instances which showcased that the utilization of multiple features instead of a single one is beneficial to the model's efficiency to properly forecast future states. In the use case which is currently being examined, the application of multivariate forecasting would enable the model to simultaneously consume information related to all of the 6 regions. This is achieved via the use of a 6×6 matrix as the input sequence. Each column corresponds to a specific region and each row corresponds to a specific time-step. The output sequence is identical to the one produced by the univariate model.

In order to test the viability of a multivariate forecasting approach, we modified the SATT-HB-ED model in a manner which allowed it to leverage inputs from various regions. Table 3 shows these results and prove that the univariate approach is superior to the multivariate one both in terms of RMSE and MAE. This is due to the fact that the mobility-based correlations, which are formed between the various regions, are not strong enough to overcome the advanced complexity of the multivariate approach. This advanced complexity derives from the fact that the multivariate model has to digest a greater amount of information in order to form contextual relationships between the input and the output sequence.

In both experiments of Single-POI prediction and Multi-ROIs prediction we have seen a significant improvement in the accuracy using the SATT-HB-ED compared with the six categories of prediction models described in the related work. This happens because ED captures the long-range dependencies and complex interactions among the different time-steps of the data. Finally, the proposed geospatial feature representation improves further the accuracy leveraging the geometric properties of the areas of interest. Regarding the limitations of the proposed model, ED requires a significant amount of historical data. In addition the training process is computationally heavy, requiring the appropriate number of resources and training time.

6. Conclusion and future work

In this paper we have studied several multistep prediction mechanisms for the distribution of people in POIs/ROIs in an urban environment. We have seen that existing models cannot jointly process the geospatial and temporal properties of this challenging problem and cannot attain high accuracy. To this end, we tried to conceptualize what affects the density of people in a look ahead window and proposed a new ED-based mechanism called SATT-HB-ED. The experimental results with two different datasets confirm the applicability of our proposed approach.

Hence, transport planners and other related stakeholders can have the most accurate model regarding the density of people distributed in an urban area using the Geo SATT-HB-ED. Additionally, we believe that ED models can sufficiently capture long-range time dependencies and complex interactions among mobile entities, which constitute major mobility challenges. In addition, the modeling of physical characteristics of a mobility task using data transformation techniques can further improve the accuracy.

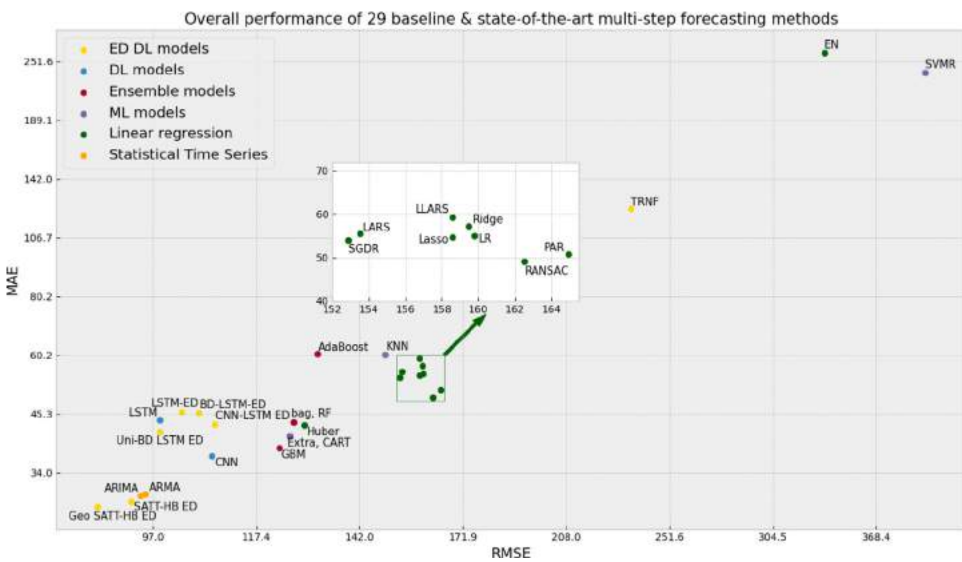

Fig. 6. Experimental results in terms of MAE & RMSE.

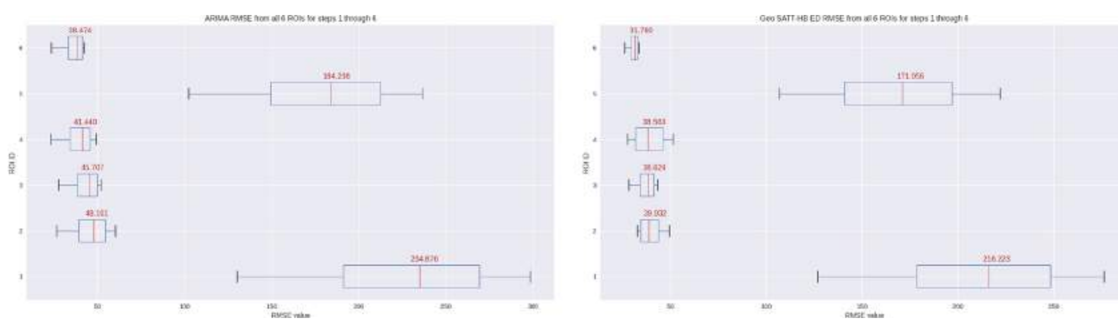

Fig. 7. ARIMA vs. Geo SATT-HB-ED.

Table 3
Comparison multivariate with univariate SATT-HB-ED.

		ROI-1	ROI-2	ROI-3	ROI-4	ROI-5	ROI-6
Multi- variate	MAE	143.145	90.573	103.262	179.017	179.839	53.088
	RMSE	277.001	119.649	124.315	225.338	316.104	76.303
Uni- variate	MAE	47.486	25.189	21.245	24.628	40.373	18.771
	RMSE	225.55	40.814	38.306	40.619	182.387	31.195

Our future work includes to adapt the proposed methodology in specific use cases and include additional covariants like parallel time series that have cross-correlation and semantic information of the ROIs. We believe that by modeling exogenous information we can find patterns from different knowledge domains that reason the mobility behavior of people. These patterns can be time dependent or time independent. This brings the challenge of how we can combine time series and batch data in a unified forecasting model. Lastly, we believe that the geospatial and mobility properties can be efficiently represented with graphs. Thus, in our future work we aim to also examine the graph neural networks for mobility prediction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

John Violos: Conceptualization, Methodology, Writing – original draft.

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Simulating micro-level attributes of railway passengers using big data

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ABSTRACT

In the absence of a comprehensive, representative, and attribute-rich population, a spatial microsimulation is necessary to simulate or reconstruct a population for use in the analysis of complex mobility on the railways. Novel consumer datasets called 'big-data' are exhaustive but they only reveal a subset of the wider population who consume a specific digital service. Further, big-data are measured for a particular purpose and so do not have the broad spectrum of attributes required for their wider application. Harnessing big-data by spatial microsimulation has the potential to resolve the above shortcomings. This paper explores the relative merits of different spatial microsimulation methodologies, and a case study illustrates how best to simulate a micro-population linking rail ticketing big-data with the 2011 Census commute to work data and a National Rail Travel Survey (NRTS). The result is a representative attribute-rich micro-level population, which is likely to have a significant impact on the quality of inputs to strategic, tactical and operational rail-sector analysis planning models.

1. Introduction

Progressively complex societal urban mobility has meant that transport planners require insights into robust rules governing movement patterns of people and the interdependencies with demography, municipal parameters, space and time, in order to provide sustainable efficient services. There is a growing need for novel geographical modelling tools, as well as attribute-rich, comprehensive and representative data to assist in such research and decision-making. Today's wide use of electronic devices has meant that novel sources of large consumer datasets are now increasingly readily available, however it is unrealistic to expect all the information required to be provided by a single dataset (De Montjoye, Hidalgo, Verleysen & Blondel, 2013; Lynch, 2008; Manyika et al., 2011). As such, methods have to be developed to combine various datasets, within mobility analysis frameworks.

Once the relevant datasets are identified, it is often found that the process of integration requires adjustments in resolution and in geographies of scale to maintain consistency between the datasets (Deming & Stephan, 1940). Often one dataset has to be systematically adjusted to fit the resolution, and system process associated with other datasets (Howe et al., 2008; Weber, Mandl & Kohane, 2014), and the hypothesis is that the adjustment methodology adopted impinges on the quality of subsequent postulations based on such integrated data. In this paper, we investigate the different methodologies for combining disparate datasets to integrate their resolution and geographies and to simulate a population represented at micro-scale (i.e. individual/household) levels. A case study illustrates how best to apply such methodologies to urban mobility in West Yorkshire. The datasets combined are the 2011 Census interaction data, the National Rail Travel Survey and big railway ticketing data for West Yorkshire study area procured from the Association of Train Operating Companies' (ATOCs) Latest Earnings Network Nationally over Night (LENNON) database.

A LENNON dataset including every railway ticket sold in the UK is large and exhaustive of railway passengers (ORR, 2016). However, for use in research to relate population mobility to demographic and other likely drivers of behaviour, LENNON data is lacking because it does not contain information on say passenger residence, final destination, nor does it identify any socio-demographic and urban morphology characteristics associated with the passenger. In order to use such ticketing data for mobility analysis, it would be necessary to combine with other relevant datasets that contain the sought attributes. The 2011 Census measures the interaction between each geography (OA, LSOA or MSOA) zone, measuring the volume of passengers commuting from locations of usual residence to places of work (Rees, Martin & Williamson, 2002; Stillwell & Duke-Williams, 2003). These measures are aggregated for a range of socio-demographic attributes (age, gender, mode of commute, occupation, ethnicity, and the cars, children, and type of household). The National Rail Travel Survey (NRTS) is another relevant railway passenger survey conducted over 2001 to 2005; it aimed to produce a comprehensive picture of weekday rail travel across Great Britain. The NRTS identifies places of usual residence and final destination (DfT, 2013), as well as a range of social-demographic and, sample passenger train station access and egress attributes. Considerations outlined below form the basis for reconciling NRTS and Census, despite that they were acquired at different times.

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As discussed, big-data[1] are advantageous in that each set offers a unique and distinctive view of real events. Combining such datasets reveal a more complete picture of reality, and this is a particular advantage of big-data which make them attractive for the analysis of a wide range of phenomena. The NRTS and Census are random samples of the UK population taken at different times; hence their variables have different crystallization times (i.e. times at which they were digitally measured). Within the time when the 2001/5 NRTS and 2011 Census were measured, there were increases in passenger volumes, changes in travel behaviour, etc., so the datasets have different conditional distributions. Whilst the NRTS is conditional on time (i.e. 2001/5) and a transport-mode (i.e. train), the Census is conditional on a different time (i.e. 2011) and different transport mode (i.e. all modes of transport). This brought about reports in the literature (Gower, 2021) that structural changes occurred in the UK rail demand, which resulted in annual sales differential growth rates in non-season tickets (~38%) and in season tickets (~26%) between 2005 and 2011. Further, in this period, rail commuters were observed to travel longer distances but less frequently (Le Vine, Polak & Humphrey, 2017; ONS-UK, 2013). This paper addresses the concern about combining such structurally different data like the NRTS and Census acquired at different times. The hypothesis developed in this paper is that disparate datasets like the NRTS and Census can be objectively combined if they do not represent concept or data drift within the model development process. Whilst concept drift occurs in a model where properties of the dependant variable change, data drift occurs where those of independent variables change.

Big-data like LENNON[2] ticketing information are exhaustive, comprehensive, and representative of individual-level rail travel within the UK. However, they are not intended to capture information on the UK population and should only be linked to a subset that uses the trains. Expectedly the distribution of LENNON will be different from that of the UK Census. Each (LENNON or Census) contains data drawn from the same population (the UK full joint distribution). Each dataset is conceived as a conditional distribution, giving the probabilities contingent upon other variables. In the instance of the LENNON and Census, the conditional on the former is 'mode of travel is by train', whilst in the later the conditional is 'mode of travel is by all modes'. The Census being representative of the full UK population joint distribution is taken as the reference. The Census frequency distribution is made up of 6% rail commuters whilst LENNON is 62% rail commuters. In this context, the 'travel-purpose' frequency distributions of the Census and LENNON are markedly structurally different. As the Census is the reference, we refer to LENNON as a conditional distribution of the Census and in so doing we concede that this does not imply underlying LENNON bias. This terminology is consistently adopted in this paper to highlight the sort of issues typically associated with disparate big-datasets. Any dataset that is not a representative sample of the wider population is a conditional distribution of the Census. Being a conditional is typical of the nature of big-data as they are typically acquired at different times for a specific purpose. This character of big-data poses challenges in integrating with other datasets from measured stated surveys; designed to be representative of the wider population.

Two broad population simulation strategies exist: the first is population synthesis (or reweighting) whereby a seed sample is optimal replicated to fit the dimensions of an aggregate target population. In this case, the simulated population created is made up of multiples (weights) of the seed sample. The second strategy is population reconstruction whereby a constructed model is used to generate a new population such that it fits the dimensions of a target population. In this second strategy the population created has no direct reference to an existing population. The population synthesis and reconstruction methodologies are both further divided into deterministic and stochastic methodologies.

The key shortcomings of the existing population synthesis and the population reconstruction strategies are summarized below. First for the population synthesis:

- Only the marginal distribution of the target is exploited, and not the full joint distribution of the target (Odiari, 2018).
- Only permits sequential fitting of disparate contingency seed data (Odiari, Birkin, Grant-Muller & Malleson, 2021).
- Yields clusters of passengers with same attribute if seed is of small sample ratio (Zhu & Ferreira Jr, 2014).
- Assumes that the seed is representative of the target and has similar distribution (Lomax & Norman, 2016).
- Only a limited number of attributes can be combined due to computational limitations (Müller & Axhausen, 2010; Odiari, 2018).
- Does not incorporate a robust statistical strategy for assessing the errors and uncertainty in results (Lovelace, Dumont, Ellison & Založnik, 2017; Whitworth, Carter, Ballas & Moon, 2017).

For the population reconstruction:

- Accuracy of the simulated population is dependant on model constructed (Farooq, Bierlaire, Hurtubia & Flötteröd, 2013).
- The simulated population is not directly related to the actual population (Müller & Axhausen, 2010).
- Incorporates assumptions inherent in regression models (Tanton & Vidyattama, 2010).

In this paper we review and validate the range of population simulation strategies for use to adjust 'big data'[3] for consistency with survey data[4] and established theory. The science behind the range of population simulation methodologies is presented in a practice orientated way, as a pre-cursor to a case study of, for the first time simulating a representative population portrayed at micro-scale interacting between zones and through the railway network.

2. Literature review

Census exigencies around confidentiality meant that despite complete counts of the populace, only a small sample of anonymized records (SAR) of cross-tabulations of all individual attributes were released. This SAR data was released alongside comprehensive sets of aggregate tables typically limited to only three variables per table (Williamson, Birkin & Rees, 1993). Despite the anonymized data and aggregation in respect of individual privacy, population geographers and transport planners realize that comprehensive and disaggregated records would enable the construction of more detailed pictures of geographic and transport phenomena. The need to create such micro-data led to develop the field of

[1] Big data is a term coined to describe the range of consumer datasets that are increasingly readily available from sensors of consumers of digital services. The data analysts refer to datasets as being 'tall' or 'fat' depending respectively on whether the data has a commensurately larger number of observations or covariates. Under such conditions, data that is both fat and tall is described as 'big'. Business analysts with an aptness for buzzwords refer to the five 'V's, and describe big data as having volume, velocity, variety, veracity and value.

[2] In Geographical Information Systems (GIS), big data refers to data that are large and unstructured that they do not fit on to conventional hardware and software information tools. About 1.3bn tickets are sold in the UK mostly recorded on LENNON, with over 200 ticket types. This is reflective of volume and variety. This dataset is further exhaustive as it is assumed to represents all railway tickets sold. The LENNON database is the digital service for recording tickets, albeit tailored to train operating companies (RDG-ATOC). As such, the LENNON ticking information is classed here as big-data.

[3] Big-data tend to come from consumers of a specific digital service, putting context on the data. This specific context often makes big-data a specific conditional distribution of the population of interest. This concept has been adopted within this paper.

[4] Survey data tend to be regular measured and stated data so they are random samples representative of a population of interest. Conventional established methods for integrating datasets are typically based on that each dataset being combined is a representative random sample of the population of interest.

study of population synthesis and population reconstruction (Birkin & Clarke, 1988).

2.1. Population synthesis

The first application of population synthesis, often ascribed spatial micro-simulation, was reported in the literature as far back as 1940 (Deming & Stephan, 1940). The method was applied to the USA Census. A synthetic population was formed from an estimate of a combination of multiples of individuals in a SAR dataset that will best fit the aggregate values defined in Census tables, using the Lagrange multiplier constrained optimization method (Bertsekas, 2014). With the development of computers and numerical analysis, instead of solving the linear equations from the Lagrange multiplier method, iterative methods gradually converging towards an optimum were proposed (Fletcher, 2013; Kelley, 1999), and it became increasingly more efficient to resort to these iterative proportional fitting (IPF) strategies, as they are faster to compute, less sensitive to numerical and round-off errors and simpler in algebra, than comparative formulations by Lagrange and Fermat (Fermat, 1891; Lagrange, 1867). The IPF algorithm has found applications in diverse fields as economics (Bacharach, 1970), transport engineering (Fratar, 1954; Furness, 1965), statistics and computer science (Lavrakas, 2008) under various names.

In population geography and demography, IPF came to prominence relatively recently with the range of policy relevant applications and solutions proffered. First, (Birkin & Clarke, 1989) used IPF to simulate individual and household incomes at small area levels, (Rees, 1994) used IPF to project age and gender structure of urban areas, (Ballas, Kingston, Stillwell & Jin, 2007) addressed in detail the use of spatial micro-simulation as a framework for decision support for policy analysis, and (Ballas & Clarke, 2001) assessed the impact of aggregate national policies within segregate local communes. The IPF methods have improved with burgeoning use, and while earlier effort concentrated on developing the microsimulation steps on different platforms, the advent of suites of statistical software packages like R-studio (Team, 2016) have enabled an automation of the processes and a look beyond the steps and stages of iteration onto the characteristics of the solution. Effort latterly has shifted to concerns of numerical stability and propagation of errors in IPF methods (Birkin & Clarke, 1995; Wong, 1992). Further concerns relate to converting fractional values to integer counts of individuals, and in developing strategies for internally and externally validating IPF results (Lovelace & Ballas, 2013; Upton, 1985).

Spatial microsimulation is now considered a mature application (Lomax & Norman, 2016), re-visiting questions like whether we can be confident that unconstrained attributes are reproduced reliably by the IPF process, thereby accurately replicating the distribution of those attributes not included in the spatial microsimulation (Birkin & Clarke, 2011). Further unanswered questions concern whether, more benchmark constraining variables generally translate to better micro-simulation results (Markham, Young & Doran, 2017; Smith, Clarke & Harland, 2009; Tanton & Edwards, 2012; Tanton & Vidyattama, 2010), the effect of the disparity in the distributions of the seed sample and target population (Tanton & Edwards, 2012), and the sensitivity of the different spatial micro-simulation strategies to sample ratios of the seed data (Tanton, 2014). These are questions investigated in this paper to explore the potential of spatial micro-simulation methods for use in harnessing mobility (spatial interaction) data acquired from consumers of digital services provided on the UK railways.

Apart from the above deterministic (IPF) spatial micro-simulation strategies which yield the same result on repeat, the alternative strategies are stochastic, typically Monte Carlo Markov chain (MCMC) based methods. The MCMC methods are efficient for converging to solutions of intractable complex constrained optimization problems (Asmussen & Glynn, 2007; Brooks, Gelman, Jones & Meng, 2011). Population geographers have developed a range of MCMC variants to complement traditional deterministic IPF. Some of these methods have been branded hill-climbing and have been compared to IPF methods (Kurban, Gallagher, Kurban & Persky, 2011). The strategies branded simulated annealing have been compared with IPF (Harland, Heppenstall, Smith & Birkin, 2012). Another MCMC based strategy the genetic algorithm, was used to simulate network traffic by reconciling observed and estimated flows, opening the realm for application to transport problems (Dimitriou, Tsekeris & Stathopoulos, 2006). Hill-climbing, simulated annealing and genetic algorithms are local search optimisation methods which start with an arbitrary solution to a problem and then iteratively makes incremental improvements to the solution by sampling alternatives. The objective functions in these methods would be similar, with algorithm differences lying in the (stochastic chain) rule for accepting or rejecting a sample that forms the alternative solution (Kavroudakis, Ballas & Birkin, 2008). Other stochastic methods include the Bayesian expectation maximization (EM) strategy (Dempster, Laird & Rubin, 1977) which performs optimization by iteratively estimating the maximum likelihood.

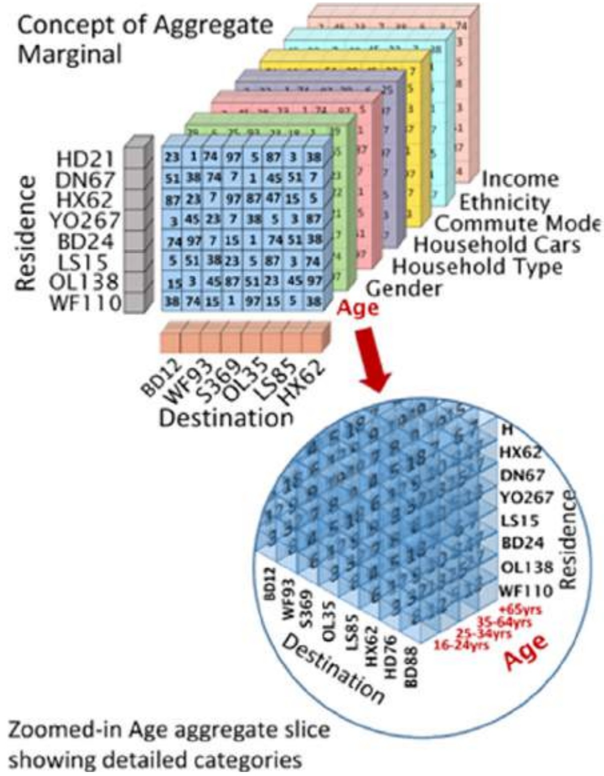
2.2. Population reconstruction

The synthetic reconstruction is another spatial micro-simulation strategy developed in the UK (Birkin & Clarke, 1988; Birkin, Turner & Wu, 2006), exploiting the probabilistic indicative potentials of the Sample of Anonymized Records (SARs) dataset from the Office for National Statistics. The synthetic reconstruction methodology is akin to the Gibbs sampling procedure (Gelfand, Hills, Racine-Poon & Smith, 1990), a variant of the MCMC. With the advent of novel consumer datasets and so-called big data which tend to be a conditional distribution of the wider population, the assumption of normally distributed errors between the target and proposal distributions no longer holds as big data tends to suffer sample bias (Kitchin, 2014). As a result, deterministic and stochastic strategies traditionally set up for representative population seed samples need to be validated for consumer data which often tend to be a conditional distribution of the target population, and structurally dissimilar to the conventional seed data. This validation forms the crux of the first part of this paper. Thereafter, the case study presented in this paper is the first application of spatial microsimulation to synthesize individual railway passengers interacting between geographic locations, using data from the Census, the NRTS and comprehensive LENNON ticketing big data.

3. Deterministic and stochastic formulation

Spatial micro-simulation fall in the wider description of constrained optimization problems (Sun & Yuan, 2006). The typical aim is to estimate a best possible (i.e. optimal) synthetic population limited such that the zonal aggregate characteristics (i.e. the constraints) are fulfilled. The concept of spatial micro-simulation is illustrated in Fig. 1. In practical applications in population and transport geography, the right table depicts a representative sample taken from the population, each row (tuple) an individual with attributes listed in the columns (fields). In literature, the sample table is severally referred to as seed sample, individual-level data, and survey or simply as the sample. The left in Fig. 1 represents the cross-tabulated form of aggregated zonal population attributes.

Each dimension of the aggregate structure typically represents the attributes of a zone and the categories therein. The vertical grey pillar (on its own) could represent the 'Residence' variable made up of categories of geographic zones. If values were included in each cube that made up the vertical grey pillar, these would be the populations associated with each residential zone. A similar description follows for the horizontal brown pillar which (on its own) represents the 'Destination' attributes and the zone categories that make up the destinations. The vertical pillar represents a one-dimensional ($1D$) aggregate constraint, just as the horizontal pillar also forms an ($1D$) aggregate constraint. If the vertical or horizontal pillars are further sliced along their lengths, they would



Concept of Individual Seed

ID	Residence	Destination	Age	Gender	Household Type	Ethnicity	Income	Household Cars	Household Children	Commute Mode	Weight
1	SE18	S97EA	25_34	M	A	Europe	step_40	car_1	No	TC	
2	ME3	BD1	16_24	M	B	Europe	step_70	car_2	No	NTC	
3	LS22	EC2M	35-64	M	C	Europe	step_50	car_3+	Yes	TC	
4	S60	WF2	65+	F	D	Non	step_30	car_no	No	TC	
5	BD1	LS1	35-64	M	C	Europe	step_40	car_1	No	NTC	
6	EC2M	SW1A	65+	F	C	Europe	step_10	car_2	Yes	NTC	
7	WF2	DN3	25_34	F	D	Europe	step_20	car_3+	Yes	TC	
8	LS1	S36	16_24	M	D	Non	step_10	car_no	No	NTC	
9	SW1A	M13	35-64	M	B	Non	step_20	car_1	No	NTC	
10	N1	TW20	25_34	F	B	Europe	step_40	car_no	Yes	NTC	
11	S60	BD9	16_24	M	A	Europe	step_70	car_1	No	TC	
12	BD1	WF2	25_34	M	A	Non	step_50	car_3+	No	NTC	
13	EC2M	S60	16_24	F	B	Europe	step_30	car_no	Yes	TC	
14	WF2	BD1	35-64	F	B	Europe	step_40	car_1	Yes	TC	
15	DN3	EC2M	65+	M	D	Europe	step_10	car_2	No	NTC	
16	S36	WF2	25_34	M	C	Europe	step_20	car_1	Yes	TC	
17	M13	LS1	16_24	F	D	Non	step_40	car_2	No	TC	
18	TW20	SW1A	35-64	F	B	Non	step_70	car_3+	Yes	NTC	
19	BD9	LS22	65+	F	C	Non	step_50	car_2	Yes	NTC	

Fig. 1. | Concept of spatial microsimulation depicted by the aggregate marginal totals on the left and the individual-level seed table on the right.

form a 2D constraint, with the second dimension representing say the age variable, sliced into the categories (16–24yrs, 25–34yrs, 35–64yrs, etc.) that make up the age range within the zone. In this illustration the blue slab in front represents an aggregate array cross-tabulation of 'Residence' versus 'Destination'.

A closer inspection of Fig. 1 however reveals that the blue slab is further sliced along the vertical axis, creating the third 'Age' variable, with categories therein. In such an instance, the blue slab aggregate constraint would be an (3*D*) array. The categories making up these 'Residence', 'Destination' and 'Age' variables are illustrated in the blown up section (highlighted in the circle). To further emphasize the nature of the aggregate data, in the blown up section, for passengers residing in Postcode WF110 and working at destinations in Postcode BD88, there are populations of 8, 12, 5 and 13 of ages 16–24yrs, 25–34yrs, 35–64yrs and over 65yrs respectively. The subsequent slabs coloured green, pink, purple, etc. also represent (3*D*) aggregate constraints ('Residence', 'Destination' and a third demographic attribute). As seen, the variables involved in each slab are 'Residence', 'Destination', and another demographic attribute. Each of the variables is further sub-divided into categories (typical of the blown up 'Age' variable in the circle). The 2011Census interaction data consists of several 3D arrays (like those in Fig. 1) made up of aggregates for location of usual residence ('Residence') and place of work ('Destination') for a range of socio-demographic attributes (age, gender, income, mode of commute etc.). These zonal population cross-table data are also referred to as aggregate, marginal, constraint, count, target or Census (as its structural form is typical of published Census counts).

In practice however, the constraints can be any combination of (1*D*),(2*D*),(3*D*), up to *nD* where ($0 \leq n \leq \infty$). Effectively implying that in practice the constraint could be made up of several differently sourced disparate multi-dimensional arrays. The 2011 Census interaction data implies a marginal constraint made up of eight (8) sets of (3*D*) slabs, a slab for the age, gender, ethnicity, commute mode, occupation (used in lieu of income), and attributes for cars, children, and type of household, all separately cross-tabulated against the residence and destination variables and categories therein (Upton, 1985). The intuition behind creating a detailed micro-level population from a sample individual-level seed and zonal aggregates of the population, is that if a zone consists of an aggregate of say 20 people, with particular zonal characteristic, for instance that are mostly aged and on high incomes: then if a seed sample representative of the entire region is available, the zone can be reconstituted from the sample by making an optimized selection of aged people on high incomes from the sample. To satisfy the constraint of sustaining the volume of people in the zone, the limited available aged and high income individuals in the sample might have to be replicated many times, hence the concept of weights which is indicative of how many times a type of individual is replicated to fulfil the synthetic population.

In our particular case of the Census interaction, the weight assigned to an individual would be indicative of how representative the individual is of passengers on a particular residence-destination flow. The concept can be extended to other scenarios involving aggregate constraints and seed data. It is noteworthy to also point out that in situations involving sample data that are a conditional distribution of the target, the weight assigned to an individual could also reflect that the measured seed data did not have a commensurate representative proportion of that particular individual when compared to the proportion in the target population. In essence the adequate population proportion of that individual is 'missing' from the sample seed. The difference in the alternative spatial micro-simulation (population synthesis) strategies lies in the numerical algorithm or probabilistic method adopted for estimating or calculating the weights assigned to individuals in the seed data. Typically, the seed sample measures each attribute for each individual forming a rich variable joint distribution which is limited only by being a sample, instead of the whole population.

On the other hand, the aggregate data (like the Census) is anonymized for confidentiality and the zonal attributes are aggregated to form a cross tabulation. This cross-tabulation creates the challenge of relating individuals within an age category say, to the same individual

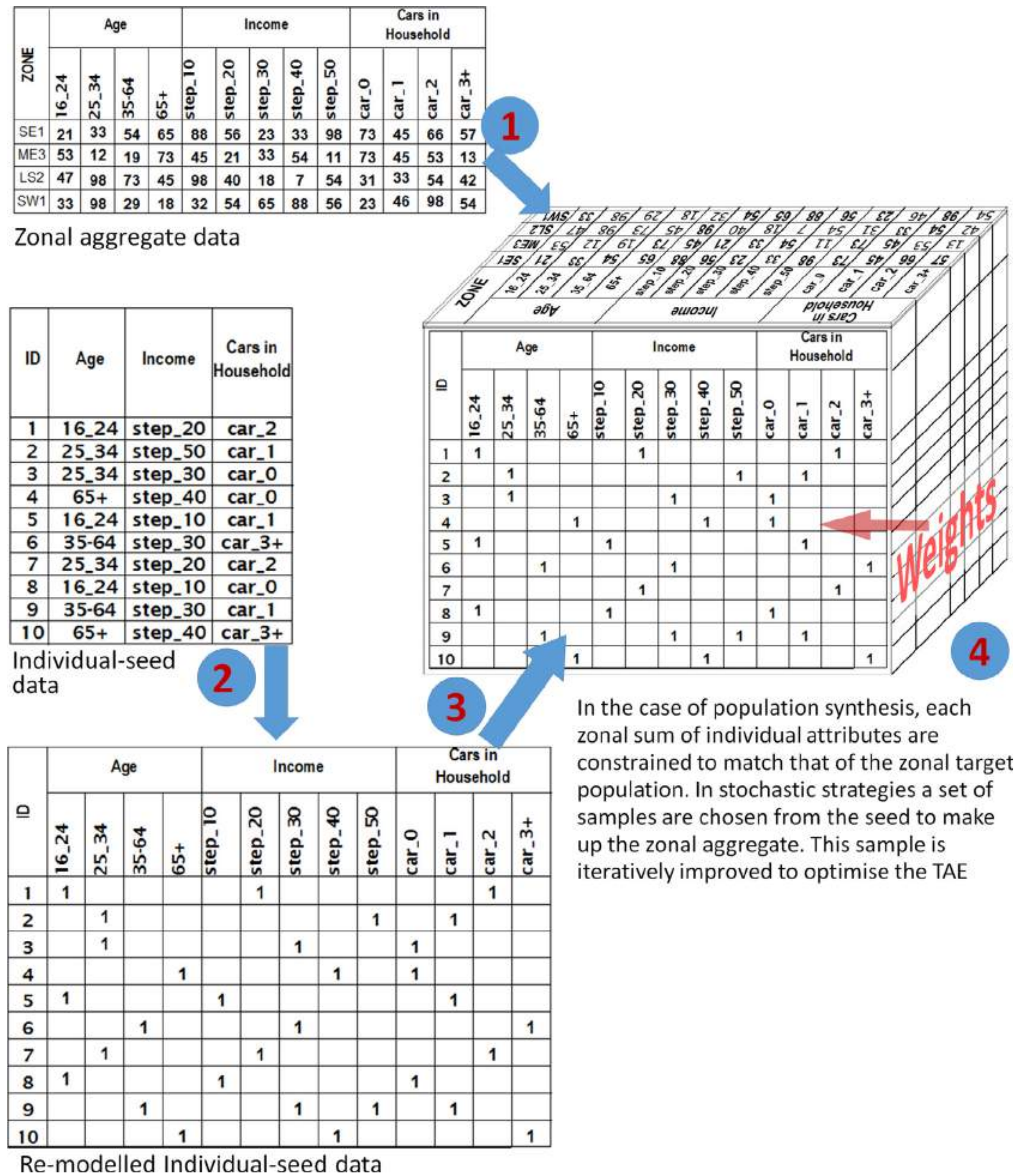


Fig. 2. | Process of remodelling the seed-data in spatial microsimulation.

within the gender, income and the other demographic attribute categories. The solution is to optimize the choice of individuals to minimize the difference between the marginal totals of the aggregate data and the synthesized population. In other words satisfying the condition that the micro-population created from the seed have margins adjusted and constrained to the aggregate margins, thus minimizing the residual between the aggregate and the synthesized population marginal.

Fig. 2 illustrates the procedure of spatial micro-simulation, showing the re-modelling process of the datasets used. The table of individual-level seed data (on the middle left side of Fig. 2) is converted into a binary data table (shown by the bottom left table). The binary table has attributes and categories now represented by data columns re-modelled such that they are commensurate with the columns within the aggregate zonal data (shown as the top left table). This concept illustrates the basis for comparison of the two (seed data and aggregate data) tables. Reconciliation of the seed and aggregate tables is depicted by the cubic array within Fig. 2 (on the right side). For each geographic zone, the seed is sampled to make up the population of the zone, and this initial sample is called the proposal distribution. The proposal distribution is optimised to yield the synthetic population for a zone.

In deterministic methods arithmetic fractions of the proposal distribution are iteratively improved to fit the aggregate constraints. In stochastic methods, random samples are taken with replacement from the seed data to improve the objective function (subject to a proposal distribution), until convergence to the target distribution. As a result deterministic strategies yield fractions of individuals, while stochastic procedures yield integer multiple counts of the individuals in the seed sample. Widely used deterministic strategies are reported in literature (Barthelemy, Suesse, Namazi-Rad & Barthelemy, 2016; Lovelace & Dumont, 2016), as well as stochastic strategies (Kavroudakis, 2015). For successful implementation of the deterministic and stochastic procedures, the same set of variables ought to exist within the seed and aggregate datasets (top left and bottom left tables in Fig. 2).

4. Merits of micro-simulation methods

The strategy in this paper is to explore the relative merits and behaviours of different deterministic and stochastic spatial microsimulation methodologies, highlighting the problems in practical implementation and advantages associated with the different strategies. This is a pre-cursor to practical implementation on the case study of West Yorkshire UK railways, for the first time simulating representative mobility behaviour of a population of railway passengers at micro-scale (i.e. individual/household levels). The case study illustrates how best to simulate a micro-population linking big data on rail trip-making with information on socio-demographic characteristics.

In assessing the controlled behaviour of the deterministic and stochastic micro-simulation strategies, a subset of the NRTS data (for West Yorkshire) made up of about 23,000 samples is used. There are a maximum of eight (8) variables for each individual in the pre-processed NRTS dataset, as such the aggregate constraints are formed by cross-tabulating and aggregating these variables forming sets of (1*D*), (2*D*), (3*D*) up to (8*D*) target constraints. The seed sample on the other hand is constructed by taking different random samples from the NRTS dataset (to reflect different sample ratios by taking more or less random samples, to reflect a conditional distribution (which is dissimilar to the target distribution) by sampling the upper or lower half of the dataset, and without replacement, etc.).

The NRTS dataset used for the test cases includes variables for passenger residence and destination, mode of commute and a number of other demographic attributes (age, gender, cars in household and household type, ethnicity and children in household). The NRTS data is zoned to geographies of Postcode Sector boundaries. The postcode geography in the UK was created for the purpose of disseminating postal mail. Within this geography, there are 124 Areas, 2987 Districts, 11,192 Sectors and about 2 million Units. As such, on average a Postcode Area will consist of 24 Districts, 90 Sectors, and 16,125 Units (each of about 15 addresses). To manage the computational demands of the spatial microsimulation algorithms, the NRTS which was originally zoned to Postcode Sector boundaries were re-zoned to larger Postcode Areas. As such, Postcode Sectors, originally 357 were converted to Postcode Areas numbering about 5. The re-zoning averts sparse data-frames which compromise the quality of the results and require special treatment (as discussed in this paper's case study).

As a consequence of re-zonation, remnants of some peripheral Postcode Sectors existed. For instance in a geographic location in the north west corner of the West Yorkshire county, a part sub-set of the Oldham Postcode Area (OL148, OL138, OL145 etc.) was captured and was included in the analysis. Similarly, other sub-sections of other Postcode Areas were captured, including Sheffield, York, Harrogate, Blackburn and Doncaster (S, YO, HG, BB and DN) respectively. Perhaps these might have been removed from the analysis, but they have however been included to replicate situations where a zone has a commensurately low number of counts. In effect, inclusion of these marginal Postcode Sectors enables an assessment of the sensitivity of the different spatial microsimulation strategies to nominally low seed counts.

This section investigates the impact on the results of four separate aspects of the microsimulation process. Each of the four investigative aspects consisted of several individual distinct runs of the microsimulation procedure using a Monte Carlo experiment (totalling over 500 runs to capture the full spectrum of results), detailed in Section 4.1 to Section 4.2. The objectives of each aspect are respectively:

1) to use a Monte Carlo experiment to investigate the effect of the number of constraints by increasing these from one through to seven (which is one less the total of eight variables).

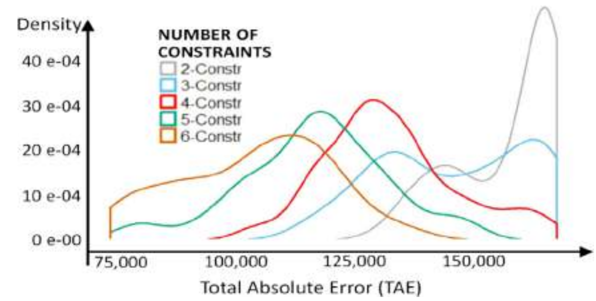


Fig. 3. | Variation in TAE with the number of constraints for the deterministic IPF spatial micro-simulation.

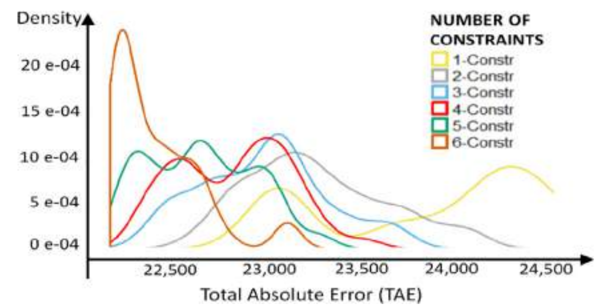


Fig. 4. | TAE from repeated random sets of a fixed number of constraint variables for simulated annealing (SA) spatial micro-simulation.

2) to ascertain ability to predict values of the non-constrained attributes by using a Monte Carlo experiment to compute the predictive accuracies of the methods for those variables not included as constraints.
3) to assess the effect of sample-ratio on simulated population by using a Monte Carlo experiment to apply different random sample ratios ranging from 0.05%, to 85%.
4) and to identify the influence of the nature of the conditional distribution of a seed sample by using a Monte Carlo experiment to recreate by sampling such scenarios where the seed data is increasingly structurally dissimilar to the target data.

4.1. Effect of number of constraints

The particular choice set of number of constraint variables would vary, as for instance there are $8P_3$ ways of choosing a set of three variables from eight options (assuming order is also important). To capture the full range of possible choices and thereby objectively establish the effect of number of constraint variables, a Monte Carlo sampling was implemented on the choice set of constraints, and on each sample occasion a distinct run of the microsimulation procedure took place. The densities of the *TAE*'s produced are displayed in Fig. 3 and Fig. 4. The density plots are normalized frequency distributions of the *TAE* values for each set of constraints. In the deterministic IPF, the scenario of 1 constraint yields a particularly high TAE which detracts the display, hence it has been excluded.

The results show that as the number of constraints increase, the *TAE* (across all constrained and unconstrained variable reduces as indicated by a drift of the density plots towards the origin as constraints increase. The deterministic methods have higher overall *TAE* values, as a full volume of the population is not generated whenever the seed sample is not fully reflective of the variety in the aggregate population. The stochastic strategies on the other hand produces a full population, with a broader range of results with lower *TAE* values, albeit yielding simulated results not reflective of the true distribution of the target population. These results may seem counter intuitive at first sight as reported in literature (Markham et al., 2017; Tanton & Edwards, 2012; Tanton & Vidyattama, 2010), as more constraints would imply a more

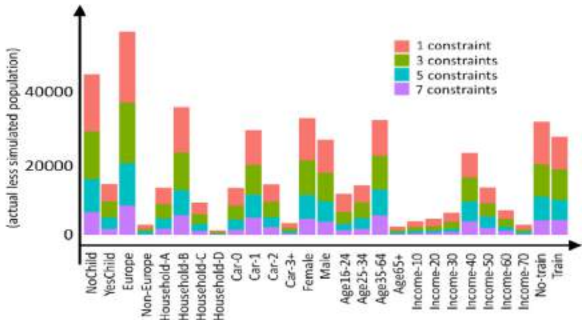


Fig. 5. | Total absolute error (TAE) for different number of constraints in the IPF deterministic spatial micro-simulation.

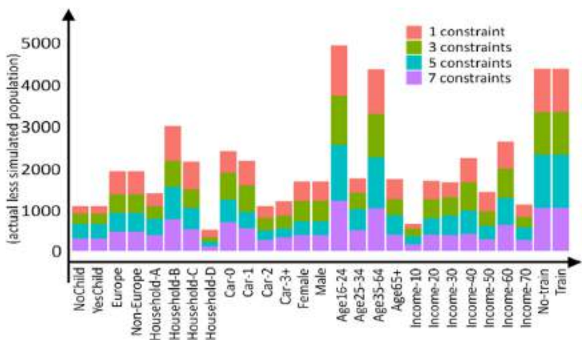


Fig. 6. | Discrepancy in the SA and actual simulated populations.

difficult set of constraints to fulfil, and the *TAE* typically adopted is the sum across constraint tables. However, provided the precautions highlighted in Fig. 2 are adhered to such that the sets of variable categories within the seed and aggregate match, the higher the number of categories would imply a provision for more consistency between the seed and aggregate data, thereby yielding lower TAE values.

4.2. Prediction of non-constrained attributes

The second experiment addresses the question: how well predicted are the values of those variables not included as constraints in the spatial micro-simulation? If a subset of the variables within NRTS is used for spatial micro-simulation, how well are the simulated zonal aggregates predicted for those variables not included in the set of aggregate constraints used in the micro-simulation procedure? In Fig. 5 and Fig. 6, 1 constraint refers to the categories within the first listed variable i.e. household children (with the two categories 'NoChild' and 'YesChild'). 3 constraints similarly refer to the categories within the first three variables of household children, ethnicity and household type. These categories are NoChild, YesChild, Europe, Non-Europe, Household-A, B, C and D). Similarly 5 constraints refers to the categories within the first five variables (on the horizontal axes of Fig. 5 and Fig. 6), i.e. household children, ethnicity, household type, cars and gender. A similarly reference is made for the case of 7 constraints. In Fig. 5 for the deterministic procedure, whilst the trend of the lines for the different number of constraints seems systematic, with higher constraint lines taking lower positions reflective of the lower *TAE* magnitudes for these lines, there are no systematic trends recorded for those variables not included as constraints.

For the stochastic procedure, it is observed that when the constrained and non-constrained variables are compared, the non-constrained ones are predicted with comparatively lower levels of accuracy. In Fig. 6, when only one variable is constrained (depicted by the first two orange bars), the errors are minimal for that constrained variable (in this case the household children variable). This is reflected in the first two red

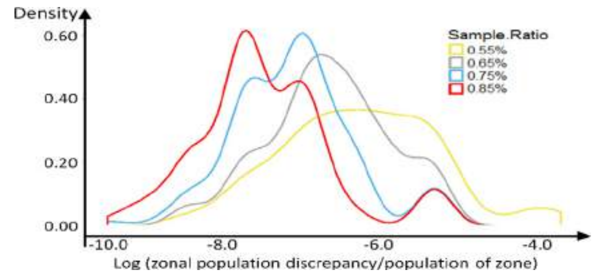


Fig. 7. | Effect of sample ratio on TAE estimates for IPF simulation.

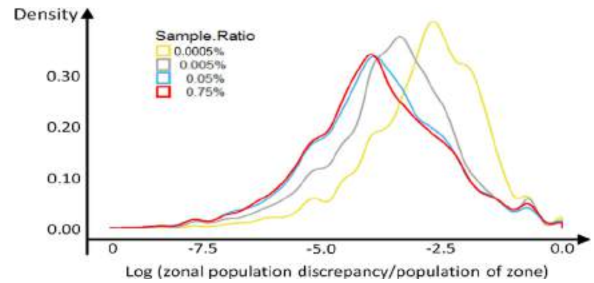


Fig. 8. | Effect of sample ratio on TAE estimates for SA simulation.

TAE bars having lowest values at locations between variables 'NoChild' to 'YesChild'. When three (3) constraints are adopted made up of household child, ethnicity and household cars, the *TAE's* are depicted by the green bars associated with these variable categories. This is reflected by the height of the green bars over the range of categories 'NoChild' to 'Household-D'. This trend is continued when there are five (5) and seven (7) constraint variables, reflecting in the blue and the purple TAE bars having lowest sizes at locations on the x-axis between categorical variables 'Car-0' to 'Male', and 'Income-10' to 'Income-70' respectively.

4.3. Effect of sample-ratio on simulation

A Monte Carlo sampling was implemented to choose various seed samples of fixed sample ratio to form the individual-level seed data for spatial micro-simulation. The procedure consisted of randomly selecting a sample with ratio v, ($0.05\% \leq v \leq 85\%$) from the full set of NRTS data, and repeating this for 250 times for each value of v, to capture and average out any variability due to the choice of particular individuals in the sample. On each occasion the difference between the simulated and actual populations (*TAE*) is computed, yielding the plots in Fig. 7 and Fig. 8. This is repeated for the deterministic and stochastic spatial micro-simulation strategies.

The *TAE* plot of Fig. 7 below shows that the accuracy of the simulated population from the deterministic method increases with sample ratio, indicated by a drift towards the left of the plots as sample ratio increases from 55% to 85%. The deterministic strategy is found to be highly susceptible to sampling ratios. The procedures fail whenever the sample ratios are lower than 25%, since at these values many of the lower population zones do not have adequate representation in the sample, reflecting where not enough samples were taken to represent zones. For the stochastic strategies, as the percentage of samples increases, Fig. 8 shows that the scatter in the *TAE* increases relative to the *TAE* scatter observed for the deterministic procedure. The *TAE* values in the stochastic procedure also show a reduction as the sample ratio is increased. The stochastic procedures are robust to low sample ratios with the procedures running successfully for the clipped NRTS dataset, for sample ratios as low as 0.05% (as seen in Fig. 8).

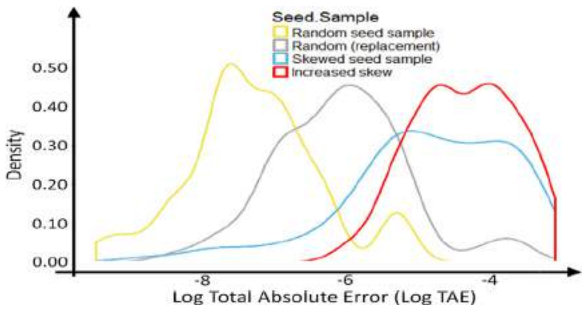


Fig. 9. | Effect of randomness of sample seed on simulated population TAE using a deterministic strategy.

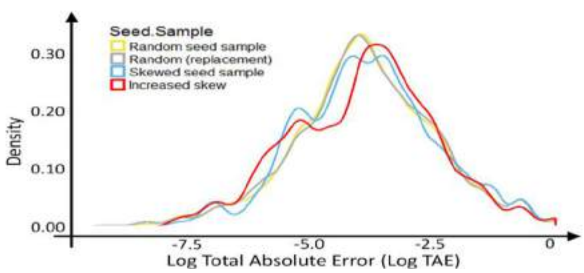


Fig. 10. | Effect of randomness of sample seed on simulated population TAE using the SA stochastic spatial micro-simulation.

4.4. *Influence of level of structural dissimilarity in seed sample*

The spatial micro-simulation process typically creates a simulated representative population by combining zonal aggregate data like the Census, with an individual-level survey like the NRTS or LENNON ticketing data. Traditionally it is assumed that the disparity in the datasets is normally distributed (Ireland & Kullback, 1968; Namazi-Rad, Mokhtarian & Perez, 2014). The robustness of the different deterministic and stochastic strategies are assessed, when for instance the seed sample is a structurally dissimilar representation of the population, typical of ‘big-data’ which are exhaustive within a specific coverage, and as such are not representative of the entire population. In addition, the effects of ‘not having enough’ sample data, (whereby the sample does not include enough information on all the zones) is assessed for both the deterministic and stochastic strategies.

A Monte Carlo experiment is conducted, sampling the seed from the NTRS data and then assessing the performance of the deterministic and stochastic strategies. The sensitivity of deterministic methods to choice of seed is depicted in Fig. 9 showing the seed progressing from a random sample representative of the wider population, to an increasingly non-representative sample achieved by sampling with replacement and then by selecting the first N individuals. As seen from Fig. 10, seeds that are better representative of the wider population produce consistently better *TAE* values, indicative of a more accurate simulated representative population. The stochastic procedure is less susceptible to the quality of the seed data. The *TAE* distribution depicted in Fig. 10 only nominally increases as the seed becomes less random, further buttressing the robustness of stochastic strategies to changes in the seed sample.

4.5. *Differences within deterministic and stochastic methods*

Reference has been made to the range of deterministic and stochastic strategies; however results are presented for just one of each of these strategies, i.e. the multi-iterative proportional filling (m-IPF) deterministic strategy (Barthelemy et al., 2016), and the simulated annealing

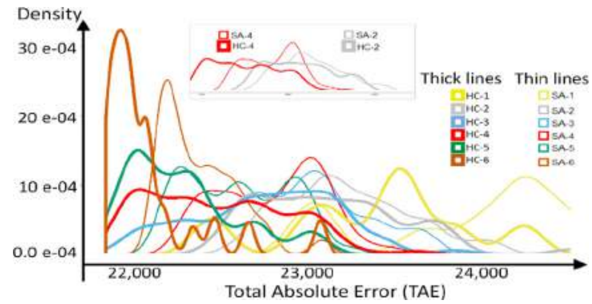


Fig. 11. | Comparison of hill-climbing (HC) and simulated-annealing (SA), both stochastic micro-simulation methods.

(SA) stochastic strategy (Kavroudakis, 2015). This is because these ones are now the state-of-the-art implementations of the two strategies. Other variants exist, for instance the least squares, Chi-squares, maximum likelihood deterministic methods, and the hill climbing stochastic procedure. These alternative methods show similar trends, but are less robust to the range of behavioural attributes investigated and hence not discussed in detail. For instance, the m-IPF, Chi-squared, least-squared and maximum likelihood methods when broadly compared revealed stability of the iterative proportional fitting, whilst the Chi squares, maximum likelihood and least squares methods did not converge and required over 500GB RAM and 66 h to run, when compared to extreme cases of the IPF which converged, requiring 136MGB RAM and 35 hrs on a 758 GB Arc3-HPC. Fig. 11 shows a comparison of the hill climbing (HC) and simulated annealing (SA) stochastic methods. Whilst the HC algorithm consistently produces more accurate simulated populations than the SA procedure, the HC strategies are subject to a high number of failures by converging to sub-optimal solutions. This phenomenon has been reported in literature (Williamson et al., 1993) and is associated with the definition of the optimization algorithm part of the HC procedure.

5. A case study of mobility on West Yorkshire railways

Having explored the relative merits of the different spatial microsimulation methodologies, the case study illustrates how best to simulate a micro-population linking big-data on rail trip making with information on socio-demographic characteristics. The case study combines the 2011 Census interaction data with the 2001/2004/2005 National Rail Travel Survey (NRTS), and the 2011 LENNON ticketing data to create the mobility behaviour of a population represented at micro-scale. The NRTS does not represent the same year as the Census (and LENNON), and as pointed out earlier in the paper, rail demand levels are likely to be markedly different in different years. Below we detail the basis for adopting the two datasets (2001/5 NRTS and 2011 Census) within the modelling framework of spatial microsimulation, despite being acquired in different years.

Our hypothesis was that disparate datasets like the 2001/5 NRTS and 2011 Census can be combined if they do not present ‘concept’ or ‘data’ drift within the model where they are used. We explain this by assessing the use of such datasets within a spatial **interaction** model (Clarke & Birkin, 2018), and then within a spatial **microsimulation** model (Odiari et al., 2021): A spatial interaction model will be of the form: $V_{ij} = P_i\, P_j \,/\, d_{ij}^{\beta}$, whereby V_{ij} is volume of spatial interaction, P_i is the population at the origin, P_j is the population at the destination, d_{ij} is the distance between locations i and j, and β is the decline in propensity to travel further distances. If the 2001/5 NRTS and 2011 Census are combined for use in such spatial interaction model, a change in volumes of passengers between the periods the datasets were measured would represents a ’concept drift’ (Žliobaitė, Pechenizkiy & Gama, 2016) and a passenger change in behaviour, resulting in a higher propensity to travel longer distances would represent a ’data drift’ (Hofer & Krempl, 2013).

This is the case because the dependant variable which is the volume of passengers would have changed, and the independent variable which is the distance travelled by passengers both would have changed between the use of the NRTS and Census data. As such, the NRTS and Census cannot be objectively combined for development of a conventional spatial interaction model.

On the other hand, a deterministic reweighting spatial microsimulation model will be of the form: $W_{i+1} = W_i(C_{ij} / S_{ij})$, whereby W_{i+1} represents a new weight for individual i , and W_i is the current weight for individual i, C_{ij} is element ij within the Census target table, S_{ij} is element ij within the NRTS seed table. The model is iteratively executed until a prescribed convergence. In this case there would be no concept or data drift, as neither properties of the dependant nor independent variables in the above spatial microsimulation model qualitatively change. This is the case since the range of attribute categories within the NRTS and the Census are the same. The modelling process aims to replicate the joint distribution of a target population subject to an objective function. As the 2001/5 NRTS and the 2011 Census have the same variable categories, replicating the Census population is limited to the choice of variable categories embedded in the NRTS. From this point of view, there is no concept or data drift.

This explanation is pertinent, forming the basis in this paper, for combining the two time-different NRTS and Census datasets within a spatial microsimulation model. The methodology facilitates replication of the NRTS seed to fit the distribution of a target Census data. Volumetric changes in a seed data are independent of the simulated target. Similarly, particular behavioural changes in the seed data do not affect the simulated target; more so as behavioural attributes of the seed do not form the dependant or independent attributes of interest. In summary, two datasets that are acquired at different times can be combined for use in analytics provided the structural difference in the two datasets does not present as a concept or data drift with respect to the model. This means that the use of either of the 2001/5 NRTS or 2011 Census datasets would yield the same result when applied to a microsimulation model. This is the case here as the NRTS and Census both have the same variable categories. However, the two datasets (2001/5 NRST and 2011 Census) would not be objectively combined in a spatial interaction model which has volume of passengers and distance travelled as variables. The two datasets in such a model would present as a concept and data drift. If either the 2001/5 NRTS seed or the 2011 Census target is used to replicate a population of specific joint distribution, the result is in principle the same. This is the case as the values of the features we define to form the micro-similation remain the same (De-Dios-Santos, 2020).

During the first spatial micro-simulation the Census is combined with the NRTS data based on shared variable attributes as illustrated in Fig. 12 (whereby the colour coded lines are used to distinguish sets of linked variables). For analysing mobility on the railways, it is essential that the distribution and identity of individuals in the simulated population be known at all stages of the procedure. The distribution of individuals is essential as origin and destination attributes combine to form a single unique individual attribute. The individual identity information refers to data ID within the NRTS dataset. For example, the first and second tuples of information in the NRTS would likely have ID of say NRTS-1 and NRTS-2 respectively. Such ID information enables the unconstrained attributes of an individual to be read from the original NRTS table and then appropriately attached within the simulated population. By so doing it is possible to compare for different microsimulation strategies, the volumes of individuals simulated and associated with those variables that were not used as constraints in the spatial microsimulation. Knowledge of individual ID is sustained by including ID information in the Census-NRTS spatial micro-simulation for example, but not imposing any constraints on this ID variable. That way identify information is carried through the spatial microsimulation procedure, and this concept is similarly applied in the second spatial micro-simulation that links in the variables of the LENNON ticketing information as shown in Fig. 12.

5.1. Data pre-processing for micro-scale mobility

As intimated earlier, the first data pre-processing stage involves rezoning the Census data from LSOA's boundaries into Postcode Sectors (or Areas) to enable comparison with the NRTS data and LENNON ticketing data which are geocoded as Postcodes. For data pertaining to interactions, the re-zoning requires special consideration in that re-zoning is performed for the origin variables and then repeated for the destination variables. Regular square fishnet mesh created across the region of interest (West Yorkshire) is used. This in-house procedure precludes the use of ONS lookup tables by dividing LSOA zones into minute fishnet squares which are subsequently integrated over the geography of the particular Postcode boundary. The accuracy of the process is as such decided by the granularity of the squares. In practice, the population proportion of an MSOA and Postcode Sector falling within each fishnet square are calculated.

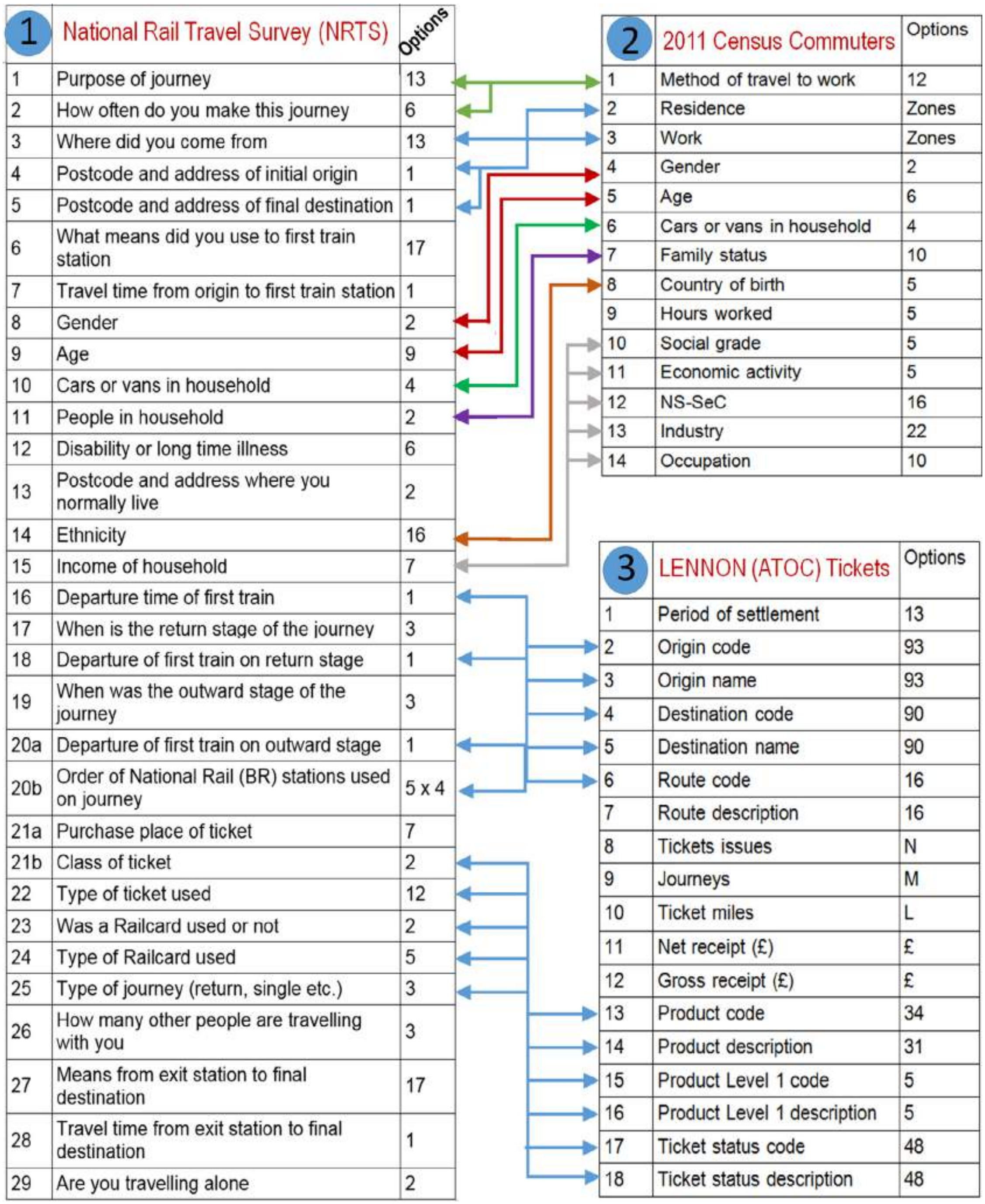
Coarse fishnet zonation is shown in Fig. 13 for the MSOA and Postcode Sectors boundaries associated with West Yorkshire. In practice the fishnets were finer (25 m squares were used in the case study to preclude MAUP[5] phenomena). 25 m was deemed adequate as the unusually small Postcode Sectors are LS155 and LS52 (~8000m^2) with rectangular shapes of about 50 m by 150 m, making a 25 m square fishnet adequate for re-zonation of West Yorkshire Postcode Sectors, bearing in mind also that the average Sector size is 6km^2.

The National Rail Travel Survey (NRTS) and the National Travel Survey (NTS) (Wardman, 2006) show about 60% of rail travel is attributed to commuting. Based on the NRTS Overview Report (DfT-UK, 2010), 77% of all passengers who commute by rail travel 5 or more days a week, whilst an additional 17% of all passengers who commute by rail travel 2–4 days a week. This amounts to a total of 94% of rail commuter travelling at least 2 times a week. The purpose of the journey (commute, business or leisure) is as such decided based on passengers rail travel frequency in addition to their activity at the destination (i.e. normal workplace, going to school/college, etc.), unless that destination is 'home' in which case the purpose is defined by the origin of the trip. These definitions are consistent with the NTS, and form the basis for the analysis of passenger commuting behaviour reported in the National Rail Travel Survey Overview Report (DfT-UK, 2010). These are adopted in this paper despite that the NRTS does not have an explicitly questionnaire on trip purpose.

A further data pre-processing stage concerned establishing a link between journey purposes (and journey frequency) in the NRTS and method of travel to work in the Census (as shown in Fig. 12). We define categories 'RC' and 'NRC' to respectively represent 'rail commuters' and 'not rail commuters' in the NRTS. We then define categories 'TC' and 'NTC' to respectively represent 'train commuters' and 'nom-train commuters' in the Census. We make this distinction in terminology as these categories relate to counts which are derived from different sources. The entire population within the NRTS would fall into either 'RC' or 'NRC', and similarly the entire UK population within the Census would fall into either 'TC' or 'NTC'. Essentially then, 'TC' represents the Census population who indicated that they commute to work by rail, and 'NTC' represents everyone else including those who commute to work by other modes and this does not preclude those who use the rail for other purposes.

As mentioned earlier, within the NRTS, passenger journey purpose and train journey frequency in a week would enable the passenger to be categorised into commuter by train ("RC") if a passenger states so and by definition makes the commute journey up to thrice a week. The only other alternative category would be non-commuters by train ("NRC"),

[5] MAUP is the modified area unit problem is the fallacy whereby the result of data aggregation is dependent on the mapmakers' definition of the geography boundaries. This phenomenon can be alleviated by using point based measures or offsetting by size attributes of the area.



1	National Rail Travel Survey (NRTS)	Options
1	Purpose of journey	13
2	How often do you make this journey	6
3	Where did you come from	13
4	Postcode and address of initial origin	1
5	Postcode and address of final destination	1
6	What means did you use to first train station	17
7	Travel time from origin to first train station	1
8	Gender	2
9	Age	9
10	Cars or vans in household	4
11	People in household	2
12	Disability or long time illness	6
13	Postcode and address where you normally live	2
14	Ethnicity	16
15	Income of household	7
16	Departure time of first train	1
17	When is the return stage of the journey	3
18	Departure of first train on return stage	1
19	When was the outward stage of the journey	3
20a	Departure of first train on outward stage	1
20b	Order of National Rail (BR) stations used on journey	5 x 4
21a	Purchase place of ticket	7
21b	Class of ticket	2
22	Type of ticket used	12
23	Was a Railcard used or not	2
24	Type of Railcard used	5
25	Type of journey (return, single etc.)	3
26	How many other people are travelling with you	3
27	Means from exit station to final destination	17
28	Travel time from exit station to final destination	1
29	Are you travelling alone	2

2	2011 Census Commuters	Options
1	Method of travel to work	12
2	Residence	Zones
3	Work	Zones
4	Gender	2
5	Age	6
6	Cars or vans in household	4
7	Family status	10
8	Country of birth	5
9	Hours worked	5
10	Social grade	5
11	Economic activity	5
12	NS-SeC	16
13	Industry	22
14	Occupation	10

3	LENNON (ATOC) Tickets	Options
1	Period of settlement	13
2	Origin code	93
3	Origin name	93
4	Destination code	90
5	Destination name	90
6	Route code	16
7	Route description	16
8	Tickets issues	N
9	Journeys	M
10	Ticket miles	L
11	Net receipt (£)	£
12	Gross receipt (£)	£
13	Product code	34
14	Product description	31
15	Product Level 1 code	5
16	Product Level 1 description	5
17	Ticket status code	48
18	Ticket status description	48

Fig. 12. | Relational table for the variables from NRTS, Census and LENNON ticket data.

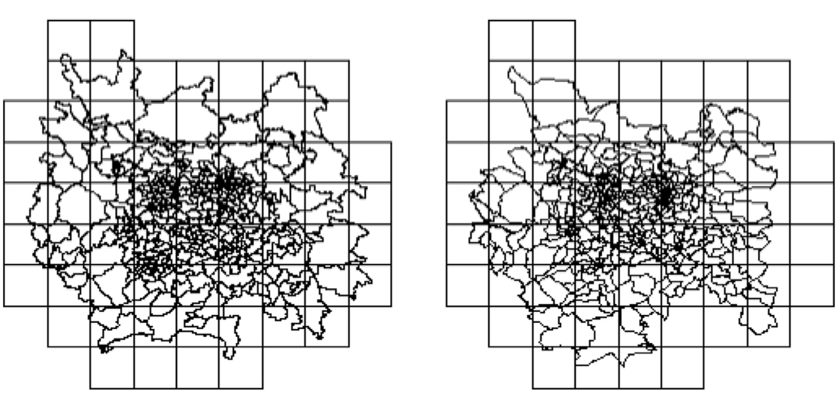


Fig. 13. | Coarse mesh zonation for MSOA's and Postcode Sectors within West Yorkshire UK.

Table 1
Regression results between Office of National statistics (ONS) Small Area Income Estimates against a range of 2011 Census interaction socio-demographic attributes.

Attribute	AIC	Deviance/DoF	R^2 value	Adjusted R^2	p-value
Social grade	8391.9	8.84 $E+10$	0.8347	0.8324	2.2E-16
Activity	8703.8	25.09 $E+10$	0.6965	0.6923	2.2E-16
NS-Sec class	8447.3	10.31 $E+10$	0.8796	0.8737	2.2E-16
Industry	8476.6	11.12 $E+10$	0.8733	0.8637	2.2E-16
Occupation	8354.1	7.66 $E+10$	0.8585	0.8541	2.2E-16

Source: Regression parameters from a Generalized Linear Model (GLM) and an LM model.

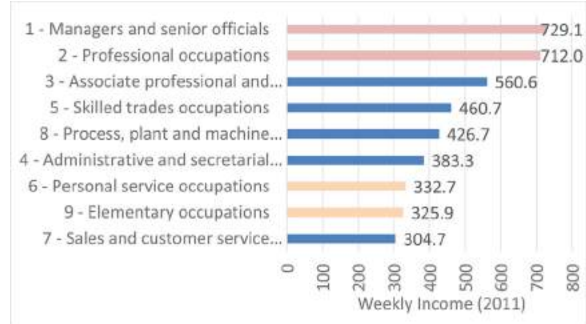


Fig. 14. | Relationship between Income and Occupation categories utilizing the 2011 UK Census.

made up of all the other passengers that do not fall in the "RC" category. The Census in turn has information on method of travel to work, and although there are several modes of travel to work, these can broadly be grouped into commute by train ("TC") and every other mode of travel would then become by definition the non-commute by train ("NTC"). In a proportional sense 'TC' and 'NTC' add up to one, forming the entire UK Census population of which the NRTS is a conditional distribution (i.e. a sub-set). The NRTS as a representative survey and as such can be expanded thus forming a comprehensive (100%) of the UK population who make use of the railways (trains). If that was the case (i.e. 100% expansion), we observe that then counts 'RC' and 'TC' would be exactly the same, and they both represent the same conditional distribution of train commuters. This strategy forms the basis of creating a link between the NRTS and the Census, to complements the more obvious links shown in the relational table in Fig. 13.

In spatial microsimulation, the sample seed is replicated to fit the volume and probability distribution of the target. If the seed has age categories say 11–30yrs, 31–50yrs, 51–70yrs etc., these are essentially multiplied by weights to match the volume and distribution of the target population. The resulting simulated population would also consist of exact same age categories 11–30yrs, 31–50yrs, 51–70yrs etc. A person described as a rail commuter (i.e. 'RC') within the NRTS, could at another time also make a non-commute trip by rail. However, they are categorised as 'RC' within the NRTS and by definition are also 'TC' within the Census. As such, 'RC' and 'TC' are mutually inclusive, and by implication 'NRC' and 'NTC' are similarly mutually inclusive. This forms the basis for relating 'RC' to 'TC' and similarly relating 'NRC' to 'NTC', and in fact adopting the nomenclature 'TC' and 'NTC' within both the NRTS and the Census. During spatial microsimulation the NRTS population within the categories 'RC' and 'NRC' are replicated respectively to yield 'TC' and 'NTC'. For brevity we have simply adopted the use of 'TC' and 'NTC', just like in the example of the age categories given above where we did not distinguish between the 11–30yrs, 31–50yrs, etc. within the NRTS and the categories 11–30yrs, 31–50yrs, etc. within the Census.

5.2. Relationship between income and occupation

Another important pre-processing feature is that we have exploited the relational structure of the dataset attributes in Fig. 12 to derive a disaggregated 'quasi-income' classification for the Census. From the range of variables: 'social grade', 'economic activity', 'NS-Sec', and 'industry' and 'occupation', we check the variable that regresses best with income from the 2011 ONS Small Area Income Estimates (Henretty, 2011/12). It is found that 'occupation' relates best with the NRTS income, such that Census 'occupation' can be used as a substitute disaggregated 'quasi-income' variable. The procedure to achieve the 'quasi-income' variable is that 'social grade', 'economic activity', 'NS-Sec', and 'industry' and 'occupation' variables aggregated from the 2011 Census interaction data (UKDS, 2011) are separately regressed against (ONS, 2016). The results from regression are shown in Table 1 for the variables considered.

Occupation' was found to relate best to the average zonal weekly income, having one of the highest R^2, the lowest AIC (Akaike, 1987), and having the most number of levels within the variable with statistically significant p-values. This formed the basis for combining categories within the occupation variable to inform an estimate of income. The 'occupation' variable also had the added advantage of having only nine variables requiring reconciliation with the seven income categories. The 'NS-Sec' and 'Industry' which have commensurate R^2 values have 15 and 21 variables, making them more difficult to reconcile with the seven income categories. As such, occupation variable was deemed best related, resulting in the classification shown in Fig. 14, yielding nine Census occupation categories (reduced to seven) and commensurate with seven NRTS income categories.

The blue coloured bars represent a unique occupation bracket. The alternative coloured bars represent groups of occupation categories that are combined into one new occupation category. For example, the personal services and the elementary occupations have been combined into one income bracket, just as the managers and senior officials combined with the professional occupations to form the highest income bracket. As mentioned earlier, this enables the Census occupation categories with seven categories to be related by proxy to the seven NRTS income categories. The map below in Fig. 15 below validates the combinations derived as the income distributions are similar when produced from the small area income estimates and when derived from occupations.

5.3. Microsimulation of passengers in spatial interaction

Another practical consideration is that each of the individuals (say of age25–34 and associated aggregate attribute) are in mobility (by spatially interacting between an origin and destination). As such the individuals age attribute (age25-34 for instance) is associated with a unique origin (out of the N many origins) and a unique destination (out of M destinations). Additional variability is as such inherently introduced to that ag25–34 category due to the association with N origins and M destinations. In essence the single attribute category ag25–34 now has N by M potential variations to it, and so also does all the other attributes and their categories. This multiplicity yields a dataset of high dimensionality, in this case by N by M times. Such increases in granularity in the aggregate dataset requires a commensurate increase in volume of the individual-level seed in order to sustain integrity of the solution (calling for a need for big data). The individual-level seed is in effect reduced in sample ratio by N by M times, commensurately affecting the accuracy and precision of the results due to effectively reduced sample ratios.

A further issue arising from an increased variability due to spatial interactions, is that the number of Census variable categories (~2192) may not be the same as the number of variable categories in the individual-level seed (~1351), indicating that the survey does not have enough data, as the seed sample only represented 1351 variables within the Census. For example, an NRTS variable category LS-NTC-BB which represents a passenger who has the behaviour of not commuting by train (NTC), while travelling between Leeds (LS) and Blackburn (BB). Had the problem not involved spatial interaction and the micro-simulation

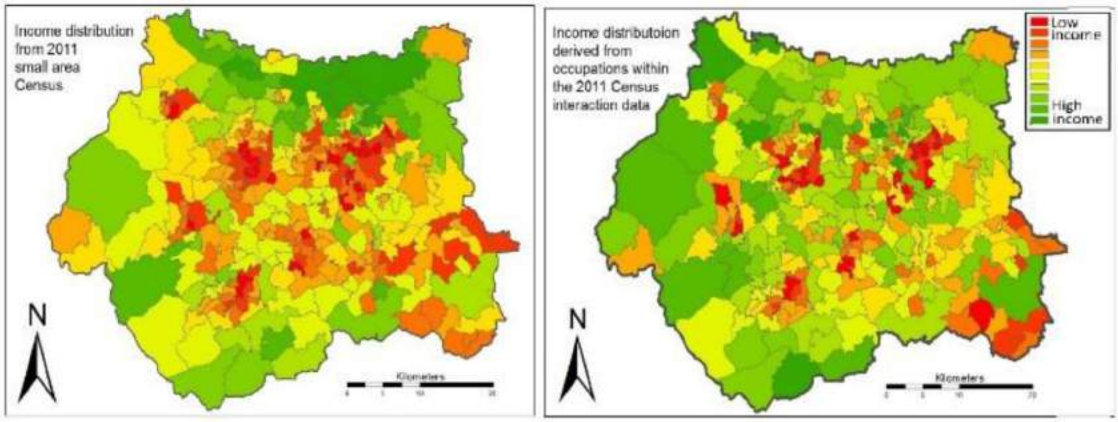


Fig. 15. | Distribution of quasi-income from Census and income from NRTS for West Yorkshire County.

of resulting origin-destination flows (with the complication of associating each individual attribute to an origin and a destination), then the variable categories would be NTC in both the Census and NRTS, and would as such have been sufficient for identification purposes. Since interaction is involved however, the seed sample would have to include a measure of not just NTC, but also of NTC associated with LS and BB. This subtlety highlights the particular advantage of 'big data' in creating the requisite data volume in spatial micro-simulation of interaction phenomena.

The deterministic spatial micro-simulation strategy copes with insufficient (non-observed) sample seed by synthesizing lower population volumes (associated with when the seed does not have the variable categories to match the aggregate). The stochastic strategy under these circumstances creates a full sub-optimal population. In some instances (as recorded in the 2004 NRTS compared with the 2011 Census), a number of individual flows were not captured in the Census. Under these circumstances it was appropriate to remove such data values from the NRTS, as the Census was the reference aggregate dataset.

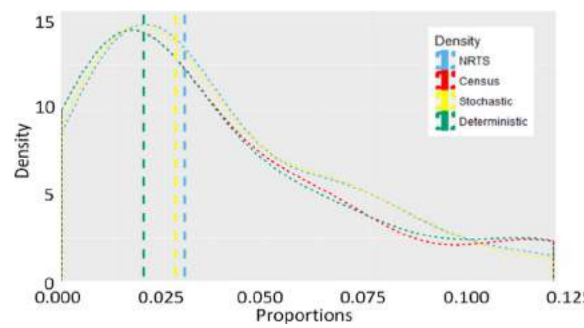


Fig. 16. | Distribution of population attributes for NRTS, Census and populations simulated by stochastic and deterministic methods (the vertical median lines are also indicated).

5.4. Linking census and NRTS data

The 2011 Census interaction data measures area of usual residence by workplace for a number of separate socio-demographic attributes, see Fig. 12. Linking this Census with the NRTS variables enables the interaction between the separate socio-demographic attributes to be established, creating representative mobility behaviour of a population portrayed at micro-scale with a rich set of attributes. Traditional spatial micro-simulation strategies for linking and combining datasets are typically premised on the seed being representative of the aggregate population, requiring similar distributions between the datasets. The NRTS distribution is a subset of the Census, derived by conditioning on 'travel by rail' variable (i.e. 'NTC' and 'TC'). As such, for validation purposes the resulting simulated populations created by the stochastic and deterministic strategies are assessed to see which one better reflects the distribution of the target Census population.

The R-script for implementation of spatial microsimulation for both the deterministic and stochastic strategies is included in the data file associated with this paper. The results presented in Fig. 16 are crucial, and illustrates that the deterministic m-IPF strategy produces a synthetic population with similar distribution (and median lines) to the target Census. The stochastic strategy on the other hand creates a simulated population distribution (and median line) similar to the NRTS sample seed, indicative that the proposal distribution from a seed that is structurally dissimilar to the target does not evolve to the target Census distribution during the stochastic spatial micro-simulation process. The deterministic strategy is as such preferred for use in spatial micro-simulation when the seed sample is a structurally dissimilar non-representative random sample of the target population.

5.5. Linking-in LENNON ticketing data

Once the Census interaction data and NRTS are combined to create a synthetic population, the challenge then lies in linking-in the LENNON ticketing data. To curtail the computer memory requirements during the first spatial micro-simulation, only the relevant variables in the NRTS data where included (these are variables indicated in the top half of the NRTS table in Fig. 12. To enable a coupling to the LENNON tickets, those NRTS variables in the bottom half of the NRTS table in Fig. 12 which relate to the LENNON data have to be re-attached to that simulated population created by the first spatial micro-simulation. The attachment is achieved by including the identity (Ind-ID) information for each seed sample in the NRTS dataset, during the spatial-microsimulation. Although the identity is included as a seed variable, it is not constrained by the target aggregate. That way the simulated NRTS-Census data includes the distribution of the individual identity (Ind-ID) within the spatial micro-population. (The R script implementation of this is available on request).

The m-IPF deterministic spatial micro-simulation strategy has been adopted as this has been shown in the last section (Fig. 16) to be suitable for combining datasets when the seed is non-representative by not having the same distribution as the target data. The results shown in Fig. 17 show the distribution of the simulated NRTS-Census-LENNON mobility population, for two cases: first when the simulated (NRTS-Census combined with LENNON) population is sampled with probability distribution equal to the spatial micro-simulation weights. As seen from the top two plots, the population created has a distribution of variable cate-

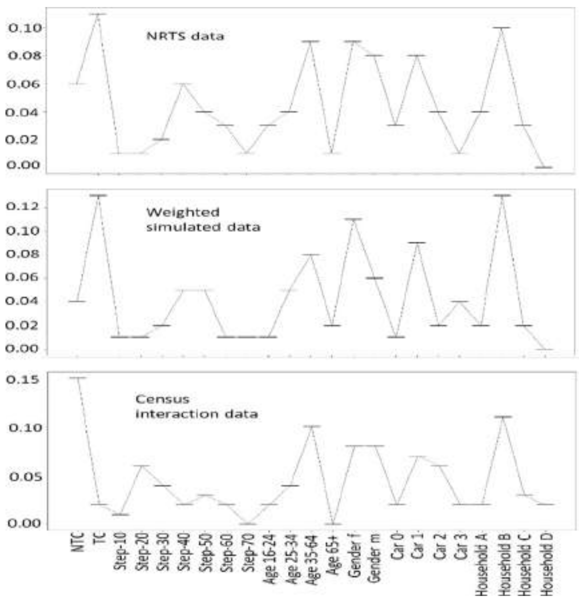


Fig. 17. | Variable categories for NRTS, simulated population and Census showing similarities in distribution of variable categories.

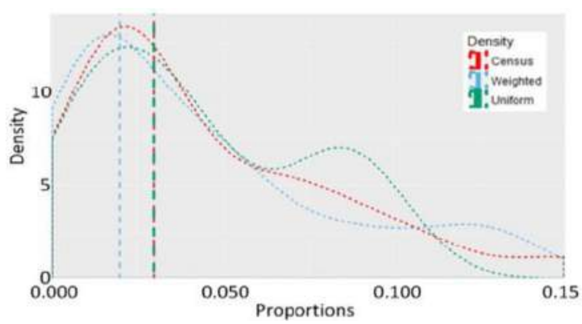


Fig. 18. | Density of variables of simulated population (weighted), uniformly sampled, and Census populations.

gories similar to the NRTS. In particular notice that the NTC is much lower than the TC typical of a population of railway passengers where there are more commuters (TC) than those who do not commute by train (NTC). The lower plot (third from top in Fig. 17) of the distribution of the Census variables shows a noticeable distinction and there are much higher values of NTC than TC, reflective of the wider population where typically only 5% of the population commute by train (TC) whilst the rest commute by alternative modes (NTC).

A uniform (non-weighted[6]) sample of simulated population produces a micro-population with variable distribution akin to that of the wider Census population. This is illustrated in the density plot of Fig. 18 with the median of the uniformly sampled population being similar to that of the Census, but distinct from population derived using the simulation weights. The results produced validates the m-IPF spatial micro-simulation methodology as the simulated population replicates the railways population and then the wider population dependant on whether systematic weighted sampling or uniform sampling is adopted. Representative populations of rail passengers that can be fed through a logistical railways system are created by the weighted systematic sampling, making up a volume equal to the number of LENNON tickets sold.

[6] The weights derived from the second spatial micro-simulation represent probabilities, such that a random sample taken from the simulated population using the probability distribution would yield the population of rail passengers (with a distribution akin to the NRTS), whilst a sample taken assuming uniform probability for each simulated population would yield the population of passengers who commute and those who do not commute by rail (with a distribution akin to the Census interaction).

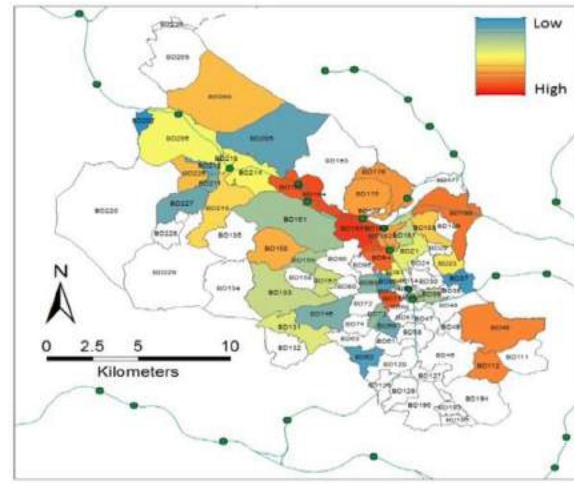


Fig. 19. | Population in the BD Postcode Area who use the train service and are in closer proximity to the train lines as seen in the map.

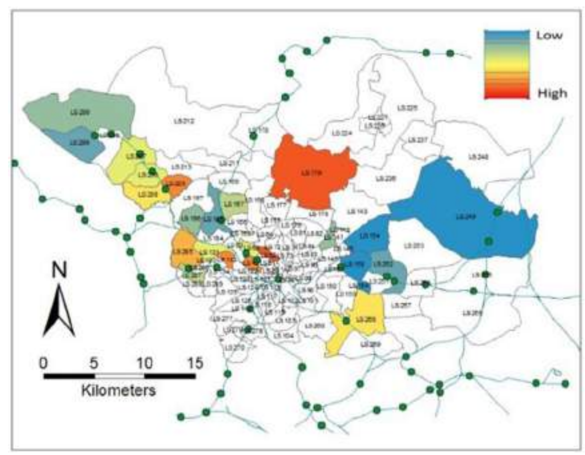


Fig. 20. | Granular query results for Postcode Sectors in the LS Postcode Area, illustrating results from spatial micro-simulation.

Validation of cross-tabulated micro-data created

Typical cross-tabulations resulting from the micro-population created are shown in the maps of Fig. 19 and Fig. 20 below. Prior to spatial micro-simulation, only a sub-set i.e. a sample of cross-tabulated data is available as the seed. The aggregate data only reveals a global cross tabulation limited to only three variables from a range of socio-demographic Census attributes. Spatial micro-simulation combines the various attributes in the disparate datasets, and produces a granular cross-tabulation of the variables. The map in Fig. 19 for example is the result of a query on the cross tabulated micro-population, showing the proportion of people residing in Postcode Sectors in Bradford, commute to work by rail, have a Rail card, regularly buy a return ticket, travel within 15 miles of their typical residence, earn between £17.5 – £35k (at 2011 rates) per annum, and live in a household with no car and no children. It is seen that Postcode Sectors in the vicinity of the railways stations (the network), expectedly tend to have a higher number of passengers as they have easier access to the railways network. This is seen in the left hand side Sectors within the Area, and consist of those passengers who are more likely to use the train based on the proximity and access to rail service from the usual residence.

Another result made feasible by the availability of the cross-tabulated micro-population is shown in Fig. 19, showing the proportion of people who reside in Postcode Sectors in Leeds (LS), who do not commute to work by rail (NTC), and live in a household with three or more cars (Car-3+). The results are intuitive and this provides some external validation of the micro-simulated population. These passengers use the train not-for-commute purposes (NTC), and the high volume of passengers simulated for the LS179 Sector near the middle of the map (Fig. 20) are perhaps reflective of an affluent neighbourhood, occupied by households with 3 or more cars (Car-3+), and who do not commute by train (NTC).

6. Synopsis and discussion

This paper contains novel analysis detailing the relative merits of different methodologies for spatial microsimulation. Then by using a case study to simulate a micro-population linking consumer data on rail trip-making with information on socio-demographic characteristics, the robustness of the methodologies developed are tested for application to big-data from a disparate source.

The assessment of the behaviour of deterministic and stochastic strategies under different circumstances enables an informed choice of spatial micro-simulation method for specific applications. The results review previously available research that indicates that the more variables used in constraining a spatial microsimulation procedure, the worse the results. This is the first time the Monte Carlo technique is used to select problem scenarios for the spatial micro-simulation. By so doing, the full range of scenarios are included in the analysis, producing robust and conclusive results that reflect better the *TAE* distribution range of possible solutions. The Monte Carlo selection process is quite distinct from Monte Carlo procedures applied within some spatial microsimulation procedures. Stochastic spatial micro-simulation methods held promise because of the use of MCMC type algorithms. However, the results from the SA and HC indicate that the exploratory and optimization routines used therein need further development. For cases where the seed data is a conditional distribution and non-representative random sample of the target distribution, the proposal densities in stochastic spatial micro-simulation methods have not converged to the target distribution, despite the definition of TAE as the objective function. The internal validation of the procedures is implied by the *TAE* values derived; however, this validation heavily impinges on the data pre-processing stage, whereby the variable categories in the seed and aggregate are required to match.

This paper marks the first case study of the application of spatial micro-simulation to the spatial interaction phenomena within the railways. The particular difficulties of dealing with non-representative railways ticketing consumer datasets (big-data) have been addressed. Such data are a conditional distribution of the wider Census population and as such do not have the distribution of a representative random sample of the population, thereby presenting challenges in use for spatial microsimulation. The high dimensionality and cross-variability in passenger attributes can only be achieved by spatial micro-simulation, thus enabling the Census demographic attributes to be combined with network variables within the NRTS and LENNON databases, showing previously unavailable variability in passenger attributes. External validation is indicated from the intuitive results of queries on the synthetic population, which shows that passengers residing or working in the vicinity of the rail stations inherently have a higher propensity of using the railways.

A limitation of the case study presented in this paper is that passenger flows considered are simply those emanating from and ending in West Yorkshire. As such interregional flows are excluded, implying that about 60% of actual flows have been analysed. This may affect some interesting boundary phenomena like rail-heading, whereby passengers travel further afield to access the rail service across a rail-zone boundary, in order to restrict travel to one zone and thereby benefit from cheaper within-zone fares. The micro-simulation developed in this paper is applied to rail passengers who are in spatial interaction between origin and destination points. Conventional microsimulation creates a synthetic population that is fixed in space by being associated with just one location. Hence conventional microsimulation re-creates households, zone populations, shoppers, etc. In this paper however, we are creating a synthetic population interacting (by mobility) between a journey origin and destination. These result in our use of the term 'mobility interaction' as the simulated synthetic population created are in mobility by virtue of spatial interaction between origin and destination points. The consequence of this mobility interaction is to effectively increase the dimensionality of the sample seed which is disaggregation into origin-destination pairs. The implication of this for microsimulation is a requirement for a commensurate increase in sample seed volume to maintain the variability of the simulated population and preclude the simulation of clusters of individuals. This augurs well for the advantages of increasingly available volumes of big data (e. g. mobile phone data on mobility flows) which when used as seeds in interaction analysis; resolve such dimensionality reduction issues and further enables the exploration of time-series cross-section (TSCS) phenomena associated with the nature of the big data phenomena.

There are current limitations on the scalability of current implementation of m-IPF strategies. This mainly results from an increase in RAM requirement as the number of covariates increase in spatial microsimulation. The particular implementation presented in the case study in this manuscript requires two repeats of the m-IPF procedure, the first between the NRTS and Census, and the second to incorporate the LENNON ticketing data. In order to link the results from each step, ID information on each simulated passenger has to be incorporated, thereby increasing the memory requirements for the solution. A further limitation is due to the R-Studio solution platform adopted which limits the size of data tables to 2ˆ31. Parallel computing strategies have the potential to limit some of these constraints; however these have not yet been explored in this research.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Struggling with inertia: Regime barriers opposing planning and implementation of urban ropeways

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A B S T R A C T

Urban ropeways are a novel option to extend public transport. Technically suited to a range of use cases, urban ropeways have not yet been implemented as part of a public transport solution in Germany. Rather than the technology itself, specific routines and practices of the public transport service regime have been identified as main challenges. Building on series of expert workshops conducted in 2017 (23 participants in total), we look beyond technical characteristics and study the preparedness of service regime actors regarding processes and routines as well as structural factors of inertia. Generally, we observe an increasing openness towards reflecting about integrating urban ropeways into public transport. However, misalignment is still clearly visible: First, lacking experiences with this new option at the local level imply a time-consuming need for information and clarification. Second, and more fundamentally, the suitability of established planning routines is questioned, which is critical because the dense regulatory framework existing in Germany currently requires these. We discuss the implications at the level of the service regime and the relevance of these structural mechanisms in considering technological potentials in a mobility transition more generally.

1. Introduction

During the last decade, ropeway[1] technology has increasingly been suggested as one suitable option to extend urban public transport networks (Alshalalfah et al., 2014; Clément-Werny & Schneider, 2012; Monheim et al., 2010), and a number of already existing installations worldwide demonstrate the capabilities of the technology. Some inherent characteristics make urban ropeways a promising option in public transport: they can help overcome topographical or other physical barriers with a system that is associated with fewer financial resources compared to conventional public transport technologies under similar condition (e.g. tunnels or bridges needed), and they promise faster implementation.

Ropeway technology comprises different options ranging from aerial tramway systems with only one or two bigger cabins using a fixed timetable (transport capacity depending on route length and the resulting minimum trip intervals) to detachable gondola systems with varying cabin capacities and cabin headways using continuous operation (maximum transport capacity: up to 6000 people per hour and direction) (Alshalalfah et al., 2014; Alshalalfah et al., 2012). Transport capacities can therefore be adjusted to the requirements of a specific route and are in the range of bus services or simple tram systems, but below light rail or rapid transit systems. Generally, ropeways use established technology which is extensively used in mountainous regions and at skiing destinations in particular, predominantly implying a touristic focus that comes with its own actor constellations and routines. However, there are still ongoing technological developments, particularly considering improvements for urban applications. For example, Težak et al. (2016) suggest new station layouts to further increase transport capacities, and a number of approaches consider combining conventional route sections (using carrying ropes) with complementing technologies, particularly rail-bound sections (Kairos gGmbH, 2016) or autonomous shuttle carriers (RWTH Aachen, 2020).

Urban ropeways are no silver bullet for urban transport problems or a substitute for established public transport technology. Rather, urban ropeways draw their potential from a range of situations where conventional modes regularly reach their limits (Monheim et al., 2010; Reichenbach & Puhe, 2018). Typical situations include overcoming physical barriers (hills, rivers, motorways, etc.), connecting major points of interest as well as peripheral sites to public transport nodes, relieving overcrowded routes in existing public transport, closing gaps in existing networks, or a combination of these.

Despite the technological potentials, however, even in potentially suitable situations urban ropeways are not yet routinely considered as an option in public transport planning, particularly not in Europe and,

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[1] Alternative terms with varying usage include ‘cable cars’, ‘aerial tramways’ or ‘gondolas’, partly referring to specific sub-types of the technology. Funicular railways are a related technology, but are not discussed in this article.

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more specifically, in Germany. Urban ropeway projects have been or are still discussed in a growing number of German cities, but until now, none of these projects has been actually implemented as a fully integrated public transport service (Reichenbach & Puhe, 2018). The few ropeway installations that actually operate in German cities have a clearly identifiable touristic focus (e.g. Koblenz, Berlin), a few more recent projects come with a clear public transport focus but are still at the planning stage (e.g. Bonn, Stuttgart, Munich).

As documented in a recent review by Tiessler et al. (2020), the scientific literature on urban ropeways is also still rather limited. For example, uncertainties and open questions relate to the fields of construction and operation costs (Težak et al., 2016), legal assessments and planning procedures (Stennecken & Neumann, 2016), or the integration of urban ropeways into transport demand modelling (Hofer et al., 2016; Reichenbach et al., 2017). Considerations revolving around technological aspects of urban ropeway technology must, however, be complemented by further analyses to actually deliver an understanding of the technology's innovation process as a whole. In this paper we seek to contribute to a more detailed understanding of whether and how relevant local actors responsible for the planning process struggle with the new options offered by urban ropeway technology. We address professional actors' perceptions and expectations with regard to urban ropeways as well as concrete factors of inertia in the service regime.

The relevance of this perspective lies not only in understanding the prospects for urban ropeways as an interest in itself, but also in illustrating typical challenges of the sector in dealing with innovative public transport solutions in a broader sense. Considering the rising public debate around a mobility transition (driven by considering both the transport sector's carbon footprint and local burdens of dense individual motor traffic) it is of crucial importance to understand the ability of public transport to handle the aspired network and service extensions. Trying to do so, the complex interplay of actors and routines in the mobility system calls for an integrated perspective that considers the interplay between technologies, industries, policies, user preferences, social norms, etc. (Geels, 2012). In a similar line, Docherty et al. (2018) call for special attention to the 'how' of managing the transition and to broaden perspectives beyond policy objectives and technological solutions. While technologies from sharing services to vehicle automation attract huge public attention, most experts agree that conventional public transport will remain an important backbone and should receive appropriate attention (cf. e.g. International Transport Forum, 2015 , 2017) – with urban ropeways being one potential piece of the puzzle.

The consideration of complex institutional contexts is the reason for focusing on a single country. We are aware that, from a technology perspective, the most prominent international examples of urban ropeway applications relate to Southern America. The institutional setting though is not readily comparable to the German context with its specific combination of regulatory framework conditions, urban planning routines, existing public transport networks, actor constellations, etc.

1.1. Research goal: understanding regime barriers for urban ropeways

In this article, we address both professional actors' general views on urban ropeways and stabilizing factors embedded in current regime practices. We conduct our analysis along the following guiding questions:

- How do professional actors from the public transport service regime at the local level perceive potentials for the application of urban ropeways as a new transport option?
- Which elements of misalignment can be observed between the requirements of potential urban ropeway projects and established planning routines in the service regime?

The first question addresses professional actors' perceptions of the general proposition of urban ropeways to potentially contribute to public transport service extensions. If professional actors agree with this proposition, it is then of crucial importance to understand any structural barriers to the actual implementation of urban ropeways. The combination of these perspectives builds the ground for a discussion of misalignment challenges in the ongoing diffusion process of urban ropeways. The relation between existing misalignment, stabilizing factors, and how the involved actors deal with it (as part of a potential realignment process) is of particular interest for assessing whether the technology may actually play a future role in a more sustainable mobility system.

1.2. Innovation processes in the public transport service regime

In order to understand misalignment (and realignment processes) and stabilizing factors in the provision of public transport, we use the multi-level perspective as a heuristic background, focussing on the level of the socio-technical regime. Geels (2012, p. 473) refers to socio-technical regimes as sets of deeply rooted rules and routines that coordinate technologies, companies, institutions, policies, users, etc. Established institutional logics and routine choices help reproducing and stabilizing regimes, with a rather incremental potential for innovations (Fünfschilling & Truffer, 2014; Geels, 2012). Yet, with regard to the transport system, there is no single transport regime, as for example different transport modes each have their established actor networks etc.; Geels (2012) refers to automobility as the dominant regime, complemented by a number of subaltern regimes, including public transport. Van Welie et al. (2018) consider the heterogeneity of (sectoral) regimes by introducing the concept of "service regimes" which exist in parallel, characterized by "specific institutionalized combinations of technologies, user routines, and organizational forms for providing the service" (p. 260). This concept has also been applied to the transport sector, considering different transport service regimes (Schippl & Truffer, 2020). One important element in the analysis of service regimes refers to (mis-)alignment and realignment processes, considering the interplay between its different elements (including infrastructures and technologies, organisational configurations and institutions, shared understandings, user practices and needs, or business models). For example, Schippl and Truffer (2020) refer to current misalignments between established diesel technology and rising health concerns, or increasing cycling shares confronted with infrastructure deficits. Alignment is a key element both regarding the internal organisation of service regimes and regarding the fit with external developments (at the sectoral regime and landscape levels) and ongoing innovation processes (Schippl & Truffer, 2018; Van Welie et al., 2018).

Regarding the German public transport service regime in particular, Monheim and Schroll (2004) as well as Karl (2014) analysed structural mechanisms that support stability and hamper innovation take-up within the service regime, particularly relating to planning routines and existing regulatory frameworks. Scherf (2018) analysed interactions between actors from the established public transport service regime and mobility providers from other service regimes. Looking at integrated mobility cards, he presented the challenges of bringing together their different practices from still separated social worlds, and how these limit the aspired effects of integrated mobility cards.

Similarly, specific challenges at the service regime level have been identified for urban ropeways. While ropeway technology is well-established in specific service regimes outside public transport (e.g. winter tourism, see above), urban ropeways require new actors from the public transport service regime to engage with that technology. In an earlier study, we identified a number of factors specifically at the regime level affecting this process (Reichenbach & Puhe, 2018): On the one hand, established planning routines and actor constellations based on extensive experiences with established means of public transport complicate the take-up of urban ropeways, which do not fit into these routines without friction. On the other hand, actors from the public transport service regime generally experience a pressure to become more innovative, often triggered by actors from outside the service regime and considering the wider discussions about a mobility transition. This also leads service regime actors themselves to discover urban ropeways as an interesting option. Drivers and barriers do also exist at the level of the technological niche (e.g. restricted route layout or interference with urban landscapes as inherent factors limiting the urban ropeway niche, or misalignment of project ideas with public transport needs) and the socio-technical landscape (e.g. search for local flagship projects as a driver, general public opposition against major infrastructure projects as a barrier). However, the interplay of the various factors at the level of the public transport service regime seems most relevant for the discussion of the ongoing diffusion process.

While the study by Reichenbach and Puhe (2018) was based on an explorative series of expert interviews on the specifics of ropeway projects in general, the added value of the present article is the systematic approach of discussing opportunities, barriers and needs with local experts in a pre-defined setting (see Section 2). This allows for a more detailed understanding of the factors sketched out above. It is also noteworthy that most recently – and after the empirical part of the present study had been conducted – a number of concrete steps towards including urban ropeways into established planning tools and procedures can be observed particularly at the federal level in Germany. We include these developments in our discussion, relating them to our direct observations.

1.3. Typical steps in extending public transport networks in German cities

For understanding our subsequent analysis of how the public transport service regime deals with urban ropeways, it is important to take a very brief look at how service regime actors in Germany 'normally' approach service extensions and new public transport network elements.

Local transport policy is closely interrelated with aspects of urban development, environmental impacts, social cohesion, etc. in local policies (Gertz et al., 2018, p. 312). In an integrated planning approach, many local authorities therefore use transport development plans. Mostly, these plans are commissioned and then prepared by external consultants in order to later build the basis for a local authority's policy measures and transport investments within a certain timeframe (Gertz et al., 2018, p. 313). Closely related to that wider framework, public transport plans are legally required, commissioned and regularly renewed by those authorities (mostly cities and counties) that are defined as responsible for organising public transport (Dziekan & Zistel, 2018; Holz-Rau et al., 2009), sometimes supported by separate public transport development plans. In these plans, weaknesses and general investment needs in the existing public transport network are identified. One important element of the different plans is ensuring that public transport delivers the desired public value defined by its function as a public service. Besides, this consideration also motivates the complex regulatory framework regarding approval and licensing procedures as well as public tendering, subsidies and service contracts in operating local public transport (Dziekan & Zistel, 2018).

Typically, when it comes to concrete infrastructure extensions and public investment – and often interlaced with the political decision-making process around the above-mentioned general plans – technical feasibility studies are done (or commissioned), followed by defining available and required financial resources and preparing for detailed engineering (Stiewe, 2006). At this stage, also other public actors beyond public transport planners are involved in order to check their interests in a project and optimize plans. One important requirement – particularly regarding the application for investment subsidies – is to prove the public value of a project, usually by means of a cost-benefit analysis. Specifically in Germany, a standardized appraisal method prescribes in detail which forms of costs and benefits need to be taken into account, and the calculation rules (e.g. factor weights) (Köhler, 2014, p. 141). Since investment subsidies depend on a positive evaluation, this standardized approach has a crucial relevance for the feasibility of a public transport project. Lastly before the actual implementation of a project, and depending on the type of the planned infrastructure, the detailed engineering phase may legally require specific procedures, including public involvement, until construction is actually permitted.

2. Case description and methods

Considering the general challenges for urban ropeways identified at the level of the public transport service regime, we present a case study that seeks to allow a more detailed understanding of these factors, particularly addressing the roles of involved actors. We conducted research to analyse expectations towards the new means of transport and identify challenges in the hypothetical planning process of potential urban ropeway lines in three cities in the federal state of Baden-Württemberg, Germany. The purpose of looking at concrete cities was to go one step further from a general discussion of potentials and barriers of urban ropeways or the analysis of previous plans bound to the specific contexts and factors beyond the public transport service regime in their respective cities. Instead, we used a consistent approach across the three cities to analyse potentials and restrictions, considering typical actor settings with regards to planning processes for new infrastructures in the context of the public transport service regime at the local level. At that level, consequences of the new option become more tangible and insights can be linked to the actual scope of action of the respective regime actors. Our study follows a qualitative research approach, using expert workshops to understand different regime actors' views, patterns of argumentations and lines of thought (Alvesson & Sköldberg, 2018).

2.1. City selection

For the study, we selected three different cities in Baden-Württemberg along several criteria: The analysis was restricted to this federal state in order to ensure sufficiently consistent framework conditions across all selected cities, particularly regarding actor constellations, transport planning routines, and the legal framework. In a first screening, we looked for cities where we could identify one or more of the typical situations challenging conventional public transport (see introduction) as relevant issues for local public transport planning.

We considered cities that were already engaged in actual discussions about extending their local public transport system (whether by an urban ropeway or by other means of transport), which we took as a proxy for the existence of potentially suitable challenges in the respective city's transport system. The final selection included Stuttgart, Konstanz and Heidelberg. The three cities come with different urban structures, different urban transport challenges, and different population characteristics, hence providing a combined and rich picture of potential urban ropeway use cases that allows a broad analysis of issues and arguments in experts' reasoning about urban ropeways.

Stuttgart (2016: 626,000 inhabitants) has got an extensive light rail system, next to regional and commuter rail. All of these are running at the limits of current capacity and service extensions are no longer easily possible. Congestion is still a huge challenge due to difficult topography in the city centre. Increasing public transport modal shares ranges high on the political agenda. A potential urban ropeway corridor had already been included as an option in the city's strategic local public transport plan (Verkehrs- und Tarifverbund Stuttgart GmbH [VVS], 2017). During the project, a second corridor started to be publicly discussed (Hintermayr, 2017).

Konstanz (2016: 83,000 inhabitants) is characterised by its location at the Rhine River, separating the often congested city centre from the almost complete rest of the city, including the university campus, with very limited bridges available. Except the railway line, the city only has a bus network. An upgrade of the city's public transport system was already debated when the project started, including tramway and urban ropeway options (Stadt Konstanz, 2017).

Heidelberg (2016: 158,000 inhabitants) has a tramway system, regional and commuter trains. The Neckar River separates its city centre and the railway station from its main university campus, including a hospital and other research facilities, with the university being the city's largest employer. A new tram line had long been planned for this area, but has been overruled by court (Stadt Heidelberg, 2016), with alternatives being publicly discussed during the project (Buchwald, 2017).

2.2. Expert workshops

In each of the three selected cities, an expert workshop was conducted in order to explore the local potential of urban ropeways and expectations of the experts regarding hypothetical planning steps for an urban ropeway. The relevant experts invited to the workshops were selected purposefully, respecting the particularities of the three cities. They included representatives from administration (incl. transport planning, urban planning, monument conservation, and finance departments), local public transport operators and local public transport associations, as well as NGOs engaged in fostering public transport. The actual workshops were held in July 2017, with seven to eight participating experts (23 participants in total) and three members of the project team for moderation and documentation. The workshops started with a brief introduction regarding technical characteristics of urban ropeways by a member of the project team. A semi-structured approach was then chosen, starting with the identification of potential ropeway corridors in the respective city's public transport system by the group. Further questions addressed potential effects on the residents' mobility behaviour, more general effects in the respective city, as well as potential planning challenges and conditions for a successful urban ropeway project. That way the experts' perspectives, closely linked to their locally established working routines, served to distil a coherent problem structuring of potential urban ropeways, respecting the variety of the respective contexts.

2.3. Analytical approach

Each workshop was digitally recorded and transcribed. The structure laid out by the guiding questions (see above) served as a first starting point for the qualitative analysis. Categories were then iteratively enriched and restructured while working through the transcripts and interpreting the course of the discussions (cf. Silverman, 2020), using MAXQDA 2018 data analysis software to support the analytical process. Arguments were systematically collected in order to understand the participants' reasoning about urban ropeways in their cities and more generally. We paid particular attention to any aspects of existing service regime misalignment or ongoing and completed realignment processes as perceived by the participating experts. We looked at whether statements related to the respective local situation and the roles of specific actors or whether general developments and framework conditions at the level of the public transport service regime were addressed. Moreover, a distinction could be made between the general perception of ropeway technology and its suitability for urban transport purposes vs. considerations regarding the concrete steps and issues in planning and implementing potential urban ropeway projects, helping to understand the relevance of the identified issues. In the results section, translated quotes from the workshop discussions serve to illustrate the identified key arguments around which the discussions evolved.

3. Results

In the following sections, potential urban ropeway use cases in the three case study cities, challenges of integrating those into public transport, potential impacts on urban development as well as expectations regarding hypothetical planning steps are presented.

3.1. Use cases for urban ropeways

In all of the three workshops, participants were generally rather open towards introducing urban ropeways as an alternative means of transport. This was despite the fact that some of them had initially perceived the urban ropeways as a weird idea, a technology that had its place in the mountains and at tourist attractions. Yet, particularly when hearing about or dealing with the first urban ropeway ideas in the three cities, the experts had come to view urban ropeways as an option that at least deserves a detailed analysis of its potentials. This was despite the many challenges, for example regarding restricted route layout and integration into urban landscapes, that were seen as obstacles and that were also discussed in detail later during the workshops. In a number of statements, this general openness was related to a wider discussion that public transport needs to be aware of ongoing innovations and also societal developments that lead to a pressure on the sector to leave beaten tracks and provide new answers to increasing challenges.

A major advantage of urban ropeways was seen in overcoming problems with limited street space at ground level, in particular where current bus lines reach their capacity limits, where bus intervals can no more be increased or buses get stuck in traffic. In line with existing literature on urban ropeways (see above), a number of typical potential use cases were discussed by the workshop participants (Table 1). Along with this, a number of potential urban ropeway corridors was identified in each of the three cities (Fig. 1), which then served as the basis for the subsequent detailed discussions.

3.2. Integration into public transport networks

In all three cities it was clear for experts that, in order to become efficient as a part of the respective public transport system, integration crucially requires thinking about the physical points of interchange as well as about tariff integration. Besides being a requirement when applying for financial support according to federal state rules (which at the same time rules out leaving the pricing completely in the hands of a private operator), this means ensuring that the introduction of the additional means of transport does not build new barriers for passengers, which was identified as one important factor for user acceptance:

> *Full integration into the public transport system [...] in all regards, both operational and regarding tariffs, is absolutely essential.*
> – regional public transport association representative –

The necessary interchanges between an urban ropeway line and other means of public transport were seen as a challenge, since interchanging was generally supposed to be a factor reducing user acceptance. However, participants argued that an interchange including an urban ropeway with its small cabins at high frequency (at least for those ropeway subtypes perceived most suitable for urban applications) is something different and might actually not be perceived as problematic by passengers. Still, interchanging was supposed to remain a challenge when scheduling transfers between the continuous passenger flow of a ropeway line and the typically discontinuous timetables of buses, trams, or trains. A related challenge was seen in providing sufficient capacity for peak demand, given the fixed technical equipment of a potential line.

A major advantage of urban ropeways was seen in their potential to not only provide direct links for some passengers in given corridors, but to relieve congested roads and existing public transport lines. By doing so, more passengers and other road users as well could benefit from an urban ropeway. However, a general concern related to the appropriateness of adding a new means of transport when there already is an established system of public transport lines using established technologies:

> *And if we now had a ropeway or a comparable means of transport moving above the surface as the third pillar of public transport, the question would be where and how I can integrate this.*
> – local administration representative (transport planning) –

Imagining potential urban ropeway passengers, experts assumed that urban ropeway lines would be a very attractive means of transport for users, not least because of being novel or even unique, and fun to ride and experience. Yet, this relates to a lack of routine with the new means

Table 1
Typical potentials and challenges of urban ropeways mentioned during the expert workshops.

Potentials	Challenges
• Corridors where topographical barriers complicate conventional public transport extensions • Improving access to areas undersupplied with public transport • Providing access to new housing or business areas • Connecting university campuses or similar major facilities with high transport demand	• Combination with ‘park and ride’ facilities is challenging when creating an unattractive transfer close to the final destination • Finding corridorswith sufficiently continuous demand throughout the day; demand should not be limited to rush hou • Identifying corridors where singular advantages of urban ropeways are not outdone by other advantages of conventional means of transport

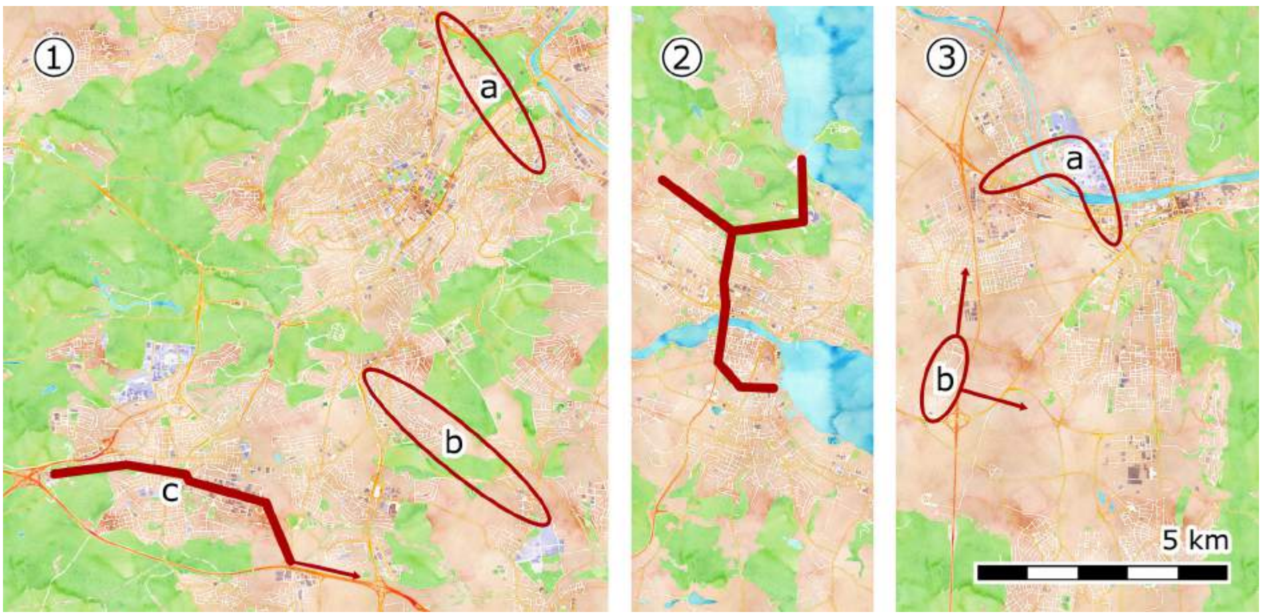

Fig. 1. Overview of potential urban ropeway corridors discussed in the expert workshops: ① Stuttgart (red: inner city basin): a) bypass to relieve city centre, b) topographically challenging link to a district without rail access, c) connecting new housing area and industrial area to public transport hub / ② Konstanz (red: Swiss-German border): potential new backbone of local public transport network, including links to university campus and new housing area / ③ Heidelberg: a) improved access to university campus, b) connecting a redevelopment area (former military housing) to existing public transport [map tiles by Stamen Design under CC BY 3.0, data by OpenStreetMap under CC BY SA].

of transport and the effect could therefore decrease over time. Generally, urban ropeways were seen as something for any kind of public transport user – only depending on whether the route fits with the respective trip requirements. Actually, this diversity was even seen as a requirement in order to justify a line that else would for example only be used by commuters during rush hours:

> *In urban areas I need to ensure that different users can actually use the system, out of different motivations.*
> – local administration representative (transport planning) –

In order to ensure attractiveness and convenience for ropeway users, a number of factors come into play that are quite similar to those of other means of public transport – and which are therefore already considered in established planning routines. Urban ropeways could offer comfortable trips and attractive travel times as well as waiting times in particular because of the continuous operation. However, it should be ensured that ticket prices are not higher than for other public transport users in the city, taking bicycles on board should similarly be possible etc., and a high availability also during adverse weather becomes a key requirement compared to tourist-oriented ropeways. Concerns related to social security when there is no staff present in each cabin, which could require specific operational measures, as well as people fearing heights. The biggest challenges were seen in the connected topics of access times, accessibility and distance between stops. Since urban ropeway stations cannot be as close as for busses or tramways, efficient interchanging points need to be designed and access and egress times should not foil otherwise attractive journey times. Ensuring accessibility, especially for persons with reduced mobility, requires considerable technical equipment at the stations, for examplelifts where those must be placed above street level, as well as slowing down or stopping the cabins to allow wheelchair access etc. This was not seen as a technical problem but rather as an area requiring significant consideration and effort during planning and operation.

Combined with the introduction of any urban ropeway line, experts saw a necessity to also think about the consequences for other means of public transport and other modes of transport. In public transport, if for example an urban ropeway aims at relieving overcrowded busses, its introduction may well imply the reduction of existing services. This will negatively affect some users and require new transfers for others. Yet, reductions that are part of a stringent reorganisation of the public transport network accompanying a new urban ropeway line were seen as a necessity in justifying that line, for example regarding financial viability. Regarding other modes of transport, particularly restrictions for private motor traffic (e.g. through closing roads or reducing parking lots) were discussed:

> *The ropeway only helps if I can lock out the cars as well.*
> – local administration representative (transport planning) –

Being aware of the challenging nature of such proposals in public discourses, such measures would aim at reclaiming urban space to improve urban quality of life, and at providing additional incentives for the actual use of the line.

3.3. Urban ropeways as a driver of urban development

Considering the perceived general attractiveness of riding and experiencing urban ropeways (see above), experts could imagine those to additionally become tourist attractions in their own right and contribute to the attractiveness of the respective city as a tourist destination. This could also provoke thinking about using private investors for building and/or operation (or letting them contribute). However, such private involvement would not fit with the requirement of orienting the urban ropeway towards efficient integration into the day-to-day public transport network, according to the experts. Still, residents would benefit from a generally improved quality of life, induced by calming crowded streets through the new transport option.

Currently, with no German city already using an urban ropeway as part of its public transport network, one considerable aspect was seen in pioneering. Being a first mover regarding the new means of transport could underpin the respective city's political support for and commitment to sustainable transport, contributing to the city's reputation:

I'd be glad if we [...] were the first to do something like this.
– local administration representative (mayor's office) –

In any case, the actual planning and/or implementation of an urban ropeway was expected to lead to intense discussion among citizens as well as in the local political arena. These may particularly be triggered by impacts of an urban ropeway line like disturbances of residents' privacy along the line, noise emissions, potentially reduced property values, as well as impacts on nature reserves and wildlife. The most challenging topic, however, was seen in an urban ropeway's impact on urban landscapes. Experts could not easily imagine what this impact would actually be like and how the ropeway installations would look in detail, hence questioning how a reasonable balance with the technical requirements could be achieved, particularly in historical parts of city centres and accounting for monument conservation:

One has to ask the question about the impairment, which will not be insignificant. And then there will be a balancing decision.
– local administration representative (monument conservation) –

While finding a reasonable balance is a standard task in monument conservation, an urban ropeway with its visual impact 'in the sky' (above the city silhouette) was seen as a non-standard case to assess. The height of the ropeway installations as well as stations were also perceived to be critical issues, which can only partly be moderated by pleasant design. The novelty and lack of experience with urban ropeways as well as the subjectivity of assessing visual impacts contribute to the challenging nature of this topic.

3.4. Planning procedures for urban ropeways

Across all workshops, experts were aware of the still special character of urban ropeway projects which was assumed to affect planning processes as well. Generally, there was a perception that an urban ropeway should not be a goal in itself; rather, thorough analyses should precede the actual decision for this means of transport, checking the technical and economic feasibility as well as its fit with the respective city's actual transport needs. If such analyses showed that an urban ropeway fits best, the planning process should generally follow the standard steps in developing a public transport project, like for example inclusion in a transport development plan, technical planning, and approval, as well as civic participation.

Comparing alternatives (different ropeway layouts as well as other means of transport) was seen as a very important step of this planning process. Considering the resource-consuming planning process as well as the potential impact on the city's transport system, the responsible actors should take their time in identifying the best solution:

I think that is the important thing: that we are now basing ourselves on criteria that enable us to decide what is the right way forward. What is economic, what makes sense in terms of transport, what is socio-economically viable? These are the issues we need to work on now.
– regional transport planning representative –

Analyses were seen to be required regarding various characteristics of any urban ropeway project: What is the transport capacity (per unit of time)? How can it deal with peak demand? Which route layouts with which stations are possible? Is there enough physical space available for the required installations? What are the journey times? What will be the investment cost of the actual ropeway installation and what will be the economic performance during operaion? How is the availability regarding maintenance works as well as adverse weather? What about fire prevention and emergency response plans? Who will operate the ropeway? Will it be accepted by users – and by citizens in general? And how will it look like? These are all examples where local experts saw a new need for external support with ropeway-specific expertise – which for them has not been relevant in their day-to-day work until now, leaving them with a multitude of individual knowledge gaps. To some extent, however, also the general readiness of established planning routines with regard to consistently including urban ropeways was questioned (e.g. in demand modelling or cost-benefit analysis), since these instruments regularly refer to reference values gained from extensive experience with established means of public transport.

Despite the many open questions and the expected challenges when it comes to routine procedures in public transport planning, however, workshop participants appreciated two major promises of urban ropeways: reduced investment costs, compared with rail-based means of transport, and the possibility that regarding the actual technical planning and construction process urban ropeways could be realized much faster. For that matter, experts unanimously welcomed that the federal state government of Baden-Wurttemberg had adapted its regulation in order to provide financial sponsorship for urban ropeways similar to tramways.

Urban ropeways were seen to be not only new for transport planners, but for potential passengers and citizens as well. Combined with the generally increasing relevance of civic participation (including calls for such by political actors), this requires intense engagement with citizen interests from the outset of any potential project:

This is of course a spectacular project, because it is entirely groundbreaking. And that is why the public will probably care about it significantly more. And we will all be dealing with a subject where no one has any experience.
– local administration representative (transport planning) –

Known issues like whom to involve and how to address also those who would potentially benefit from the new transport option add to this challenge. Considering the additional lack of experience with how urban ropeways work and look like, experts saw a need to explicitly address this in the planning process and to potentially bring in additional external support.

3.5. Openness vs. uncertainties

As a recurrent theme, bringing together the various topics presented above, *uncertainty* can be identified in as a major workshop result. We therefore want to put a particular focus on this uncertainty and its elements.

A first considerable aspect of uncertainty relates to all kinds of minor and major knowledge gaps and open questions with regard to the technical characteristics and possibilities of urban ropeways as well as their visual impact on urban landscapes, regulative aspects, investment costs etc. Correspondingly, this applies to all kinds of involved actors, ranging from those involved in actual public transport operation to a bit more distant administrative representatives who need to be involved during specific planning stages:

I do have a real knowledge deficit for some topics, where I don't know what it's like at all.
– local public transport operator representative –

You're pretty much fishing in murky waters. I feel a great uncertainty for my part, I can't judge it correctly. I'm still putting a big question mark behind it, but I think it's good that the city is working on it in a well-founded and open-ended way.
– local administration representative (monument conservation) –

However, workshop participants have taken the filling of these knowledge gaps as their task, and the open questions generally relate to issues that can be addressed by additional studies, consulting ropeway experts etc., and participants could actually see progress:

My learning curve then went steeply upwards.
–regional public transport association representative –

Therefore, in accepting the challenge (as opposed e.g. to denying the viability or general suitability of urban ropeways), urban ropeways can be read as generally accepted by the public transport service regime, i.e. regarding its perception as a serious transport alternative. This alone is a noteworthy difference to earlier years of the diffusion process when a general scepticism regarding the suitability of the technology for urban public transport prevailed.

However, specific knowledge gaps of the mentioned kinds are a typical issue in diffusion processes, and as such they are neither a fundamental problem (since they may easily be overcome through expert advice and increasing experience) nor a specific challenge for urban ropeways (since other innovations confront local planners with similar knowledge gaps). In a second, more serious perspective, though, uncertainties voiced during the workshops relate to the capability of established planning procedures to handle urban ropeway projects in the first place. The unavailability of empirically validated reference values complicates certain planning procedures, reduces their reliability, or even inhibits their application:

I believe that even an expert today cannot really assess the effects of such a ropeway for urban purposes, because nothing has really been realized anywhere yet.
– regional public transport association representative –

Moreover, experts argue that certain established planning procedures systematically cannot deal with the characteristics of urban ropeways such as their continuous operation, thereby inhibiting sound comparisons which would in turn be an important factor in arguing for an urban ropeway. Experts saw that for urban ropeways some aspects may become arguments in favour or against a certain line which are currently not reflected in planning routines at all. As a consequence, a certain degree of misalignment of urban ropeways with the existing public transport service regime remains. Still, this is not necessarily specific for urban ropeways. Rather, core regime actors themselves have identified some of the respective planning procedures as generally problematic and not fit for innovation, calling for an adapted regulation (VDV, 2018). It is thus the specific context of the dense regulatory framework in the German public transport service regime which lets this general challenge become a major barrier for the take-up of new and/or innovative solutions.

Yet, this does not imply that the complex regulatory frameworks and standardized approaches are useless obstacles that should just be eliminated. Experts acknowledged that these follow important rationales, particularly in providing procedures that ensure meeting the goals of an integrated public transport system and the efficient use of public money. Rather, the challenges identified show that the current planning system is not well prepared to use technological progress and service innovations in the pace that service regime actors themselves see as becoming a necessity.

At this point, the relations of service regime actors with actors both in the sectoral regime (particularly regulators) and in the socio-technical landscape (particularly political actors at the local level) come into play. On the one hand, with something innovative like an urban ropeway, the planning process may uncover regulatory need for action (see above). On the other hand, political actors may actually trigger debates about introducing the new means of transport and political decisions – as well as citizen sentiments and public discourse may critically influence the course of such a project. Experts also voiced an expectation that an urban ropeway project could play an important role as a milestone for urban development. But despite that, most experts did not see too much emotion in their work, focussing instead on their respective tasks to provide a sound basis for decision-making and accepting that the actual decision will ultimately be in the hands of political actors:

It's actually still passionless for me. I am in favour of a means of transport with which we can handle our traffic, because that is where I see my responsibility.
– local administration representative (building department) –

Though, a general openness towards considering urban ropeways as a serious option was voiced several times during the workshops.[2] This openness must be read as an important factor in allowing the required realignment processes also through action from within the established public transport regime:

I believe that this is a very important issue: openness to innovation, openness to different patterns of mobility among different people and not being strictly in one's own line.
– local public transport operator representative –

This comes in addition to the developments at the niche and socio-technical landscape levels (cf. Reichenbach & Puhe, 2018). In turn, experts sometimes wish they received more political support also when they are actually implementing measures and projects, in a state of projects when they also experience opposition from affected residents etc. However, the representatives of the public transport service regime involved in the workshops have accepted the challenging realignment process.

4. Discussion

Our results highlight different kinds of knowledge deficits and uncertainties as crucial barriers opposing the planning and implementation of urban ropeways. Considering our analytical lens, we can differentiate these issues by their relevance for the general diffusion process of urban ropeways, ranging from simple, case-specific questions to systematic challenges at the level of the service regime (Fig. 2).

First, we have documented a general appreciation of the technological potentials of urban ropeways by local public transport actors, whether or not that option may fit with the requirements of their specific issues in their local transport systems. There may thus be open questions, but no general misalignment can be observed. When it comes to imagining detailed planning steps of any potential project, individual actors' knowledge gaps become more manifest and increase the efforts needed to overcome them, particularly when compared to established means of public transport. For example, additional external expertise may be required that needs to be paid for (e.g. commissioning reports). The same holds true for balancing out transport needs with, for example, urban development and monument conservation. Similarly, and bring-

[2] The discussion dynamics during the workshops may have contributed to this consistent tune. However, the open atmosphere (incl. space for controversial views) and participants' repeated references to earlier skeptical reactions give us confidence in trusting our observation.

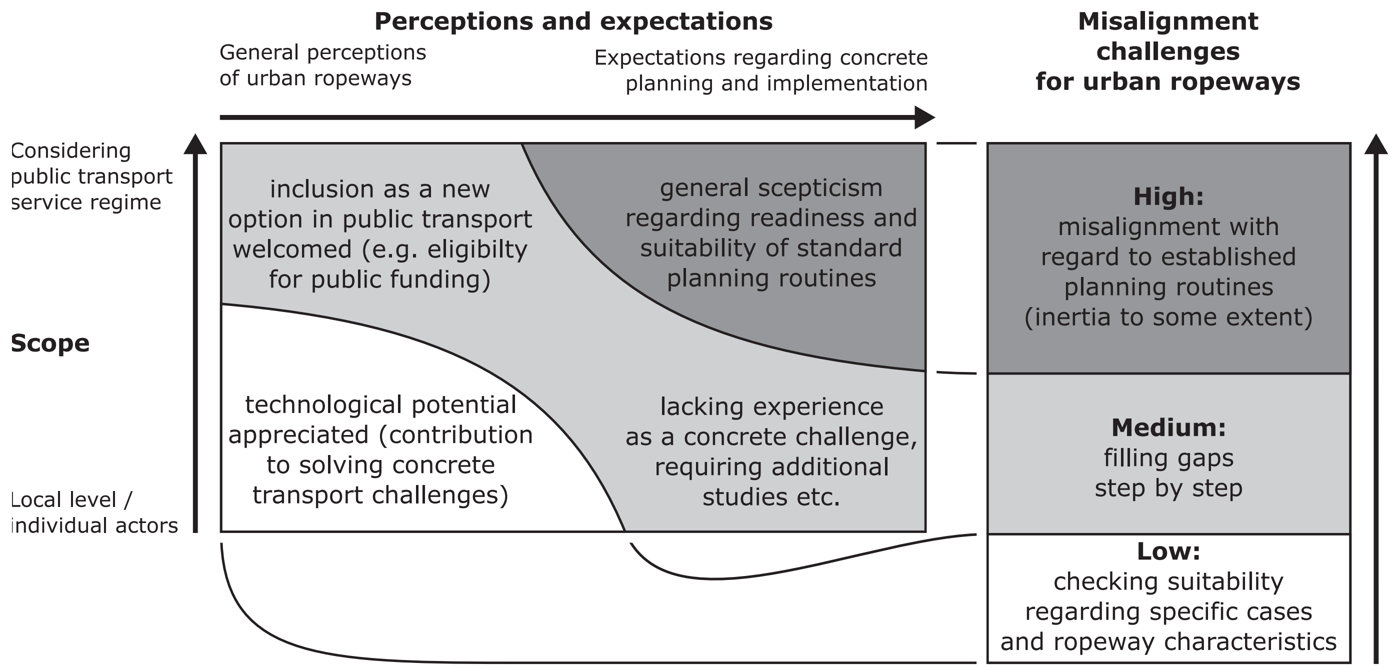

Fig. 2. Misalignment challenges for urban ropeways (own figure).

ing the wider service regime framework into consideration, some legislation etc. has already been updated to cover urban ropeways, but some gaps remain and urban ropeways are not yet covered at the same level of detail (e.g. adding or altering assessment criteria). However, barriers become more fundamental when envisioning concrete planning procedures: While filling knowledge gaps during a diffusion process is a typical step, the dense regulatory framework, since it is partly built around existing reference values (particularly in project appraisal), complicates entering that learning process in the first place, when knowledge deficits still exist. Only through the specific arrangements in the service regime, this mechanism gets its chicken-and-egg problem nature. This is where misalignment between urban ropeways and the public transport service regime is most clearly visible. Moreover, those setting and developing further the regulatory framework (thereby potentially reducing misalignment and inertia more generally) do not coincide with those confronted with inertia in their local planning practice. From a local perspective and considering again the identified general openness, this further adds to the issue, since local actors – apparently bound to available planning tools – do not see themselves in a position to challenge the general framework.

Recent developments beyond the expert workshops and our study indicate that the service regime itself also acknowledges the identified challenges, as also indicated in the introduction. Most prominently, a federal law guiding financial support for transport investments has been changed (as a result from the parliamentary process) to include urban ropeways as a public transport option. The Federal Ministry of Transport and Digital Infrastructure invited a working group on urban ropeways that is also continued under the 2021 government, and urban ropeway characteristics are expected to be considered in an ongoing revision of the standard cost-benefit analysis tool. Two publicly funded projects currently work towards providing specific guidelines and planning tools for urban ropeways. At the level of the federal states, actors are considering guidelines or provide specific financial support for cities requiring additional expertise. These developments provide concrete examples for an active step-by-step closing of existing gaps, which reduces misalignment. Altogether, this further illustrates the current realignment process working towards an integration of ropeways into the standard repertoire of public transport planning and provision. At the city level, the ongoing studies in Konstanz and Stuttgart fit our observations, as well as broad media coverage and recent urban ropeway projects from a number of other German cities (e.g. Bonn, Munich, or the Frankfurt region). Adding to our research results presented above, this underlines the re-orientation of service regime actors towards the potentials (and challenges) of new and innovative solutions where established public transport solutions do no more suffice to solve transport challenges.

Yet, these initiatives challenge the structural factors of inertia built into the general framework just as little, at least not systematically. At the same time, it becomes obvious that the sector needs to bring itself in a position where it becomes easier – or possible at all – to learn and use innovative approaches (incl. specific technologies) that reach out beyond conventional categories. It remains questionable whether this can be done by adding new instruments (e.g. regulatory sandboxes or the various kinds of experimentation, cf. McCrory et al., 2020), or whether putting into question the general assumptions and approaches of the regulatory framework will also be necessary (cf. Lyons & Davidson, 2016).

5. Conclusion

Our findings add an important lens to understanding the potential of urban ropeways to contribute to a mobility transition and more sustainable urban mobility. The technical characteristics and limitations clearly rule out urban ropeways as a silver bullet to transport problems, limiting those to cases where they can show their specific advantages compared with established modes. Our study complements this technological view with a perspective on specific challenges in planning and implementing urban ropeways in the context of the practices and routines of typical public transport service regime actors.

In a wider sense, our case study of urban ropeways also serves to illustrate the structural conditions for innovation in the public transport service regime more generally. We have used the rather clearly defined case of urban ropeways to learn about structural barriers and factors of inertia in Germany that oppose the diffusion process of the technology, how actors engage with alternatives and organise realignment, and how remaining aspects of misalignment are dealt with. Other technological developments, for example considering the still much fuzzier fields of ride-sharing, ride-pooling, or autonomous shuttles, are currently affecting and will further affect how the transport system is organised. These technologies are assumed to have a considerable potential of changing the sectoral regime as a whole, including a new balance between transport modes, user expectations, patterns of use, extensive need for regulation etc. For example, new routines for public transport network planning or public tendering may be needed, or new criteria for cost-benefit analyses may need to be developed, similar to urban ropeways, but possibly with an even more fundamental need for new methodological approaches. In many cases, the new technologies will also imply a growing multitude of involved actors, particularly considering stronger links with information and communication technology providers. These developments pose significant challenges to the public transport service regime and its future relevance. However, the different material natures of the various technological developments should also be considered. The testing of new sharing or shuttle services, for example, does not require built infrastructure to an extent comparable to urban ropeways. As a consequence, such differences also affect the ways in which technologies can be tested and how institional learning may take place.

Altogether, the results of our study further underpin our perspective that the future of public transport is not just a technology issue. Public transport plays an important role in ensuring climate-friendly mobility and reducing negative effects of the current mobility system. It is crucial to improve our understanding of how socio-technical reconfiguration processes in the public transport service regime take place, how it keeps pace with technological progress, and which role practices and routines as well as structural factors of inertia play in these processes. Combined with rising political and public awareness (and rising funding opportunities for cities), this perspective may provide additional scientific support for a mobility transition, particularly considering the challenges for ambitious actors at the local level who are confronted with the practical effects of structural barriers. The insights gained from our study aim at enriching that knowledge base by a small piece of the puzzle. They also provide a number of links for future research, namely regarding the transferability of our findings to the more complex reconfiguration processes to be expected as a consequence of the more far-reaching technological developments identified above.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Unravelling the spatial properties of individual mobility patterns using longitudinal travel data

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ABSTRACT

The analysis of longitudinal travel data enables investigating how mobility patterns vary across the population and identify the spatial properties thereof. The objective of this study is to identify the extent to which users explore different parts of the network as well as identify distinctive user groups in terms of the spatial extent of their mobility patterns. To this end, we propose two means for representing spatial mobility profiles and clustering travellers accordingly. We represent users patterns in terms of zonal visiting frequency profiles and grid-cells spatial extent heatmaps. We apply the proposed analysis to a large-scale multi-modal mobility dataset from the public transport system in Stockholm, Sweden. We unravel three clusters - Locals, Commuters and Explorers - that best describe the zonal visiting frequency and show that their composition varies considerably across users' place of residence. We also identify 15 clusters of visiting spatial extent based on the intensity and direction in which they are oriented. A cross-analysis of the results of the two clustering methods reveals that user segmentation based on exploration patterns and spatial extent are largely independent, indicating that the two different clustering approaches provide fundamentally different insights into the underlying spatial properties of individuals' mobility patterns. The approach proposed and demonstrated in this study could be applied for any longitudinal individual travel demand data.

1. Introduction

Human mobility has been known to exhibit some common features that extend beyond time and space. There is evidence to suggest that individual's daily travel time budget has been limited to approximately 70 minutes a day throughout human civilisation history and across cultures and geographies, whereas travel distances have increased as a result of technological advancements (Ahmed and Stopher, 2014). Notwithstanding, the geographical area and the diversity of destinations visited, as well as the frequency of these visits vary considerably across the population.

The statistical properties of aggregate mobility patterns have been subject of extensive research. In particular, in the last decade, smart card data has been increasingly used to examine temporal daily and weekly variations (Cats and Ferranti, 2022a; Deschaintres et al., 2019; Egu and Bonnel, 2020; Ghaemi et al., 2017; Goulet-Langlois et al., 2016; He et al., 2020; Ma et al., 2013). Cats (2022) offers a review of past work using smart card data to study human mobility. Hasan et al. (2013) develop a model for estimating macroscopic travel demand properties such as visiting frequency and origin-destination flows using smart card data. Schläpfer et al. (2021) estimate the frequency of visits to different parts of the city as a function of travel distances and demonstrate that related variables follow universal laws. Tu et al. (2018) analyse spatial variations in passenger ridership in public transport and Zhu et al. (2020) compare the spatio-temporal heterogeneity in the usage of different shared mobility systems. There is thus a growing understanding of the macroscopic properties of human mobility based on disaggregate mobility traces. Notwithstanding, the same macroscopic properties may emerge from different compositions of mobility patterns at the individual level.

It is therefore paramount to better understand how disaggregate travel patterns vary across the population. With public transport systems being increasingly equipped with automated fare collection (AFC) systems which passively collect data concerning individual transactions, it is possible to analyze individual travel patterns and identify patterns among those. In the following we focus on individual's travel or mobility patterns in terms of the spatial features characterising the complete set of all travel performed during the course of a sufficiently long period. Following the work of Schneider et al. (2013) who identify recurrent and distinctive motifs that represent individual daily mobility using travel survey and mobile phone data, temporal graphs were constructed by Lei et al. (2020) to represent trip sequences using smart card data.

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The analysis of motifs neglects the geographical aspects of individual mobility by limiting the representation of destinations to nodes in motif graphs. Goulet-Langlois et al. (2017) measure the extent to which individual travel patterns are stable over time in terms of frequency, sequence and activity duration. They distinguish between regular and irregular travellers using percentile values of an entropy-based metric.

A couple of studies have also considered some spatial aspects among the set of features used for clustering user travel patterns. Gutiérrez et al. (2020) focus on clustering tourists travel patterns into latent profiles using a series of variables related to number of stops, municipalities and zones visited, main stops visited, number of routes used, and the share of transactions at main stops and areas. Kaewkluengklom et al. (2021) analyze the year-by-year changes in user cluster membership by applying k-means clustering with respect to the distribution of trips over four daily time periods, the top three most used origin-destination pairs and the most used stations. Zhang et al. (2021) examine variations in activity spaces of vulnerable travellers' groups for example in terms of travel distance radius and the entropy of activity locations.

Based on the review of the literature, we conclude that little is known on market segments in regards to their geographical characteristics. The analysis of longitudinal travel data enables the investigation of how mobility patterns vary across the passengers' population and identify the spatial properties thereof. The approach proposed and applied in this study could be applied for any longitudinal individual travel demand data.

The objective of this study is to unravel the commonalities and differences in the spatial properties of individual mobility patterns. In our analysis we address the following key questions: (i) to what extent do users visit different parts of the network?, and (ii) what is the spatial extent of individual travel patterns? In answering both questions we aim to identify distinctive user groups in terms of the spatial extent of their mobility patterns. We propose two representations of user profiles that are then subject to clustering. Study outputs can be used to devise targeted mobility products information and subscriptions. We apply the proposed analysis to a large-scale mobility data set from the public transport system in Stockholm, Sweden.

In the following section we detail the input mobility data and the underlying network partitioning used in this study, followed by two approaches for user segmentation pertaining to zonal visiting profiles and the spatial extent of locations visited. In section 3 we provide a brief description of our application for the Stockholm County's public transport system. Next, we present and discuss the results of the proposed user segmentation clustering analysis for our application. We conclude with a discussion of study implications and suggestions for further research.

2. Methodology

In this section we describe the sequence of steps performed in order to unravel the spatial properties of individual mobility patterns. Two key ingredients are mobility data and a spatial partitioning of the geographical area under consideration. In the first two subsections we describe the features of the disaggregate longitudinal travel data required to enable the proposed analysis and the data-driven approach which we have adopted for generating travel demand zones. Next, we detail the two segmentation method proposed in this study. First a method based on a visiting profile which is agnostic to the specific locations visited is presented, followed by a method based on the spatial extent of the areas visited by users.

2.1. Mobility input data

Our analysis requires information on mobility records with longitudinal data on time and location stamps for the origin and destination of each journey for each traveller $i \in N$, Where N is the set of all travellers considered in the analysis performed. Such data can be available for example from travel surveys, travel app tracking data, synthetic populations used in activity-based agent-based models, derived from car plate recognition records, ride-hailing or shared-fleet usage records.

In the context of public transport journeys, observed origin and destination locations correspond to stops where the set of stops is denoted by S. A travel diary consisting of all journeys per traveller throughout the analysis period can be inferred from smart card data records by applying alighting location (Munizaga and Palma, 2012; Trépanier et al., 2007) and transfer inference algorithms (Gordon et al., 2013; Yap et al., 2017), depending on the fare validation scheme. Note that the analysis requires that the data contains card holder identifier which is consistent throughout the analysis period.

For certain investigations it might be relevant to examine the socio-demographic characteristics of the obtained user classes. In some cases certain socio- demographic variables might be directly available from card holder information or based on the subscription/concession program (e.g. pensioners, students). However, some variables of interest may not be directly available at the individual passenger level. We therefore adopt the approach proposed by Amaya et al. (2018) and Sari Aslam et al. (2019) and adapted by Kholodov et al. (2021) to identify the most likely home zone per traveller based on the frequency of each zone serving as an origin for each card holder. The zones used in this procedure can correspond to any zonal aggregation for which detailed socio-demographic (e.g. census) data is available for the relevant study area.

2.2. Travel demand zones generation

Our analysis of users mobility patterns involves the identification of their visiting patterns of different parts of the geographical area under analysis. It is therefore essential to determine which set of zones will be used for describing passengers' visiting patterns. Zones can be based for example on those readily available from the official central bureau of statistics or by overlaying a grid and defining equal size grid cells. We hereby adopt a data-driven technique for generating travel demand zones that has been proposed and applied by Luo et al. (2017).

The aim of the adopted travel demand cluster generation technique is to cluster groups of stops based on information concerning both passenger flows and spatial distances. Hence, in addition to the passenger origin-destination matrix, the geographical coordinates of each stop is provided as input. The clustering of stops thus results with geographically compact zones (i.e. sets of stops) which exhibit similar travel demand patterns in terms of the distribution of travel destinations for journeys originating from stops included in the same zone. In the following we omit the time indexes because the analysis can be performed for any analysis period of choice without loss of generality.

The method used to generate the demand zones follows the four-steps K-means-based station aggregation method proposed in Luo et al. (2017). The four steps consist of:

1. Use K-means to obtain clusters of stops.
   The clusters $\{C_k\}_{k=1,\dots,K}$ are a partition of S with centers $\{\mu_k\}_{k=1,.,K}$. Consider geodesic distance $d(\cdot,\cdot)$ between stop $s \in S$ and cluster centers when performing the algorithm. Store the clustering results for a range of possible values of k.
2. Compute the distance-based metric. For each k calculate:
   - Intra-cluster squared distance: $D^{intra} = \frac{1}{N}\sum_{k=1}^{K}\sum_{s\in C_k} d(\mu_k, s)^2$
   - Inter-cluster squared distance: $D^{inter} = \min_{k=1,.,K}\{d(\mu_k, s)^2\}$

   With the aim of minimizing D^{intra} and maximizing D^{inter}, we consider the problem of minimizing their ratio $\tau = \frac{D^{intra}}{D^{inter}}$
3. Compute flow-based metric. For each k=1,.,K calculate:
   - Intra-cluster flow: $F^{intra} = \frac{1}{k}\sum_{k=1}^{k}\sum_{s1,s2\in C_k} f(s1, s2)$

- Inter-cluster flow: $F^{inter} = \frac{1}{k\times(k-1)} \sum_{k=1}^{K} \sum_{l=1}^{K} \sum_{\substack{(s_i \in C_k, s_j \in C_l) \\ i \neq j}} f(s1, s2)$

  Where $f(s1, s2)$ is the observed passenger flow from stop $s1$ to stop $s2$ during the time period under consideration.

  With the aim of maximizing intra-zonal flows and minimizing inter-zonal flows, we maximize the quantity $\delta = \frac{F^{intra}}{F^{inter}}$.

4. Determine the number of clusters.
   Normalize the metrics to a [0,1] range ($\tau \rightarrow \tau'$, $\delta \rightarrow \delta'$) and look for high values of the integrated metric $m(k) = \frac{\delta}{\tau}$. $k^* = \arg\max_K\{m(k)\}$ gives the optimal number of clusters within our range.

The resulting partitioning is such that all stops $s \in S$ are grouped into a k number of zones denoted as $z \in Z$. Where the set of zones Z is a collectively exhaustive and mutually exhaustive clustering of all the stops in S. Once the number of clusters is selected, we name and refer to each cluster of stops by the stop with the highest passenger volume included in each set.

2.3. User segmentation based on zonal visiting profiles

Our goal is to identify groups of users that exhibit a similar behavior in terms of the frequency and diversity of zones visited. Note that in this user segmentation we are not interested in which specific zones are visited by individual users but rather the general properties of the zonal visiting profile. For example, if two individuals visit one zone 50% of the time, i.e. have journeys for which this zone serves as the destination, 30% for a second most-frequently visited zone and 20% for their third most-frequently visited zone, then they are considered to have identical travel patterns for the sake of this analysis, regardless of the identity and locations of these zones. Hence, the key information needed for this analysis is to calculate for each individual user the number of journeys destined to each zone. The zones used here are those generated in the data-driven travel demand zone generation described in the previous section.

For this analysis we consider the count of journeys ending in each zone for each user: $W_{i,z} = \sum_{s_i \in S} \sum_{s_j \in z} f_i(s_i, s_j)$

Where $f_i(s_i, s_j)$ is the total flow, i.e. number of journeys, performed by user $i \in N$ with stop s_i as an origin and stop s_j as a destination.

Each user $i \in N$ is characterized by a vector W_i with each entry denoting the number of visits to each of the collectively exhaustive and mutually exclusive zones. These vectors are calculated and normalized for each user, so as to consider the share of the journeys destined to each zone rather than the absolute numbers.

We sort W_i by descending values, i.e. from the most visited zone to the least visited. Consequently, we obtain an ordered and standardized vector per user which contains information about the visiting profile, where the first entry represents the percentage of journeys destined to the most visited zone, the second entry represents the percentage of journeys destined to the second most visited zone and so forth. This procedure results with *zonal visiting frequency user profiles*.

Next, we cluster these profiles using the K-Means algorithm. The resulting centers from the K-Means algorithm are then interpreted based on the number of zones visited as well as the share of journeys attracted to each of the explored zones. According to the distribution of journeys share one can progressively define the clusters from the most to the least local.

For illustration, consider a study area partitioned into five zones: A, B, C, D and E. Let us consider the case of three users: Adam, Eve and Abel. Table 1a displays the number of trips each of them conducts towards each of the destination zones within a given time window. The first transformation is to transform the number of trips per zone into the percentage share of the total number of trips per traveller, see Table 1b. Subsequently, each traveller's vector is sorted from the zone most frequently visited to the one least frequently visited while disregarding the information on zone ID. This results in the zonal visiting frequency user profile vector for each of the three users as shown in Table 1c.

The analysis can be further enriched by analyzing how the visiting profile clusters manifest themselves spatially, i.e. how does the share of users belonging to each visiting class varies geographically across home-zones as well as in relation to key socio-economic variables.

2.4. User segmentation based on the spatial extent of locations visited

While the analysis described in the previous section allows identifying clusters of users in terms of visiting patterns, it does not contain information on the spatial extent of user's mobility patterns and the shape thereof. In this subsequent step, we are interested in characterising users in terms of the spatial extent of the locations they visit during the course of the analysis period based on individual travel diary data. Unlike the visiting profile, the identity of the areas visited is of importance in this analysis. For each user's journey, we consider the origin and destination stops as two pinned locations. For this analysis, we choose to aggregate stops into grid cell zones by overlaying a grid over the study area, but this can be substituted by any other aggregation of choice. The grid cells avoids the problem of large variations in geographical size among zones. Each stop s is linked to a grid cell/zone z. We then count for each zone how many journeys originated from this zone or destined to this zone. The user visit count per zone is thus $V_{i,s_x} = \sum_{y \in S_x} f_i(s_x, s_y) + \sum_{y \in S_x} f_i(s_y, s_x)$

Each user visiting pattern is then represented using an array with each entree corresponding to the probability that a user visits this zone in relation to the overall visiting volume of the respective zone. To obtain this probability-representation, the data are normalized: $\tilde{V_i, s_x} = V_i, s_x / \sum_{j=1}^{N} V_i, s_x$. This procedure results with *spatial visiting extent user profiles*.

In the following we explain how the visiting extent user profile vectors used in the clustering process are created from user activity data. Let us consider a squared area partitioned into nine zones, as shown in Table 2a, and let us consider a single user that travels from $Z_{1,1}$ to $Z_{2,3}$. This trip would count as one instance at $Z_{1,1}$ and one instance at $Z_{2,3}$ (see Table 2b). Next, we project the 2D grid in one dimension, resulting in the vector represented in Table 2c for our example. For illustration, consider a more elaborate travel activity of one user during a selected time window as shown in Table 2d, resulting in the grid representation of Table 2c, and projected into our uni-dimensional array of Table 2d.

Next, we cluster users according to their normalised visit probability array. The clustering approach adopted is based on a Gaussian Mixture model, implemented using the Expectation Maximization algorithm. The choice of this method is mainly motivated by its capability of performing a soft classification, i.e. it considers the probability that a data point (user) belongs to each cluster and assigns it to the one for which it is most likely to belong (i.e. has the least distance from the centroid of the respective cluster).

3. Application

Stockholm County is comprised of 26 municipalities expanding over 6519.3 km^2 built over an archipelago and is home to 2.37 million inhabitants. Stockholm Region is the public transport authority overseeing all public transport services in the county. The multi-modal public transport system consists of bus, tram, metro, commuter train and ferry services. The network consists of more than 5700 stops served by a rail network of 469 km and more than 9,000 km of bus service network. More than 1.2 million trips are performed on an average weekday by about 600,000 travellers.

The fare scheme in Stockholm county involves tapping-in only. As part of a previous study, the virtual tap-out location was inferred for each trip and a transfer inference algorithm was applied. The details of

Table 1
Zonal visiting frequency user profiles.

	A	B	C	D	E
Adam	0	30	4	0	24
Eve	2	3	16	18	0
Abel	0	0	0	13	3

(a)

	A	B	C	D	E
Adam	0.0%	51.7%	6.9%	0.0%	41.4%
Eve	5.1%	7.7%	41.0%	46.2%	0.0%
Abel	0.0%	0.0%	0.0%	81.3%	18.8%

(b)

	Most visited	2^{nd} most	3^{rd} most	4^{th} most	Least visited
Adam	51.7%	41.4%	6.9%	0.0%	0.0%
Eve	46.2%	41.0%	7.7%	5.1%	0.0%
Abel	81.3%	18.8%	0.0%	0.0%	0.0%

(c)

Table 2
Visiting extent user profiles vector.

$Z_{1,1}$	$Z_{1,2}$	$Z_{1,3}$
$Z_{2,1}$	$Z_{2,2}$	$Z_{2,3}$
$Z_{3,1}$	$Z_{3,2}$	$Z_{3,3}$

(a)

1	0	0
0	0	1
0	0	0

(b)

Z	$Z_{1,1}$	$Z_{1,2}$	$Z_{1,3}$	$Z_{2,1}$	$Z_{2,2}$	$Z_{2,3}$	$Z_{3,1}$	$Z_{3,2}$	$Z_{3,3}$
N	1	0	0	0	0	1	0	0	0

(c)

$Z_{1,1}$	$Z_{2,3}$	20
$Z_{2,3}$	$Z_{1,1}$	20
$Z_{1,1}$	$Z_{2,2}$	4
$Z_{1,1}$	$Z_{3,2}$	2
$Z_{2,3}$	$Z_{2,1}$	3
$Z_{2,2}$	$Z_{2,3}$	1

(d)

46	0	0
3	5	44
0	2	0

(e)

Z	$Z_{1,1}$	$Z_{1,2}$	$Z_{1,3}$	$Z_{2,1}$	$Z_{2,2}$	$Z_{2,3}$	$Z_{3,1}$	$Z_{3,2}$	$Z_{3,3}$
N	46	0	0	3	5	44	0	2	0

(f)

these inference algorithms and a discussion of their validity and limitations are available at Kholodov et al. (2021). Consequently, given a disaggregate tap-in transaction database, a travel diary can be constructed for each card-holder where each entree is a journey performed during the course of the analysis period, containing the origin stop and (inferred) destination stop along with their respective time stamps. The output of this process constitutes the main input for our study.

Since our interest here is in exposing the range of destinations visited by individuals, i.e. diverse shopping, recreational, social visits and errands-related destinations that each traveler visits, a relatively long analysis period is needed in order to accumulate sufficient data that allows establishing the spatial extent of one's travel patterns. The latter are subject to seasonal variations (especially in places with stark seasonal characteristics, such as Stockholm) and we therefore choose to perform the analysis using records from one year, 2019, as an analysis of a shorter period might be biased towards travel patterns characteristic of the respective season(s). Our analysis is therefore based on data from January 1, 2019 to December 31, 2019, with the exception of the month of July during which the data warehouse was under maintenance works. In total, 468,596,472 journeys were performed by 7,191,376 card holders during the 11-months analysis period. This dataset has been processed and employed to study user temporal travel patterns (Cats and Ferranti, 2022a) and classify urban areas in terms of their attractiveness as activity centers (Cats and Ferranti, 2022b).

While no personal information is available at the card-holder level for this study, we use zonal-level socio-demographic and socio-economic data made available by the Swedish central bureau of statistics per census zone (there are 1251 such zone in the case study area). As described in Section 2.1, we do so based on the inferred home zone per card holder.

Given our interest in analyzing longitudinal data to study user behavioural patterns, we remove card-holders that use single tickets. This resulted in removing 38% of the cards, associated with 20% of all journeys. Consequently, we are left with a total of 4,423,783 remaining cards which performed 371,285,809 journey records.

An additional filter is applied solely for the analysis described in Section 2.3. Here users for which a home zone cannot be reasonably inferred are excluded. The total remaining users and journey records for this specific analysis are 3,782,954 and 368,710,217, respectively. Note that while this reflects a loss of 14% of the users (e.g. visitors and tourists), only 0.68% of the journeys are discarded, since frequent passengers are not affected by this filtering.

4. Results and analysis

4.1. Generating travel demand zones

The clustering procedure detailed in Section 2.2 has been applied for our case study. The values of the integrated metric, $m(k)$, for different number of clusters are shown in Fig. 1. Even though 15 clusters yield the optimal metric value among all values tested (up to 150), we have chosen to opt for $k = 29$ since it allows for a more nuanced analysis of geographical variations for our case study area and is the second-best local optima. In Fig. 2 we display geographically the stop clustering results along with the respective number of card holders residing in each of the obtained zones based on the results of the home zone inference procedure described in Section 2.1.

4.2. User exploration segments

We now turn to the clustering of users into distinctive exploration profiles. For each of the 3,782,954 cards included in our analysis we construct a vector consisting of 29 entrees, the number of zones for which stops have been clustered as described in the previous sub-section. Each of the entrees indicates the number of journeys for which the respective passenger has visited a given zone, i.e. this zone has served as a travel destination, during the course of the analysis period. For illustration purposes, we show in Fig. 3 an example of a zonal visiting frequency user profiles for a selected traveller.

For each of the possible number of clusters considered, we have run the algorithm 30 times using different starting conditions in order to find the best performing partitioning. The goodness of the clustering is assessed using the silhouette index which is calculated based on the mean intra-cluster distances and the mean nearest-cluster distance. The silhouette index value ranges between -1 and 1 with a higher value indicating that members of a cluster are similar to each other and distinctive from other clusters (Rousseeuw, 1987). The average silhouette index values obtained for number of clusters of up to 8 are shown in Fig. 4. We opt for three clusters in this case since, using the elbow rule-

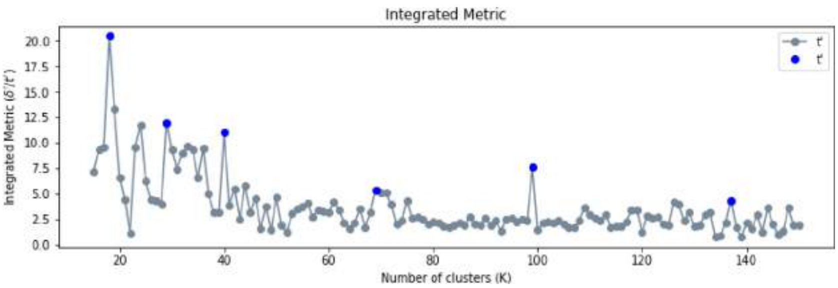


Fig. 1. Integrated metric $m(k)$ value per number of clusters within the considered range.

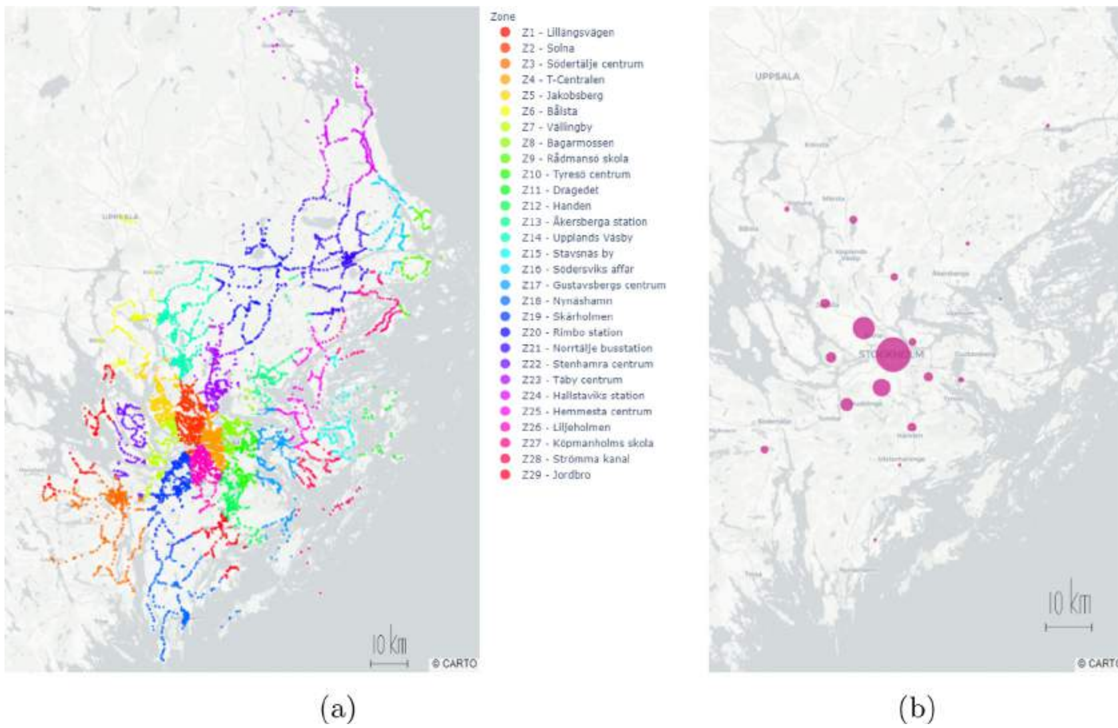


Fig. 2. Travel demand zones resulting from the 29 clusters (left), number of card holders residing in each zone based on our home-zone assignment results (right).

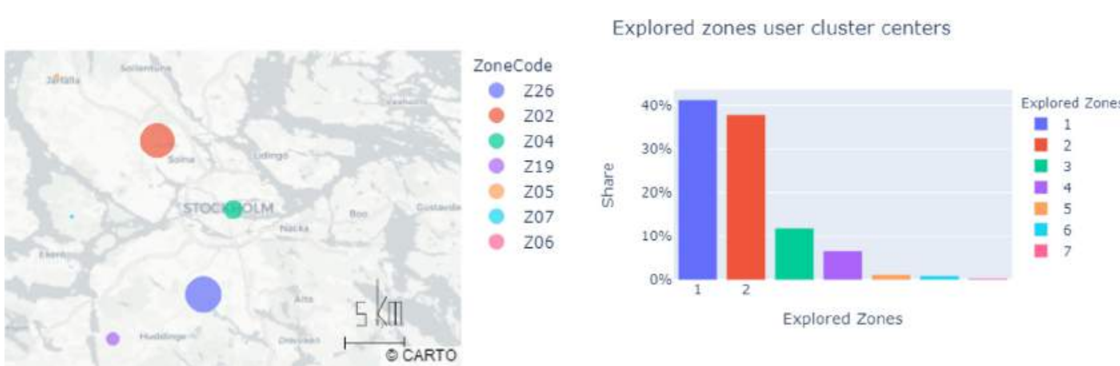


Fig. 3. Geographical representation of a zonal visiting frequency user profile for a single traveller with larger nodes indicating zones visited more frequently (left) and the corresponding visiting frequency profile with zones presented in a descending order (right).

of-thumb. In addition, we found the results of three clusters to capture the most interesting patterns from an interpretative point of view.

The resulting cluster centers are presented in Fig. 5. The y-axis shows the share of trips performed by users belonging to a certain cluster that are destined to the first most visited zone by each user, the second most visited zone by each user etc. As described in Section 2.3, the profiles are characterised in terms of the distribution of trips made over zones. As can be seen the identified clusters considerably differ in terms of the variety of their travel destinations. We identify three user profiles with regard to their zonal visiting frequency profile:

- **Local**: users which mostly (more than 90% of the trips) travel to a single zone in the system. These users are mostly travelling within their home-zone area for a variety of trip purposes.
- **Commuter**: users that visit primarily two zones and for which the two most frequented zones are visited almost equally frequently (50% and 40% of the trips). These users are arguably likely to be

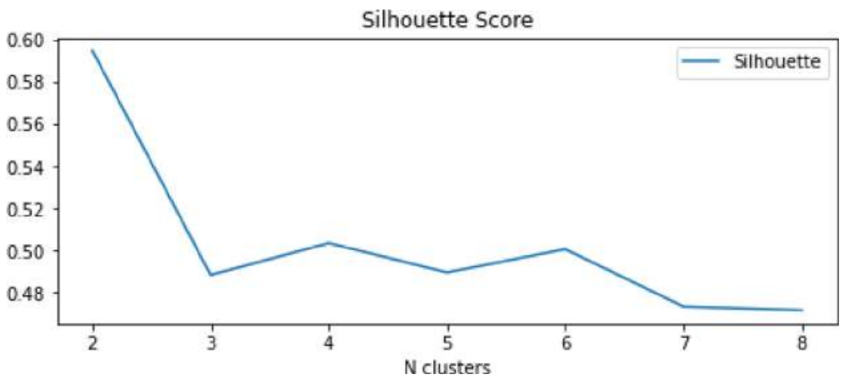


Fig. 4. Silhouette index for number of clusters selection.

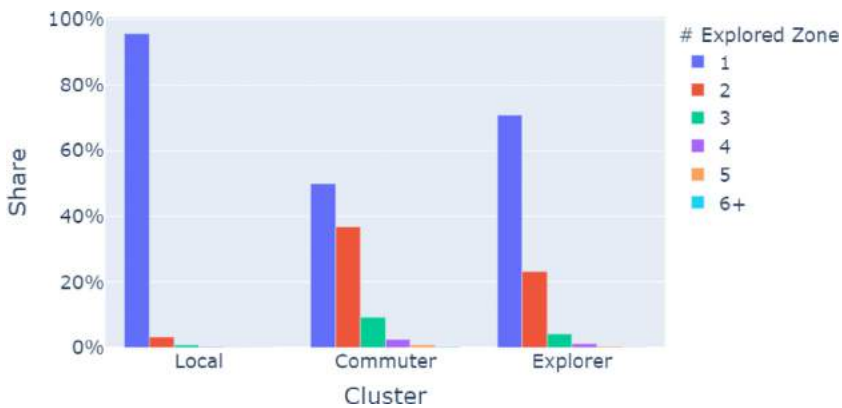


Fig. 5. Zonal visiting profile per user exploration segment.

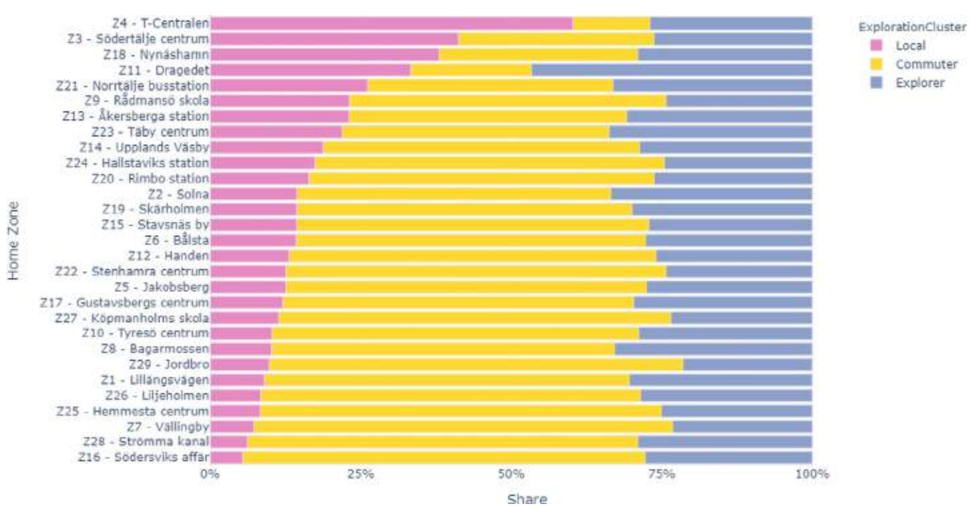


Fig. 6. Share of user visiting pattern segment per home-zone area.

commuters travelling back and forth between the home-zone and work-zone.

- **Explorer**: users for which there is a predominant destination zone (the destination of about 70% of their trips), but they still visit several other regions of the city to various extents.

The plurality of the card holders belong to the 'Commuter' cluster with 39.1% of all of the card holders, followed by 'Local' with 32.3% and only 28.6% of the card holders categorised as an 'Explorer'. Clearly, the geographical size of the travel demand zones considered is highly consequential for the number of zones visited by any individual travellers. For example, the selected travel demand zonal clustering resulted with zones that have a diameter of more than 10 km for some of the more peripheral parts of our case study area. Consequently, travellers residing in these zones will be labelled as 'Locals' if they mostly travel within its boundaries. For reference, such a diameter corresponds to the grouping of 3–4 stations along a commuter rail line.

We then turn to analysing the composition of user segments per home-zone. The share of each segment amongst card-holders residing in each of the zones is shown in Fig. 6. The reader may refer to Fig. 2 in order to geographically identify the zone using the displayed zone number and name. As can be expected, areas with high job intensity such as the central parts of Stockholm city (Z-4 T-Centralen, service and retail), Södertälje (z-3, manufacturing) and Nynäshamn (z-18, harbor), have a higher share of 'Local' users. The 'Commuter' type is predominant for those areas that are close to an urban center, e.g. Z-7, Vällingby and Z-29, Jordbro. The share of users belonging to the 'Explorer' type is overall evenly distributed across zones, with a peak for users residing in the archipelago areas (i.e. z-11, Dragedet).

Fig. 7. Visiting heat map representation of for an individual traveller over the 2km by 2km pixels grid.

Table 3
Socio-economic attributes per user visiting profile.

Attribute	Commuter	Explorer	Local	Mean
Income (annual in '000 SEK)	269	280	299	281
Social Index (1–10)	7.74	8.44	9.09	8.35
Foreign background	12.56%	11.86%	9.87%	11.58%

Next, we examine key socio-demographic attributes of users assigned to each of the three visiting profile clusters. Note that this information is obtained from the underlying census zones. Summary statistics are summarised in Table 3. Social index is an aggregate metric that is determined per census zone based on an array of social variables of the respective residents (including employment, education, dependency on social benefits). Residents born in a foreign country or born to at least one parent that was born in a country other than Sweden, are considered to have a foreign background by the Swedish central bureau of statistics. As can be seen, users following a 'Commuter' visiting pattern reside in areas characterised by a lower social index, lower than average income level and a higher than average share of residents from foreign background. The opposite holds for 'Local' users. 'Explorer' users reside in areas which are on par with the overall mean values across the case study area.

4.3. User segments by travel pattern spatial extent

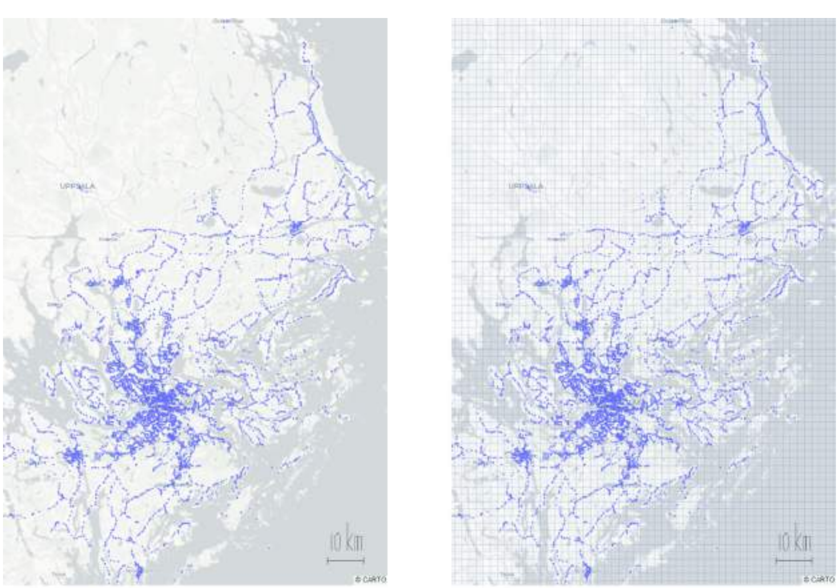
We follow the method described in Section 2.4 in order to analyze the spatial extent of the area visited by each user. For each of the 4,423,783 cards included in this analysis we generate a spatial visiting extent user profile with the share of journeys destined to each spatial unit considered. We illustrate this using a heat map representing the share of visits per grid cell as shown in Fig. 7 for an example user.

For the analysis of spatial analysis extent, we choose to overlay a grid over the case study area. On the one hand, a more finely meshed grid implies a larger number of cells, posing the risk of over-fitting and scarcity of stops per cell in peripheral parts of the network. On the other hand, a more dispersed grid would instead bundles many stops within the same cell, and may compromise geographical nuances. We have experimented with various grid sizes ranging from 0.5km on 0.5km to 2.5km on 2.5km with 0.5km increments. In addition, the type of co-variance matrix to adopt for the Gaussian Mixture Model has to be specified.

To evaluate the different configurations we calculate for each of them the BIC and the AIC of 10 randomly sampled 10% subsets of the data, based on which we have selected using grid cells of 2km on 2km. The configuration using a mesh with 2×2 km cells and a diagonal type of co-variance yielded a total of 15 clusters.

With this size, the grid covering the entire case study consists of 54×86 cells (see Fig. 8. The number of active cells in the grid, i.e. the number of cells where at least one stop of the network is situated, is 1,154, whereas the total number of cells is 4644 (largely due to the large bodies of water in our case study area).

The mean of the Gaussians determining the centers of the 15 clusters are shown in Fig. 9, along with the share of users assigned to each cluster. The city center of Stockholm is clearly dominant in all clusters, in line with the highly monocentric structure characterising the structure of the Stockholm metropolitan area despite the recent emergence of secondary activity centers (Cats et al., 2015).



(a) (b)

Fig. 8. Overlaying a 2km on 2 km grid on the Stockholm County.

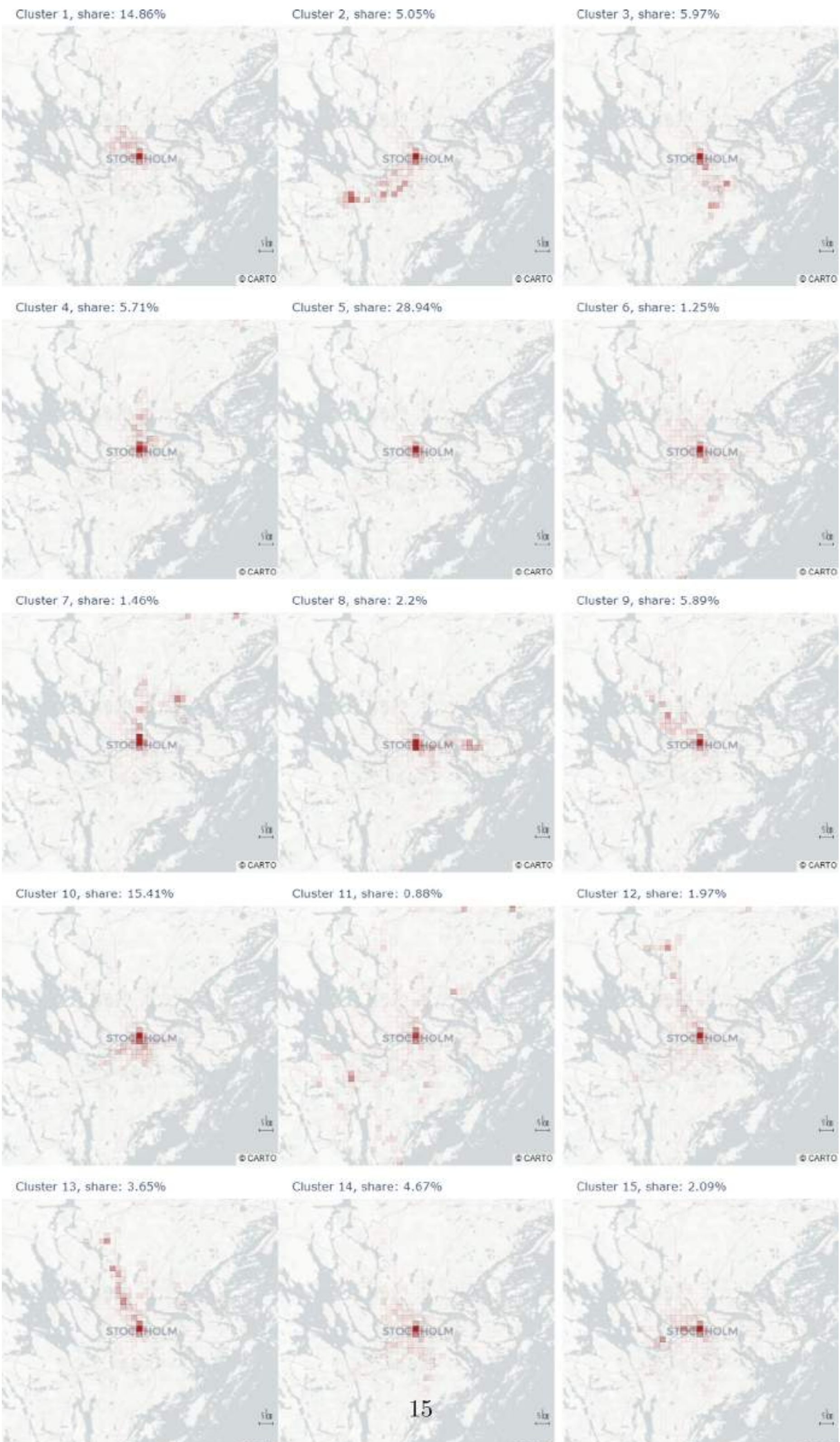


Fig. 9. Visiting heat maps of the 15 identified user segments.

In the following we discuss key observations from the clusters obtained. The largest cluster, gathering almost 29% of the users (three out of ten cards), is cluster 5. This cluster represents users that the spatial extent of their travel pattern is almost entirely limited to the central areas of Stockholm city - 66% of their journeys are confined to 7 neighbouring zones, i.e. 28 km^2.

We observe that the remaining clusters can be loosely described as falling into one of three categories. Several clusters exhibit similar shapes of travel extent yet oriented in different directions. For example, cluster 2 corresponds to users that travel between central parts of Stockholm and the city of Södertalje (south-west end of Stockholm County) as well as visit areas situated along the corridors connecting these cities.

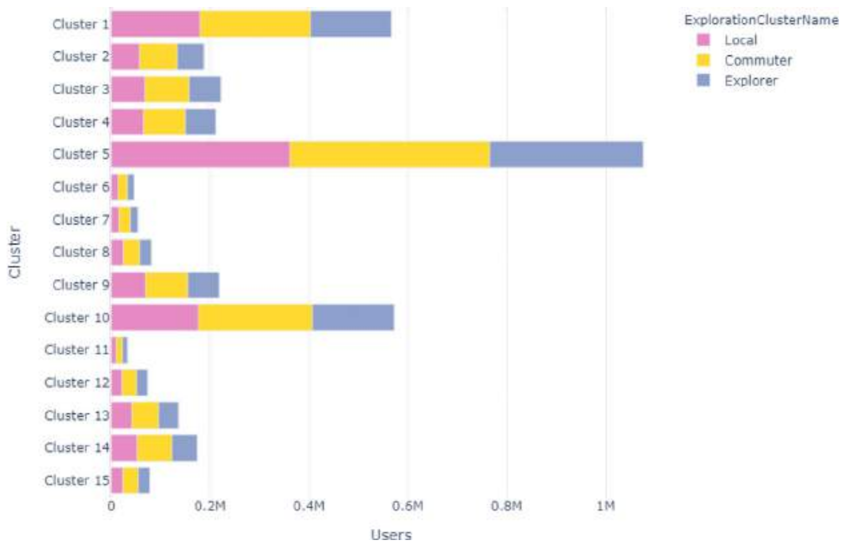


Fig. 10. Relation between the two clustering results - composition of user exploration patterns per user spatial extent segment.

A similar pattern emerges for cluster 8, but instead of Södertälje the spatial extent profile is oriented towards Gustavsberg-Värmdö. Other clusters following this pattern include cluster 7 (Stockholm - Norrtälje direction), cluster 9 (Stockholm - Jakobsberg-BÄlsta), and cluster 13 (Stockholm-Märsta).

Another group of clusters includes those exhibiting more sparse visiting patterns, forming a cloud shape with a variety of locations visited more uniformly, yet mostly confined to a limited part of the case study area. The following clusters fall in this category: cluster 1 (North-West area of Stockholm city - Solna), cluster 3 (South-East area of Stockholm city - Tyresö, Handen), cluster 4 (North of Stockholm - Danderyd, Täby), cluster 10 (South-West area of Stockholm - Skarholmen, Huddinge, Farsta), and cluster 15 (West - Ekerö, Bromma)

The last group of clusters includes those that exhibit a more disperse pattern, characterized by scattered visits to non-neighboring parts of the case study area: cluster 6, cluster 11, cluster 12, cluster 14.

Next, we turn into investigating the relation between the results of our two methods for clustering travellers based on the spatial features of their travel profiles: (i) exploration pattern, and; (ii) spatial extent. Fig. 10 shows the number of users belonging to each of the exploration clusters for each of the 15 spatial extent clusters identified, also providing a graphical indication of the share of users assigned to each cluster. As can be seen, members of all clusters are widely distributed over the three exploration patterns. The share of Commuters is the lowest amongst Cluster 1 members (37.6%) which is highly concentrated in the center and highest amongst Cluster 6 members (41.0%) which has the central station area as the only hot-spot with large parts of the case study area visited with lower frequency. The mirror picture for these clusters are the shares of Locals, which are the lowest at Cluster 6 (30.3%) and highest at Cluster 1 (33.6%). The share of Explorers is highly stable across spatial extent clusters, hovering between 28–29% for all clusters.

5. Conclusion

We proposed two methods for clustering travellers based on the spatial properties of their mobility patterns using longitudinal travel data. These methods were applied for the case of smart card data from the multi-modal public transport system of Stockholm County. After partitioning the network based on a data-driven approach, we represent users patterns in terms of zonal visiting frequency profiles and grid-cells spatial extent heatmaps. We identify three clusters - denominated Locals, Commuters and Explorers - that best describe the zonal visiting frequency and show that their composition varies considerably across users' place of residence and related demographics. We also unravel 15 clusters of visiting spatial extent which form four groups that follow the same overall trend in terms of intensity and concentration of the zones visited, yet prevalent in different locations across the network. The cross-analysis of the results of the two clustering methods reveals that user segmentation based on exploration patterns and spatial extent are largely independent, i.e. the shares of Locals, Commuters and Explorers being overall on par with the overall composition for all spatial extent clusters. This indicates that the two different clustering approaches provide fundamentally different insights into the underlying spatial properties of individuals' mobility patterns.

The user segmentation approach proposed in this study can be used to devise products and fare schemes that cater for specific mobility patterns in terms of frequency and extent of locations visited across the network. For example, users that exhibit 'Locals' travel patterns might be offered subscriptions that are confined to their home zone. In contrast, 'Commuters' can be offered to select subscriptions that cover a limited number of zones of their choice, whereas 'Explorers' might prefer a subscription that covers a larger part of the service area. In a similar fashion, the visiting heat maps can be used to define fare products that pertain to specific parts of the service area. For example, in the case of Stockholm a number of user clusters and a considerable share of all travellers are mostly confined to either the northern part of the service area or the southern part of the service area, with very seldom visits across the water. Thereby, the geographical demarcation of fare zones might be revisited based on the visitation profiles.

Additional applications of research findings include the identification of gaps in the network that may benefit from increased accessibility. The analysis conducted in this study can be performed for specific time periods of interest (e.g. off-peak, weekends) to reveal the characteristics and composition of user segments for different time windows as the relations between those and the underlying zonal generation. The choice of the number of travel demand zones should be made by the analyst based on the desired level of granularity relevant for potential applications. Furthermore, future research may investigate the interactions between alternative clustering techniques for demand zones generation and the user clustering results or even attempt to fuse the two clustering steps into a single integrated clustering exercise. Moreover, future research may also test how the user clustering results may change as a function of the observation period. We do not expect however significant changes for observation periods that extend beyond one year.

Future research may also investigate how the identified segments have evolved over a long period of times, for example in relation to various developments and events. In the case of Stockholm, this includes long-term policies such as stimulating a more polycentric regional development and specific interventions such as the change from a zone-based fare scheme to a flat-fare scheme. Furthermore, this can be especially insightful in understanding changes in mobility patterns and user segmentation as a consequence of major network developments like the opening of new infrastructure and services or significant disruptions such as the COVID-19 pandemic. Future research may also characterise different parts of the network in terms of the composition of users they attract.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.urbmob.2022.100035.

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What if Air Quality Dictates Road Pricing? Simulation of an Air Pollution-based Road Charging Scheme☆

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A R T I C L E I N F O

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Toll
Traffic simulation
Intelligent transportation system
Smart city

A B S T R A C T

Road tolls serve various purposes, such as to refinance the road infrastructure or to regulate traffic. They are typically levied for the use of a freeway or the entire road network of a region or country. Toll charges may depend on the duration of use, the vehicle's emission class, the time of the day, the distance travelled, or the traffic volume. The primary objective of a few recent toll system deployments is to internalize externalities with respect to vehicle-caused air pollution. However, the air quality along the toll roads has so far not been considered to directly influence road usage prices. This article investigated by simulation the expected monetary expenditure for drivers and the traffic impact of applying a new distance and air pollution-based charging scheme in the metropolitan region of Berlin. The road usage charges were determined on a per-trip basis by taking the vehicle's emission class, the distance travelled, and the air pollution levels along the route into consideration. The simulation results indicate that it is beneficial for drivers to avoid areas of high air pollution in order to reduce the trip's total road usage charges. The average additional detour distance is thereby short in comparison to the route's length and the resulting additional emissions do not increase to the same extent as the number of detours, since detours are partly even shorter in terms of distance. The explorative analysis gives initial insights into the traffic effects of a charging scheme in which air pollution dictates road pricing.

Introduction

Urban air pollution originating from the sector of road transport is known to significantly increase the mortality and morbidity rate of the affected population (Künzli et al., 2000). For 2018, 18,400 premature deaths in the U.S. can be attributed to the exposure of traffic-related air pollution (Dedoussi, Eastham, Monier & Barrett, 2020). The situation is further complicated by the fact that the global traffic demand is expected to increase over the next decade (International Transport Forum, 2019). Successfully applied regulatory measures to fight traffic-related air pollution include the promotion of environmentally friendly means of transport (Xia et al., 2015), introduction of traffic control signal systems (Wood & Baker), or the development of more efficient combustion engines and aftertreatment systems. Nevertheless, the air pollution in many metropolitan regions remains to exceed many times the limits recommended by the World Health Organization (2016) or as set by The European Parliament & the Council of the European Union (2008).

In Germany, local authorities of cities particularly affected by urban air pollution are being forced (due to possible penalties) to introduce driving bans for vehicles of particular emission classes (Fensterer et al., 2014) or to tighten speed limits on particular road segments (Vardoulakis et al., 2018). However, depending on how driving restrictions are implemented, they may have little or no effect on the urban air pollution (Davis, 2017), worsen the air quality situation (Zhang, Lin Lawell & Umanskaya, 2017), or even encourage illegal behavior among drivers (Wang, Xu & Qin, 2014). Driving restrictions that proved to significantly reduce air pollution are - among others - the vehicle pollution charge Ecopass in Milan (Rotaris, Danielis, Marcucci & Massiani, 2010), the low emission zones (LEZ) in Germany (Jiang, Boltze, Groer & Scheuvens, 2017; Wolff, 2014), and the driving bans in Quito (Carrillo, Malik & Yoo, 2016). The regulatory measures are different and customized to the local particularities, but the impacts on the air quality are on a similar order of magnitude. In Milan, the European vehicle class dictates whether downtown Milan can be entered for free or by paying a charge that depends upon the vehicle's emission class. In Germany, older and high polluting vehicles are generally prohibited to enter LEZs. In Quito, the last digit of the vehicle plate determines the day a vehicle is prohibited to enter the restricted area during peak hours. These and similar driving restrictions are of intrusive

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nature and are not meant to change over a long period of time. They are set by municipalities and apply no matter how the urban air pollution eventually develops at each day and time of the day. Vehicles may be banned, and drivers be charged although on some days, for example, the fine dust concentration within the air might turn out to lie far below a value that is harmful to health.

To be more flexible, a few municipalities and urban areas started to introduce temporary LEZs that are only active in case high urban air pollution is predicted or happened in the past days. In Geneva, only vehicles with a state-issued vignette can drive within the LEZ during its active period. The last day's level of air pollution determines thereby the type of restrictions that apply for the vehicles. Despite operating in a more flexible manner with respect to changing environmental circumstances, an activation still needs to be announced a few hours in advance and an activation is valid throughout the day or at peak hours. These regulations prevent the system to react spontaneously to an unforeseen change of the air quality at the day of activation. A further drawback of currently deployed systems with temporary LEZs is that the extent of LEZs corresponds to administrative areas or are limited by well recognizable ring-shaped closed transport routes such as city-rings or circular railways. The range of a fixed LEZ roughly corresponds to the extent of the urban area that is affected by urban air pollution, but it does not necessarily represent it accurately on days with exceptional weather and traffic conditions.

Another principal challenge of applying access-based charging schemes to reduce air pollution lies in the fact that the costs of using the road network within an LEZ do not depend upon the real usage. The more a vehicle drives within an LEZ, the more it pollutes, but the costs remain constant in Geneva and for all LEZs deployed around the globe. The Green Activity Zones research project proposed a first-best toll, namely, to charge a driver of heavy-duty vehicles within a LEZ based on the emissions measured within the vehicle (Tretvik, Nordtømme, Bjerkan & Kummeneje, 2013). A similar first-best toll approach simulates vehicles in Munich that are charged based on their modeled emissions (Kickhöfer & Kern, 2015; Kickhöfer & Nagel, 2016). Both approaches propose charging schemes that are closely related to distance-based charging; a charging scheme that has gained more and more popularity in recent years. At toll plazas in France, a driver pays a charge that depends upon the distance travelled on the freeway. In Germany, drivers of heavy goods vehicles are obliged to pay a more fine-grained distance-based toll in case they use the federal highway network (Broaddus & Gertz, 2008). Instead of toll plazas, an on-board unit – as part of an electronic toll system - records the exact route so that a fine-granular charge based on a price per driven kilometer can be applied. But distance-based charging is currently not applied to deal with urban air pollution despite the proportional correlation between the distance travelled and the amount of emissions (Etyemezian et al., 2003).

Yet, the technological progresses of the last decade in the fields of mobile computing, mobile communication, outdoor localization, and electronic road pricing made it possible - today - to determine the route of a vehicle by satellite, accurate to the meter, at low cost, and to transmit it reliably to a central authority for control and accounting purposes (Donath et al., 2009). Hence, with the proven technical and economic feasibilities of distance-based charging schemes, the European Union plans that until 2023, all European toll systems for heavy good vehicles as well as buses must switch to distance-based charging to improve fairness and environmental protection[1].

[1] https://www.europarl.europa.eu/news/en/press-room/20181018IPR16551/reform-of-road-use-charges-to-spur-cleaner-transport-and-ensure-fairness

At the same time, sensors for measuring air quality have become more compact, more reliable, and less expensive (Jovašević-Stojanović et al., 2015). The unit price has even reached a level that allows private households to measure air quality with their own sensor stations and share the results with the community (Muller et al., 2015). Coupled with communication modules, they can now be an integral part of city-wide dense sensor networks, enabling the urban air quality to be measured in real time and across the entire city (Sivaraman, Carrapetta, Hu & Luxan, 2013). It is therefore technically possible to develop an intelligent transport system (ITS) that takes the current air quality distribution within a metropolitan region into account. What role the urban air quality can play in an ITS depends on the primary objectives, local conditions, and political decision-makers. If, for example, air pollution hotspots should be relieved by additional traffic-related emissions, then the spatial and temporal extent of LEZs could be dynamically determined based on the time-dependent spatial distribution of the air pollution across an urban area (Rodriguez Garzon & Küpper, 2019). In other words, the city-wide air quality dictates the shape, size, and location of temporary LEZs. In combination with distance-based charging, a driver could then be charged based on the real distances travelled through dynamically determined LEZs. A temporary LEZ based on high air pollution levels can thereby be associated with high transit prices per kilometer to make a transit through an air pollution hotspot less attractive for a polluter than passing through low polluted area. The charging scheme can also optionally be combined with emission class-dependent pricing. The tariff per kilometer and air pollution level will then - in addition - depend upon the vehicle's emission class. A distance and air pollution-based charging scheme may lead drivers to avoid passing through heavily polluted LEZs, respectively to stop worsening the situation by an additional polluter, and to switch, instead, to more environmentally friendly means of transport.

To the best of our knowledge, a highly dynamic road pricing scheme with spatially and temporally evolving LEZs has not been investigated yet. To do so, a multitude of research questions arise and need to be examined with respect to, among many others, the technical feasibility, usability from the perspective of the road users, the acceptance among road users, the predictability of returns for the toll operators or collectors, its implications on the mobility behavior, its influence on the urban air pollution and its socio-economic effects. This article investigates the implications of such a distance-based and air pollution-aware charging scheme on the mobility behavior by exemplarily simulating road network usage within the city of Berlin. LEZs are hereby modeled based on the spatial distribution of the urban air pollution across the city. The traffic of 10% of the population was simulated for a period of 24 h on three days with significantly different air pollution characteristics. An open data-based transport demand model for Berlin was used in conjunction with real measurements of the particulate matter concentration taken by privately-owned sensors that were located within the limits of Berlin. Although needed to finally evaluate the charging scheme with respect to the objective of improving the overall air quality in an urban area, its influence on the urban air pollution was not determined because of a lack of yet to be developed particulate matter dispersion models, a fine-granular spatiotemporal wind and weather model for the city of Berlin and a comprehensive list of location-specific polluters other than motorized vehicles with their individual contributions to the particulate matter concentrations. However, the results of simulating road usage - with a hypothetical charging scheme being in place and the air pollution being modelled by means of real world measurements - are intended to give first impressions of how parts of the traffic might shift to alternative routes, what daily volume and compositions of toll trips can be expected in Berlin for days with low, medium, and high urban air pollution and how the vehicle-caused emissions might change due to road users intentionally bypassing LEZs with high transit costs.

In the following section, recent approaches to set road, parking facility, and public transport prices based on the predicted or current urban air pollution are discussed. The core concept of the new air quality and distance-based charging scheme is then introduced in Section Concept. In Section Simulation, the simulation setup for Berlin and the simulation results are presented. Assumptions, limitations of the simulations, and the charging scheme in general are summarized and discussed in Section Discussion. The article concludes with the major findings, open research questions, possible applications, and extensions of the charging scheme.

Related work

The pros and cons of applying dynamic road pricing schemes to tackle congestion and air pollution have been discussed extensively over the past decades (Saharan, Bawa & Kumar, 2020; Yang & Huang, 2005). The main property that distinguishes the concept of dynamic road charging from its static counterparts is the fact that either the road usage fee as a whole or only a fraction of it may vary depending on the situational circumstances. Time of the day (Chen, Xiong, He, Zhu & Zhang, 2016), road network load (Supernak, Steffey & Kaschade, 2003), and car occupancy are the most widespread discussed and considered price-influencing situation factors in literature or in real world deployments. Despite the considerable amount of work examining the impact of different charging schemes on the air quality (Beevers & Carslaw, 2005; Cavallaro, Giaretta & Nocera, 2018; Johansson, Burman & Forsberg, 2009; Rotaris et al., 2010), only a few research articles suggest that the urban air quality should be considered, directly or indirectly, through metrological properties, as an additional variable for dynamic road pricing. Coria, Bonilla, Grundström & Pleijel (2015) propose to adjust road prices dynamically so that the sum of traffic-related emissions do not exceed the maximum air pollution capacity of an environment (assimilative capacity). Coria et al. (2015) use the wind speed to estimate the current assimilative capacity and the current traffic load to vary the prices accordingly, instead of measuring the emissions respectively air quality. The location-specific correlations between wind speed, air pollution dispersion, and traffic network load are thereby predetermined based on historical hourly wind speed, air quality, and traffic flow data for the city of Stockholm. The road usage prices do not reflect the current air quality itself but the atmosphere's ability under the current wind and traffic conditions to cope with traffic-related air pollution, without suffering from long-term environmental damage. Further investigations revealed that pollution peaks indeed can be smoothed if road charges take the air pollution dispersion into consideration (Coria & Zhang, 2017). Coria's approach and the approach taken in this article differ in the sense that Coria et al. (2015) examined the impact of a traffic-, weather and environment-aware charging scheme on the air quality while this article deals with the impact of an air quality-based charging scheme on the traffic itself. Despite not dealing with road usage charges, Reddy, Yedavalli, Mohanty, & Nakhat, 2017 sketched the idea to link future public transit prices in general to the predicted urban air pollution. Poorzahedy, Aghababazadeh and Babazadeh (2016) follow a similar idea and propose to determine the next day's cordon access fees and rates for park & ride facilities at public transport hubs based on the current carbon oxide concentrations and the next day's weather forecasts. The objective is to make public transport pricewise more and private vehicle transport less attractive in case high air pollution levels are forecasted. Although lesser flexible with respect to price determination, Costabile and Allegrini (2008) present a prototypical ITS that forecasts air pollution levels for Beijing and automatically imposes driving restrictions in case thresholds will likely be exceeded. Today, similar systems for air quality-dependent driving restrictions are successfully deployed in Geneva, Budapest, Madrid, and Oslo. But road prices remain to be determined or driving restrictions be imposed based on air quality estimations or forecasts. The estimated or forecasted air quality does not only deviate from the actual air quality at the time a car ride is charged but may even not be experienced everywhere in a fixed LEZ or cordon with the same intensity. Rodriguez Garzon and Küpper (2019), in contrary, describe the concept of an air pollution-aware and distance-based charging scheme in which the price per kilometer depends upon the urban air pollution that is measured along the route. It incorporates distance-based charging to fairly price the environmental damage caused by a single car ride and it adjusts the fees dynamically to the urban air pollution to make the worsening of an already critical air pollution situation more costly than the worsening of a non-critical situation. This article adopts this new and highly dynamic concept of road pricing and applies it in a customized way hypothetically to the city of Berlin.

Air pollution-aware charging

The road charging concept under investigation comprises of distance-based charging and air pollution and emission class-dependent road usage prices. The principal idea of the concept is that the road usage price per kilometer increases as urban air pollution levels rise along the way, no matter, whether the air pollution originates primarily from traffic or other sources such as wood burning or the industry sector. The concept's main objective is to reduce the urban air pollution at pollution hotspots by encouraging or incentivizing the drivers to reconsider the transport mode and/or the route decision. By changing their route, drivers are supposed to spread the emissions more evenly across the city. The charging happens independently of the traffic load or assimilative capacity of the environment. Even if the environment might be able to cope with a very high air pollution without suffering long term damages, prices per kilometer will be high if air pollutions levels are high. This does not mean that the proposed charging scheme is not able to take the assimilative capacity or traffic load into consideration. However, in this article, it will solely be investigated in an isolated and unbiased manner to simplify the interpretation of the results. In further studies and possible extensions, the assimilative capacity could, for example, be used to support the tariff specification process while the variable traffic load can serve as another dynamic variable for the price calculation.

In general, air pollution caused by traffic is made up of different components. Gas emissions in form of nitrogen dioxide, carbon monoxide, and sulfur dioxide or particulate matter are only some of the well-known waste products of burning fossil fuel in combustion engines (Berkowicz, Winther & Ketzel, 2006). The urban air pollution is usually given in the form of an air quality index (AQI) (Cheng et al., 2007). An AQI groups together different pollutants and maps the combination of pollutant concentrations to a few pollution levels, e.g., low, medium, and high. Instead of progressively linking the road usage price directly to the individual concentrations of pollutants in the air, in the proposed concept, the road usage price at a location depends primarily on the location-specific and discretized AQI level. A current AQI level can either be determined for a whole toll area as applied in Geneva for the air pollution-dependent LEZ, or at each position individually. An individual AQI level per arbitrary position, however, is only possible if the air quality can be determined with high accuracy, at any road within the toll area. Hence, the air quality sensor density across the toll area needs to be sufficiently high to be able to accurately interpolate air pollution levels without significant deviations from the real exposure. Given these requirements are fulfilled, then, at each point in time, a toll area can be spatially segmented into coherent zones with the same AQI level. Fig. 1 illustrates exemplarily the particulate matter-driven AQI zones as determined for the 24th of January 2020 at 9:00 AM in the downtown of Berlin. The charging scheme interprets each blueish AQI zone as a temporary LEZ with a fixed price per kilometer as applied throughout the whole LEZ. AQI zones might contain holes in which different AQI levels are measured or interpolated. The resulting temporary LEZs may therefore contain smaller LEZs that are associated with different road usage prices. Since temporary LEZs are not statically defined by a human instance but being processed based on the urban air pollution distribution,

Fig. 1. Particulate matter-driven AQI zones for downtown Berlin on the 24th of January 2020 at 9:00 AM, given in μg/m^3.

city, district limits, or distinctive infrastructures, such as city highways, do not serve as delimiters for the temporary LEZs

As the measured air quality at a given position can vary considerably within a short period of time, e.g., due to a single gust of wind, so can the extent of the temporary LEZs vary significantly or the LEZs even "move" or disappear. To deal with the dynamics of urban air pollution and the operational implications on an air pollution-based charging scheme, two distinct measures are taken. To cope with strong short-term fluctuations at a sensor, the air pollution is measured over a certain period and the sensor readings being averaged using the inverse distance weighting method. The values measured last are thereby given a higher weight to take trends into account. The resulting LEZs thus reflect the geographical distribution of air pollution more accurately, but still change over time. If temporary LEZs were determined in very short time intervals under adverse weather conditions, it would be difficult, if not impossible, to predict the road usage charges for a longer car ride. However, according to the Smeed Report (Ministry of Transport, Great Britain, 1964), price stability and ascertainability by the road user are crucial factors for the success or acceptance of a road charging scheme. To make the price of a journey more predictable, temporary LEZs are active for a certain amount of time by freezing the measurement results (AQI zones) for an activation period. For example, the air quality is measured from 1:45 PM until 2:00 PM and the resulting temporary LEZs are active from 2:00 PM until 3:00 PM. The longer the activation period is, the more predictable are road charges for a car ride. On the other hand, towards the end of an activation period, LEZs may tend to inappropriately represent the air pollution distribution because of changing weather conditions. Hence, there is always a trade-off between the accuracy of the air pollution distribution representation by means of temporary LEZs and the length of the activation period. To find the right balance, local conditions such as average driving time, driver acceptance, and the local dynamics of weather conditions must be considered.

In the proposed concept, the road usage price is not only linked to the temporary LEZ a vehicle is driving through but also to the vehicle's emission class. As it is common in today‘s ITSs and toll system installations, the higher the emission of a vehicle is, the higher is the base price per kilometer. The total road usage charge c_{total} of a car ride results from the LEZ transits charges for all passed AQI zones 1 to z:

$$c_{total} = \sum_{i=1}^{z} d_i * p(l_i, e)$$

An LEZ transit charge is determined by multiplying the distance travelled within the LEZ d_i with the price *p()* per emission class e and AQI level l_i of the AQI zone *i*. Thus, road usage charges are determined individually per trip, depending on the distance a vehicle traveled across air polluted zones. In contrast to LEZs in Germany and Switzerland, all vehicle types are permitted to enter temporary LEZs with arbitrary AQI levels.

For an operational deployment of the proposed charging scheme within an ITS, vehicles must be accurately locatable in a continuous fashion and air pollution must be directly measurable by connected sensors on a fine granular manner in a city-wide scale and accurately interpolatable at positions where no air pollution sensors are located. In addition, road users should be able to examine expected road usage fees prior to a trip and be notified of sudden price changes via a sort of connected mobile device such as a smartphone or on-board unit. But the investigations conducted in this article assume the dynamic charging scheme to be hypothetically applied to road network users independent of any concrete technical implementation of it. The reader is referred to the article "Pay-Per-Pollution: Towards an Air Pollution-Aware Toll System for Smart Cities" (Rodriguez Garzon & Küpper, 2019) for a more detailed discussion about the requirements of such a charging scheme like price predictability, the corresponding challenges like user acceptance and its technical feasibility.

Simulations

The traffic in Berlin was simulated with the air pollution-aware charging scheme being applied in order to determine the daily volume of transit journeys through AQI zones exemplarily on days with varying levels of urban air pollution. This makes it not only possible to estimate future revenues for the toll collector and local authorities, but also to examine the impact of the road charging scheme on the traffic and the traffic-induced emissions. The research questions investigated in this article are the following:

- **RQ1**: What is the overall toll volume in terms of expected AQI zone transits per day?
- **RQ2**: How often are tariff changes experienced by the drivers during a trip?
- **RQ3**: To what extent are AQI zones bypassed?
- **RQ4**: What are the characteristics of the detours?
- **RQ5**: To what extent are emissions from motorized vehicles changing?
- **RQ6**: What is the impact of detours on the traffic distribution?

Whether the proposed air pollution-aware charging scheme reduces the overall air pollution or, at least, helps to evenly distribute the emissions across the urban area are not investigated and remain as open questions for further research.

The greater area of Berlin was chosen as the hypothetical toll area because Berlin has sufficient air quality sensors distributed across the city area, only a minor amount of deep urban canyons due to mostly low multi-story or single-family buildings, flat terrain, and city-wide homogenous weather conditions. In addition, there is an open data-based transport demand model for Berlin publicly available (Ziemke, Kaddoura & Nagel, 2019). The synthesized transport demand model was developed by Ziemke et al. (2019) using different open data sources such as, e.g., a nation-wide census of Germany, commuter statistics, and local traffic counts. A comparison of the model's results with those of two independent travel surveys shows that it realistically emulates transport demand in and around Berlin. The reader is referred to the work of Ziemke et al. (2019) for more details about the synthetization and validation of the transport demand model. The investigations of the proposed charging scheme can then be conducted with urban air pollution and transport demand models that represent or, in case of the transport demand model, well approximate real-world conditions.

In the following, the experimental setup of the simulations is described, including the general assumptions and configurations. Afterwards, the simulation results are presented in detail.

Setup

Berlin has an urban area of approx. 891.68 km^2, a population density of approx. 4115 inhabitants per km^2 and a road network of approx. 5437 km length. Berlin is in a moderate climate zone with prevailing continental southwest winds and maritime northwest winds. Due to lesser traffic, flat terrain, weather conditions, and only a small manufacturing industry within the city limits, the air pollution is not as severe as in cities with a similar population of about 3.7 million. Nevertheless, on 27 days in 2018, a state-operated measuring station in Berlin recorded an exceedance of the limits for fine dust pollution with PM_{10}[2]

[2] https://www.berlin.de/sen/uvk/presse/pressemitteilungen/2019/pressemitteilung.775788.php

Table 1
Particulate matter-driven air quality index.

PM_{10} (μg/m^3)	0 - 20	20.1 - 35	35.1 - 50	50.1 - 100	>100
AQI level Air quality	0 very good	1 good	2 moderate	3 poor	4 very poor

(particulate matter with a diameter of 10 μm or less). However, 6 of the 16 state-operated and connected air quality measuring stations are located especially at major roads and 5 out of 16 are located at the outskirts or forests where a particularly high respectively low air pollution is expected[3]. Measurements taken in urban background roads may significantly vary from the air pollution levels measured along major roads (Boogaard et al., 2011). Hence, measurement stations along major roads are only of limited help to properly interpolate air pollution levels in their surroundings due to their strong bias towards high air pollution. Only a "*well-placed site*" allows to estimate proper air quality values for the surroundings (Williamsand et al., 2014). Privately-owned and operated air pollution sensors are installed at windows, on balconies, walls, or roof-top terraces and are arbitrarily located across a metropolitan region. Community-driven air quality measurement initiatives, in general, gained popularity over the last decade, leading to multiple deployments worldwide. In Berlin and similar metropolitan regions, the amount of privately-owned and operated sensors, as used for crowdsourcing air quality data, exceeds the number of state-operated sensor installations many times. During the first half of 2020, between 375 and 430 private air pollution sensors within the limits of Berlin contributed their sensor readings to the citizen science initiatives Luftdaten.info[4] (Blon, 2017) and OpenSenseMap[5]. Fig. 2 shows the location of Luftdaten.info- and OpenSenseMap-connected sensors across the metropolitan region of Berlin. Nine most probably faulty sensors were not considered because they delivered constantly air quality values that reached far beyond the ones of their closest neighboring sensors. Automatic outlier detection and filtering was deployed as well. The local sensor density correlates in Berlin roughly with the population density (Arandelovic & Bogunovich, 2014). The low sensor density in the north-west, mid-west, south-west, and south-west is attributed to a low population density because lakes and forests predominate the respective outskirts of Berlin.

Every two to three minutes, the air quality is measured by the privately-owned and operated sensors and the readings being transmitted to a central unit managed by the initiatives. Based on these crowdsourced and publicly available measurements in Q1 and Q2 of 2020, three days were selected to adequately represent days with low, medium, and high PM_{10} concentrations in Berlin. Fig. 3 visualizes the AQI zones for Berlin at each of the selected days at different day times. The discrete mapping of PM_{10} concentrations to AQI levels is based on the air quality index provided by the Federal Environment Agency in Germany[6]. Table 1 shows the mapping from PM_{10} values to AQI levels and air qualities as used throughout this article. AQI level 0 is considered as harmless to health and a transit through an AQI zone of level 0 will therefore not be charged. At the 25.03.2020 (low average PM_{10} concentration), southeast winds with wind speeds of about 7–17 km/h were measured throughout the day. At the 11.06.2020 (medium average PM_{10} concentration), northeast winds of about 6–8 km/h were registered while on the 24.01.2020 (high average PM_{10} concentration), north and east winds of about 2–14 km/h were measured. In general, wind speeds were low which in turn increased the accuracy of interpolations as described in the next paragraph. In this study, gases such

[3] https://www.berlin.de/senuvk/umwelt/luftqualitaet/de/messnetz/blume.shtml
[4] https://www.luftdaten.info
[5] https://www.opensensemap.org
[6] https://www.umweltbundesamt.de/berechnungsgrundlagen-luftqualitaetsindex

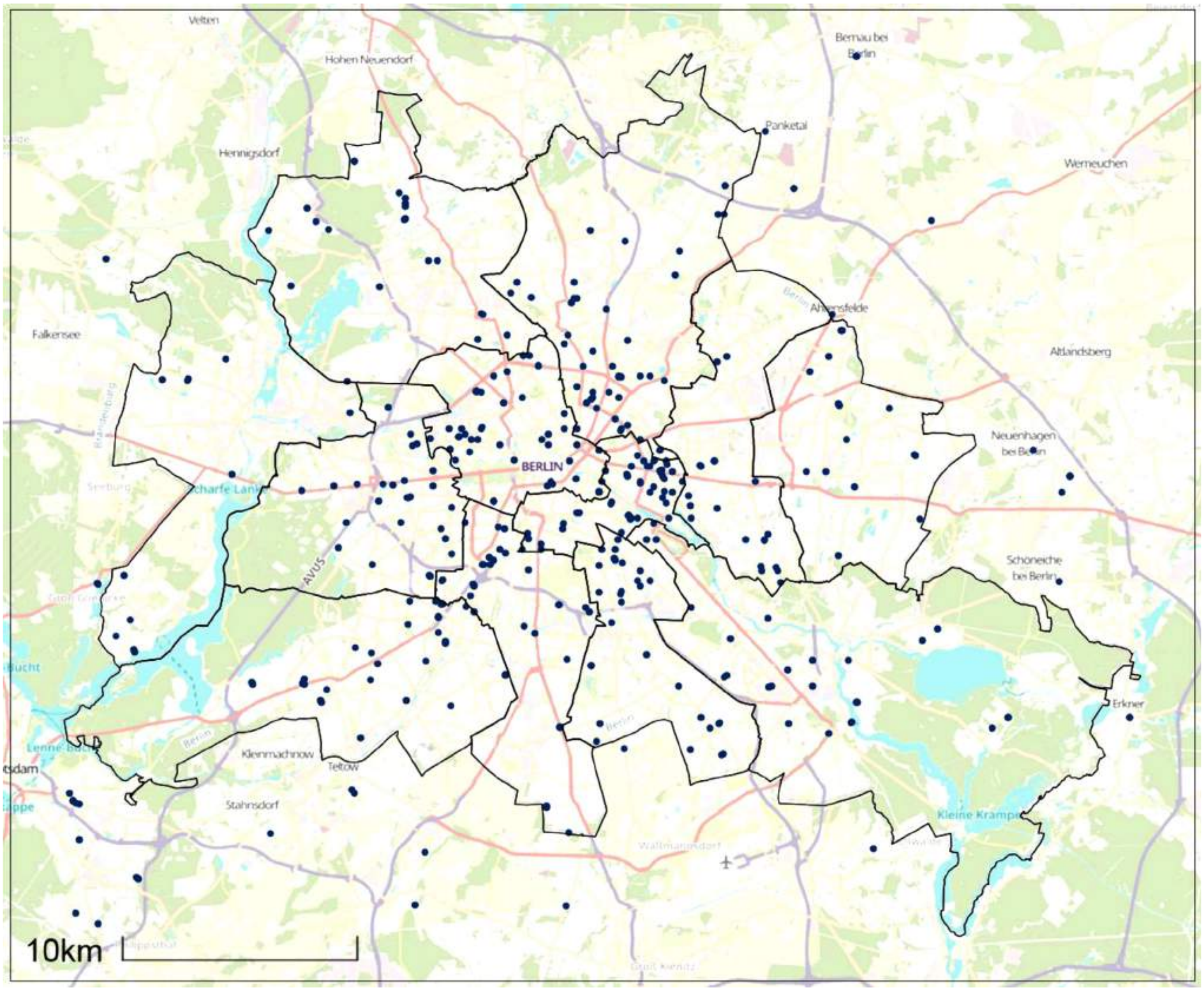

Fig. 2. Privately-owned and operated air quality sensors (blue dots) that are registered at Luftdaten.info and OpenSenseMap within the metropolitan region of Berlin as of January 2020. Background map source: https://www.openstreetmap.org.

as carbon monoxide, carbon dioxide, and nitrogen oxide were not considered since their emissions of motorized vehicles are likely to decline significantly with the introduction of hydrogen or electric vehicles. Particulate matter in the form of $PM_{2.5}$ or PM_{10}, on the other hand, will still be an issue because, for example, about 73% of traffic related PM_{10} concentrations in UK originate from the brake, tire, and road surface wear (Department for Environment, Food and Rural Affairs (Defra), Northern Ireland, 2019). In Berlin, these non-exhaust traffic sources contributed to about 80% of the PM_{10} concentrations in 2019[7].

In between air quality sensors, the air pollution needs to be approximated by interpolation because the charging scheme requires a gapless spatial air pollution distribution. The outcome of an air pollution spatial interpolation process depends significantly on the interpolation method (Wong, Yuan & Perlin, 2004). To simulate with accurate air pollution distributions in the form of AQI zones for the days under investigation, a 7-fold-cross-validation per spatial interpolation method was conducted with ten repetitions each. Berlin's inherent property of having mostly flat terrain and low-rise buildings made it an ideal spot to apply spatial interpolation without the need to take artificial obstacles or uneven terrain into consideration. The three days of investigation were also chosen because of the low wind speeds which otherwise would need to be considered within the interpolation process. The spatial interpolation method Inverse Distance Weighting (IDW) with a power parameter of 2 was finally selected as IDW won the vast majority of validation runs among the twelve test candidate methods Nearest Neighbour, Natural Neighbour, IDW, Linear Radial Basis Function (RBF), Gaussian RBF, Cubic RBF, Quintic RBF, Multiquadratic RBF, Inverse Multiquadratic RBF, Thin-plate RBF, Ordinary and Universal Kriging. The Marching Squares algorithm is then used with a grid size of 100 × 100 m for the contouring, namely, to extract the isolines (forming the AQI zones) for the particulate matter distributions. In the simulations, the activation period for AQI zones was set to ten minutes. Hence, every ten minutes the AQI zones were recalculated, and the results being applied for the next ten minutes. Air quality sensor readings of the last 30 min. contributed thereby to the calculation of the AQI zones, whereby the latest readings received a higher weighting.

For the traffic simulation, the microscopic traffic simulator Eclipse SUMO (called shortly SUMO hereafter) (Lopez et al., 2018) was used

[7] https://www.berlin.de/sen/uvk/presse/pressemitteilungen/2020/pressemitteilung.881368.php

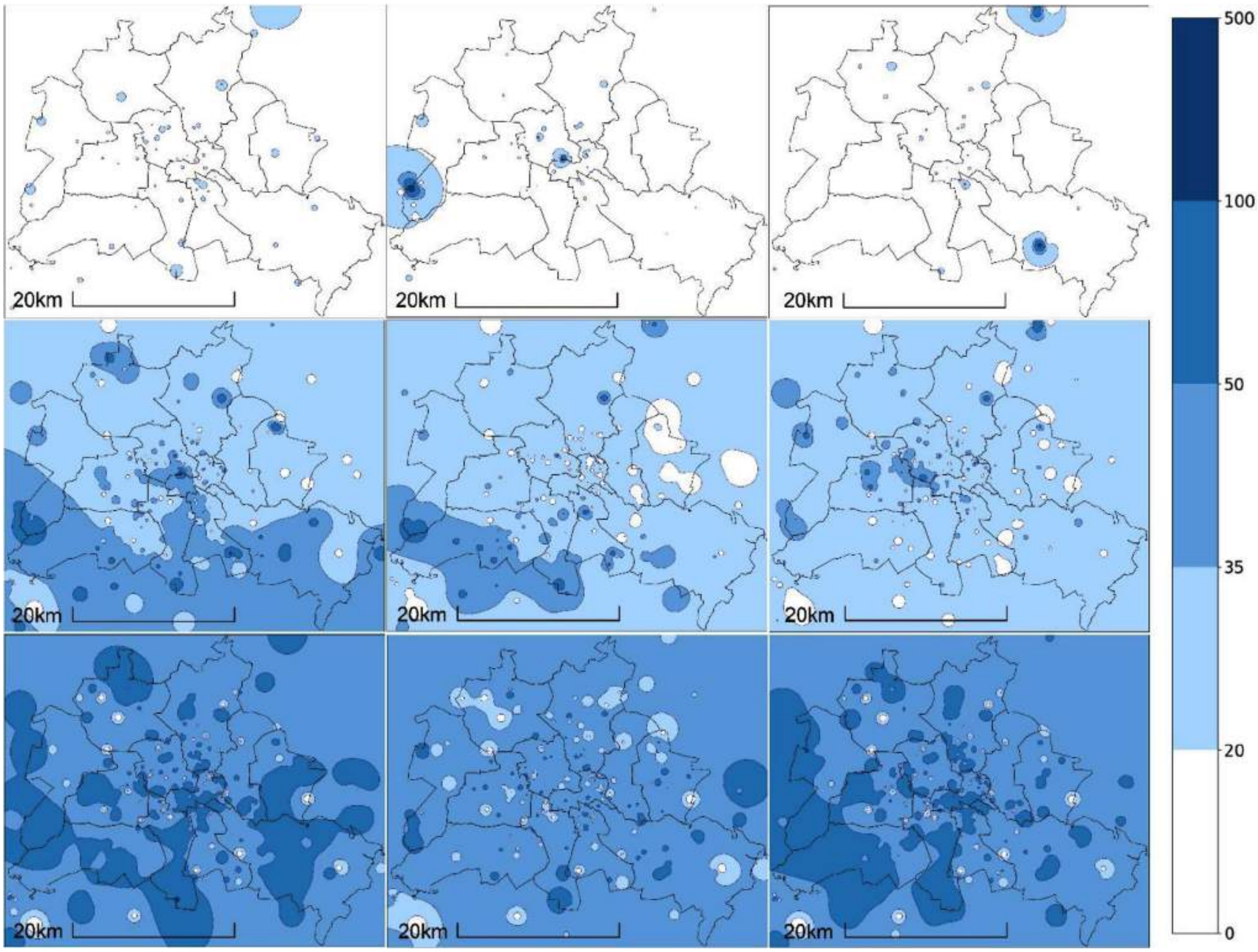

Fig. 3. AQI zones in Berlin. First row: 25.03. (low air pollution), second row: 11.06. (medium air pollution) and third row: 24.01.2020 (high air pollution). From left to right: AQI zones at 9:AM, 12:00PM and 5:00PM. AQI zones are given in μg/m^3 (PM_{10}).

because individual routes and their transit passages through AQI zones needed to be determined at each step of the simulation. In contrast to large-scale microscopic traffic simulators such as MATSim, streets are modeled in SUMO with their real-world shapes instead of direct connections between two endpoints. This is an important feature that makes it possible to determine precise routes and their exact trajectories through AQI zones. One second was chosen as the timestep length respectively time resolution of the simulation. At each timestep of the simulation, the positions of all vehicles are calculated by SUMO and the corresponding AQI zones are determined and logged for each vehicle. The road network was extracted from publicly available map data provided by the OpenStreetMap[8] project. As a transport demand model, the publicly available MATSim Open Berlin Scenario (Ziemke et al., 2019) for the multi-agent transport simulator MATSim[9] was used. Since MATSim creates individual activity plans to model the network load, the planned car trips of all synthetized individuals needed to be converted into a single origin-destination (O/D) matrix with annotated trip start times that is suitable for SUMO.

To make the road fees also dependent on the level of emissions of a vehicle, a Euro emission class was randomly assigned to each origin-destination pair (of the O/D matrix) based on the vehicle emission class distribution for Berlin (Kraftfahrt-Bundesamt, 2020). Table 2 shows the fuel and emission class distribution in Berlin for 2020 as used within the simulation. Since no information was available on emission class-dependent driving behavior, the possible differences, particularly regarding the frequency of vehicle use, could not be considered in the simulated trips. Although the total shares of hybrid and gas vehicles and vehicles with other alternative propulsion systems are rather small (hybrid 2.0%, gas 1.2% and other 0.03%), they were considered during the simulation, in particular, because of their non-negligible emission contribution. Electric (0.4%) vehicles were simulated (contributing to simulated traffic) as well, but due to the lack of appropriate emission models, they did not contribute to the simulated emissions.

The enhanced O/D matrix was then used throughout the evaluation in the simulation runs for each of the days under investigation. It incorporates 289,207 trips (with 63,554 distinct drivers) characterized by the origin, the departure time at origin, the destination, the Euro emission class, and the driver ID. The distribution of trip departure times across the day is shown in Fig. 4. The set of trips corresponds to about 10% of the daily traffic volume in Berlin and its close surroundings.

One of the main goals of the simulation is to determine how many AQI zone transits can be expected in Berlin on days with different air pollution characteristics under the assumption that all vehicles follow the shortest route in terms of trip duration. Other objectives are to deter-

[8] https://www.openstreetmap.org

[9] https://www.matsim.org/

Table 2
Vehicle type distribution for Berlin (as of 2020) in% as used in the simulations.

Fuel	Total Share	Euro 0	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6
Gasoline	72.62%	0.71	1.74	7.86	7.16	30.27	21.35	30.90
Diesel	23.63%	0.40	0.46	3.67	9.56	15.76	30.05	40.10

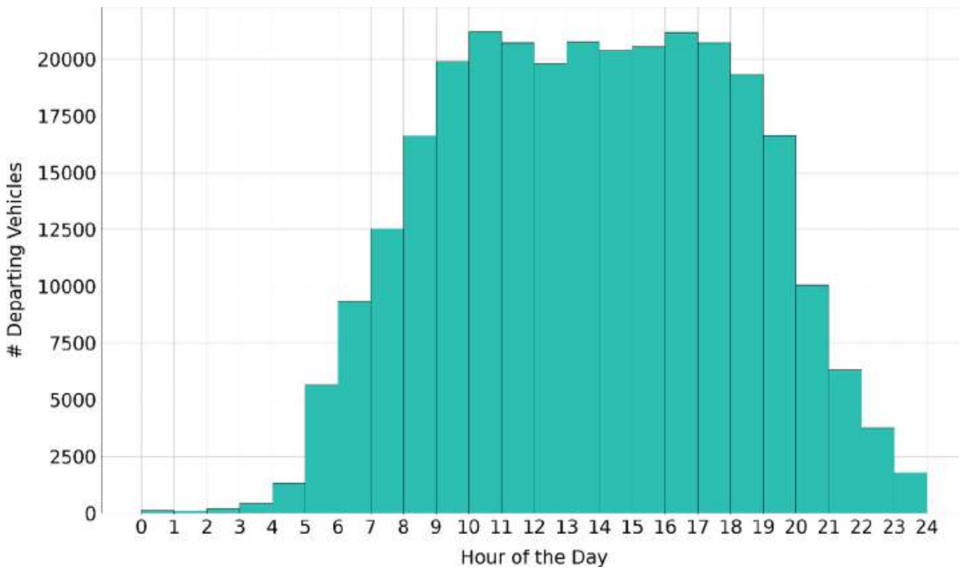

Fig. 4. Departure time distribution across the day.

mine how the traffic, AQI zone transits, and emissions of the motorized vehicles evolve if drivers decide to circumvent costly AQI zones, under the assumptions that all drivers evaluate their route with respect to road usage costs and no driver switches to public transport. Hence, this is an investigation of an edge scenario in which every driver evaluates the route before departure. It is intended to give first insights into the consequences of applying the proposed dynamic charging scheme in Berlin under the assumption that drivers are well-informed about the current AQI zones.

Results

To reveal the baseline first, vehicles were simulated to travel from their origins to their destinations with given vehicle-specific departure times and without intervening into the routing decisions made by SUMO. In SUMO, routing decisions are made based on weights at the edges of the transport network. The edge's current travel time, resulting from the fixed distance and speed limits, and the dynamic road occupancy, serve as the edge's weight in SUMO. The situation-specific aspect of the edge's weight leads to a proportional increase of an edge's current travel time with increased traffic along the edge. The Dijkstra algorithm is then applied in SUMO at the start of a trip to determine the fasted route to the destination in terms of trip duration. Every five simulated minutes, SUMO reevaluates the remaining portion of the route for a simulated vehicle based on the current travel times. After the reevaluation, SUMO adjusts the vehicle's driving speed at each remaining edge or even reroutes the vehicle. As a result of the simulation, all detailed routes, including the distances and the trip durations, were determined for each O/D pair. Fig. 5 shows the resulting distributions of the trip distances and trip durations. The average distance of a trip is 8.27 km with a 25%-quantile of 2.73 km, a 50%-quantile of 5.68 km, and a 75%-quantile of 11.30 km. The average trip duration is 11:30 min. with a 25%-quantile of 4:40 min., a 50%-quantile of 8:51 min., and a 75%-quantile of 15:45 min.. All vehicles covered a total distance of 2391,993.08 km with a total duration of 55,421.39 hrs..

Table 3
Accumulated AQI zone transit kilometer per day with low, medium, and high air pollution.

Day with	AQI Levels Level 1	Level 2	Level 3	Level 4
low air pollution	294,968	2650	1068	161
medium air pollution	1577,691	475,688	26,551	907
high air pollution	160,227	1374,271	811,445	3283

At the next step, the detailed routes were compared with the AQI zones for each day under investigation to tackle **RQ1**. The primary objective was to reveal the amount of AQI zone transits under the assumption that the charging scheme does not influence driving decisions. In other words, it was determined how many km in total were driven within an AQI zone with levels 1, 2, 3, and 4, without the drivers changing their route due to the existence of the road charging scheme. This information is particularly relevant for toll operators and collectors or, more generally, for the economic viability of a toll system and indicates the orders of magnitude with which environmental compensation measures could be implemented.

Since AQI zones are updated every ten minutes, it was required to map the 24-hour day's PM_{10} concentrations to 144 AQI zone snapshots. An AQI zone snapshot contains all AQI zones that are active within the toll area for 10 min.. Fig. 3 shows exemplary AQI zone snapshots at 9 AM, 12 AM and 5 PM. Table 3 shows the accumulated transit kilometer per AQI zone for each of the days under investigation. The total road charges per day for 10% of the population can then be calculated by breaking down the accumulated AQI zone transits into transits per emission class (given the emission class distribution in Berlin in Subsection Setup) and by applying concrete tariffs per AQI zone level and emission class. For example, if approx. 30% of the gasoline vehicles in Berlin (gasoline vehicle's total share in Berlin is approx. 72%) are Euro 4 gasoline vehicles and if they are hypothetically charged 5 Cent per kilometer in AQI zone level 1, then the total road charges for Euro 4 gasoline vehicles in AQI zone level 1 at a day with low air pollution results in

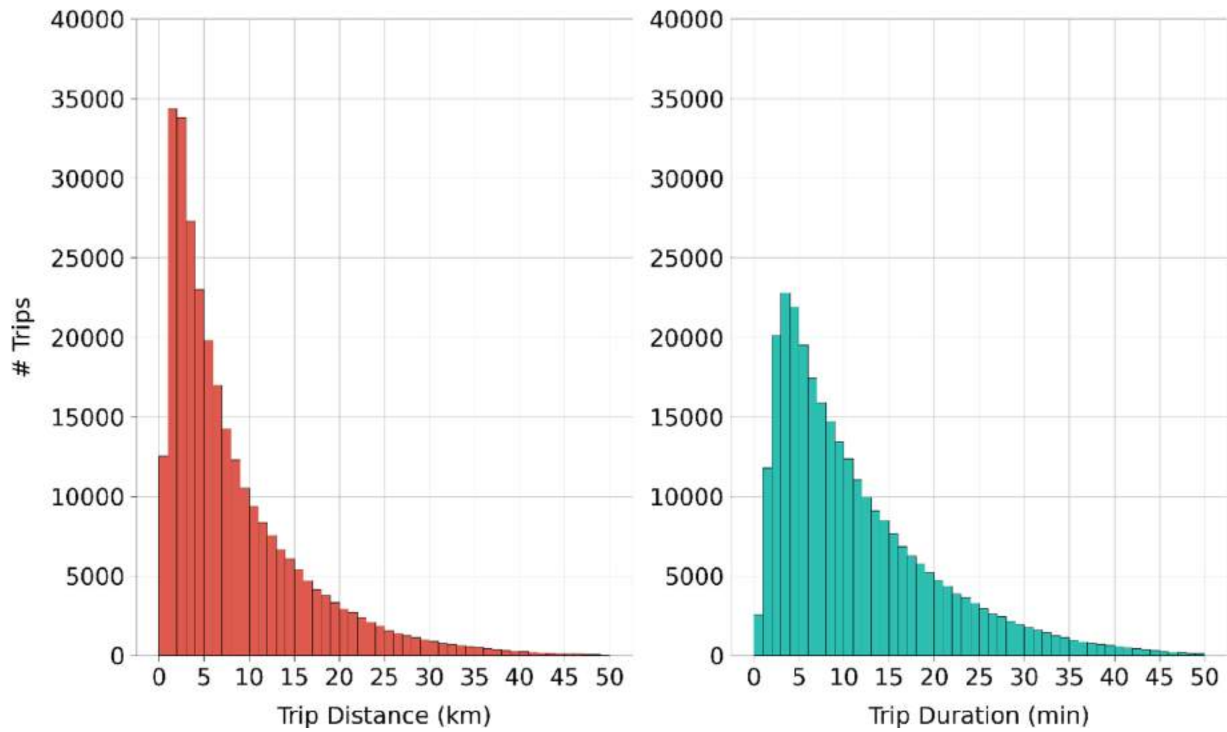

Fig. 5. Distribution of trip distances and trip durations for the baseline.

Table 4
Average number of times a tariff change is experienced per trip at a day with low, medium, and high air pollution.

Air Pollution	Tariff changes	25%-Quantile	50%-Quantile	75%-Quantile
low	0.58	0	0	1
medium	3.05	1	2	4
high	4.07	1	3	5

approx. 294,968 km * 0.72 * 0.30 * 0.05 Euro/km = 3185.65 Euro for 10% of the population. The higher the average air pollution in Berlin, the higher are the total road usage charges under the assumption that no driver switches to alternative transport means or adjusts the route to minimize the trip's road charges. Fig. 6 shows the relative distribution of AQI zone transits per time of the day. It illustrates that the likelihood of passing through an AQI zone of level 3 at a day with high air pollution is higher at rush hours between 6 and 10 AM and between 4 and 10 PM. This corresponds to the clearly visible higher air pollution at 9 AM and 5 PM compared to 12 PM at the day of high air pollution in Fig. 3. An indicator that car rides during the rush hours will be significantly more costly than car rides during off-peak hours, at least at a day with high air pollution.

To tackle **RQ2**, it was investigated how often a driver experiences a tariff change per trip. The tariff is defined as the current toll price per kilometer for a motorized vehicle of a particular emission class. Table 4 shows the results for days with low, medium, and high air pollution. A tariff change during a trip can be triggered in two ways: (1) the vehicle actively leaves an AQI zone and enters a new AQI zone or (2) the vehicle suddenly drives in a new AQI zone because the activation period of the current AQI zone snapshot expires and the new valid AQI zone snapshot with a new AQI level at the vehicle's location becomes active. This metric is an indicator of how dynamic the charging scheme will be experienced by the drivers in case the activation period is set to ten minutes. The price stability is an important criterion to evaluate the practicability and acceptability of a dynamic road charging scheme (Ministry of Transport, Great Britain, 1964).

At the next step, cost-conscious drivers were introduced. A cost-conscious driver evaluates at the start of a trip whether an alternative route, possibly circumventing an AQI zone with high transit costs or detouring through an AQI zone with low transit costs, should be taken to reduce the total trip charges. In SUMO, this can be simulated by switching a cost-conscious driver to effort-based routing instead of routing by travel time. The edge's effort (previously referred to as weight) can be customized individually per edge to suit the needs of the scenario under investigation. For cost-conscious routing, the edge's effort does not only consider the actual travel time but also the transit costs. The effort associated with an edge for cost-conscious routing is therefore defined by

$$effort_{edge} = \begin{cases} \Delta t \; if \; l = 0 \\ \Delta t \, + \left(\frac{d}{s} * c(e) * p(l) \right) if \; l \neq 0 \end{cases}$$

with actual travel time Δt, edge distance d, edge speed limit s, emission class factor function $c()$, vehicles emission class e, pollution factor function $p()$ and AQI zone level $l \in \{0, 1, 2, 3, 4\}$. The additional costs caused by the charging scheme are thereby represented by a pollution level- and emission class-dependent percentual increase of the actual travel time. In other words, the monetary additional expenses are translated into additional travel time per edge. The magnitude of Values of Travel Time Savings (VTTS) is thereby assumed to be similar for all drivers. The additional travel time is given by the time it takes for a vehicle to pass the edge ($\frac{d}{s}$) without considering the current traffic situation, an emission class factor representing the percentage increase for the given emission class ($c(e)$) and a pollution factor representing the percentage increase for the given AQI level ($p(l)$). Hence, the additional transit costs in terms of hypothetical additional edge travel time do not depend upon the current traffic situation (as already considered by Δt) because the charging happens only in a distance and not time-based manner. A vehicle is charged the edge's transit costs no matter how long it needed to pass the edge.

The taxation of the various pollutant classes for vehicles in Germany served as the basis for determining the percentage differences among the emission class-dependent factors. For example, if a Euro 2 diesel is

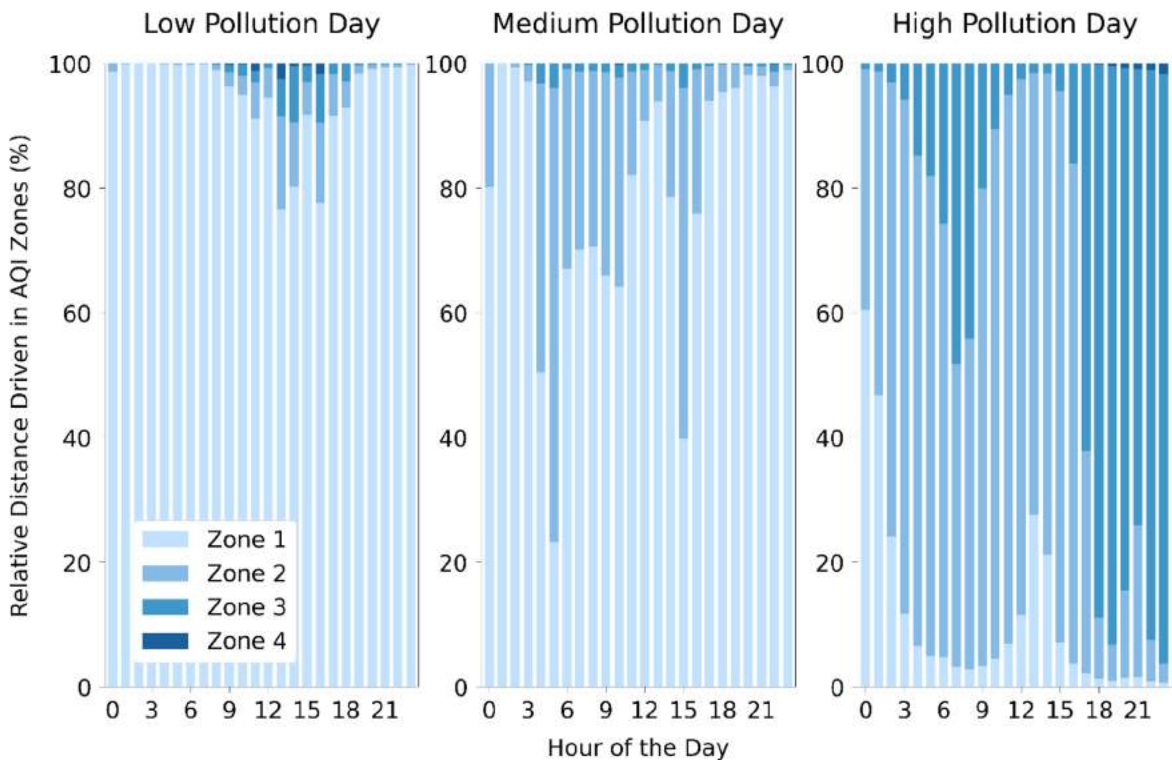

Fig. 6. Relative AQI zone transit distance per day with low, medium, and high air pollution.

Table 5
Differences of emission class taxation in comparison to Euro 6 gasoline in Germany as of August 2020 given in%.

	Euro 0	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5	Euro 6
Gasoline	376	224	109	100	100	100	100
Diesel	557	405	238	229	229	229	229

taxed 3.9% more than a Euro 3 diesel, then c ("*Euro* 2 *diesel*") is 3.9% higher than c ("*Euro* 3 *diesel*"). The percentage differences in relation to the taxation of a Euro 6 petrol vehicle are given in Table 5. Electric, gas and hybrid vehicles have a discount of 10% on the Euro 6 taxation. If one $c(e)$ is fixed, then the other emission class-dependent values for the emission class factor can be inferred from the percentage differences.

The pollution factor function $p(l)$ maps an AQI level to a concrete pollution factor. It increases with the amount of air pollution. The actual design of the function depends on various factors. It is, for example, possible to make the form of price increase with higher air pollution dependent on the increasing health hazards to correlate the probability of a related disease with the price per kilometer. However, the causal relationship between particulate matter concentration and morbidity rate was examined to be of linear (Liu et al., 2014) or non-linear (Szyszkowicz, 2018) nature. Some results indicate even no statistically significant relationship at all (Ren et al., 2017). But at first, the type of price increase depends upon the air pollution quantization used to infer the AQI level. For the simulations, which made use of the air quality index provided by the Federal Environment Agency in Germany, the pollution factor function is exemplarily defined as

$$p(l) = s * l^2$$

The factor increases exponentially with the AQI level. The slope is controlled by the parameter s. The higher the slope parameter, the faster grows the pollution factor with the AQI level. An exponential increase was chosen to better study the effects of bypasses because it was assumed that the higher the transit price for an AQI zone (given as additional edge pass time) is, the more likely it is expected that an AQI zone will be bypassed. A linear increase of the price is possible as well and would most probably reduce the simulated number of bypasses. At the border of a zone, it is possible that an edge may cross two or more zones. In this case, the highest zone level of all zones concerned is used to calculate the individual effort for the edge.

The number of drivers that are considered cost-conscious within a toll area depends upon several factors such as potential road charges, driver's educational background, income, and trip urgency. Due to the related complexity to model a region-specific decision finding process it was decided to simulate an edge case in which all drivers are considered cost-conscious. During the simulations, a driver evaluates possible bypasses at the start of the trip, chooses the best route with respect to the edge efforts and keeps following the route to the destination.

The primary objectives of the simulations with cost-conscious drivers are to investigate the extent of bypassing (**RQ3**), the characteristic of detours (**RQ4**), the change of vehicle emissions (**RQ5**) because of bypassing, and the impact of rerouting on the traffic (**RQ6**). Since cost-conscious drivers are highly price-sensitive, simulations were conducted with different tariffs. Instead of simulating with different concrete prices per kilometer (for emission class and AQI level), the slope parameter of the pollution function was varied. It was increased from 0.2 to 1.4 with a step length of 0.2 while c ("*Euro* 6 *gasoline*") was fixed to 0.1 for all simulations. According to the effort function, the percentual increase of travel time for a Euro 6 gasoline vehicle in an AQI zone with level 1 at slope parameter of 0.2 is 2%. At the other end, for a Euro 0 diesel vehicle the additional travel time results in 11%. A maximum slope parameter of 1.4 was selected because the percentual increase for a Euro 6 diesel vehicle in AQI zones with level 4 is very high at 1247.00%. With such an additional travel time, Euro 6 diesel vehicles were expected to bypass - by all means - AQI zones with high associated road charges.

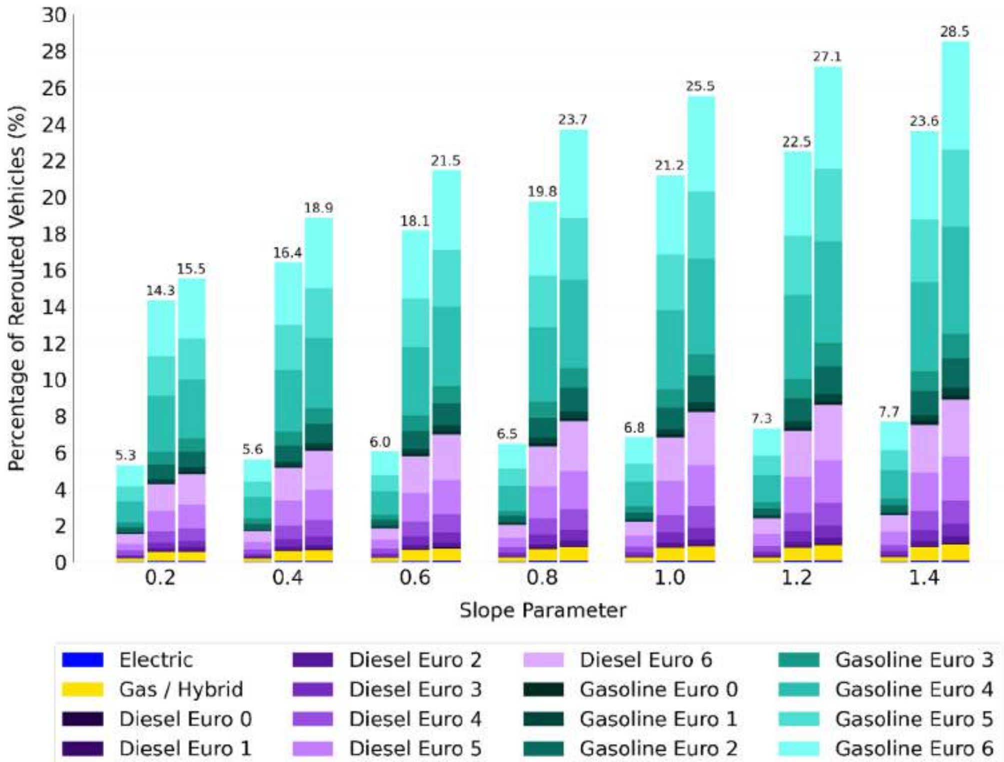

Fig. 7. Share of rerouted vehicles of all trips for days with low (left bars), medium (middle bars), and high (right bars) air pollution and increasing slope.

Hence, in this investigation, the slope parameter was used to vary the road charges (represented by additional travel time) and to observe how the cost-conscious drivers influence the traffic, the amount of AQI zone transits, and the emissions of the vehicles.

The first subject investigated here is to what extent cost-conscious drivers bypass AQI zones, depending on the vehicle emission classes (**RQ3**). Fig. 7 shows the relative number of vehicles that take a detour out of all trips broken down by emissions classes and days under investigation. Fig. 8 supplements this information by illustrating the share of rerouted vehicles among each emission class. Since Euro 1 diesel vehicles are more affected by higher road charges it is more worthwhile for them to take a detour at all days under investigation. At the day of medium air pollution, the numbers of detours for all emissions classes are at similar order of magnitudes as the ones at the day with high air pollution. The reasons can be manifold, ranging from detour roads reaching maximum capacity over the shape and size of AQI zones until the location of AQI zones at major roads with more attractive detour possibilities in general. However, the distribution of air pollution during the day with medium levels of pollution has many small AQI zones with level 0 that are worth passing through, even in a detour. On the other hand, the AQI zones with level 3 during the day with high pollution are more extensive and therefore less attractive to circumvent. The short drops, e.g., for rerouted Euro 1 diesel vehicles at slope 1.2 at the day of low air pollution, indicate that detour roads were already busy and thus less attractive. They become attractive again - even if busy – after the slope increases even more.

The next step of investigation dealt with the characteristics of the detours (**RQ4**). Table 6 lists the average trip distance differences of the rerouted vehicles in comparison to the baseline. The detours remain rather short in distance, culminating at days with a medium air pollution of about 220 m for slope 1.4. However, a few outliers were identified for long distance trips of more than 30 km. Fig. 9 shows exemplarily the distribution of detour distance differences for the days under investigation for a slope of 1.4. It illustrates how many detour trips are longer or shorter in distance, in comparison to the baseline. As a result, a trip with price-guided detours can even be shorter in distance. In some cases, driving directly through the notoriously crowded downtown area instead of using the bypassing city-circle helps to avoid passing through highly polluted areas as well as to decrease the trip distance. But it leads to an increase of the trip duration. Nevertheless, on average, rerouted vehicles cover a longer distance compared to the baseline. Fig. 10 shows the relative amount of the trips rerouted, grouped by trip distance. The longer the trip distance is, the higher is the chance that road charges can be avoided by detouring. Towards trips with longer distances, the trend can no longer be clearly identified. The reason lies in the number of total trips which gets smaller with increasing distance up to a point where small changes have too much influence on the overall result. Higher distance results should therefore be interpreted with due care. See the baseline results in Fig. 5 for more details about the trip distance distribution. However, at the day of medium and high air pollution, the shares of rerouting vehicles reach their peaks already for trips with medium distances (>20 km) while on the day with low air pollution, the peak is reached for trips with longer distances (>35 km). The very sporadic and relatively small zones with level 1 within a city-wide clean air in Berlin lead to the result that the probability of choosing a favorable bypass on a route increases more slowly than on days with medium and high air pollution.

The more cost-conscious drivers are bypassing zones with high air pollution or detouring through zones with less air pollution, the higher are the average distances travelled. This leads inevitably to an increase of the overall vehicle emissions during the day. Since not every rerouted

Table 6
Distance differences of rerouted vehicles (* in km).

	Low Pollution Day		Medium Pollution Day		High Pollution Day	
Slope	0.2	1.4	0.2	1.4	0.2	0.4
Mean*	0.01	0.09	0.03	0.22	0.02	0.17
σ*	0.92	1.11	0.90	1.37	0.91	1.23

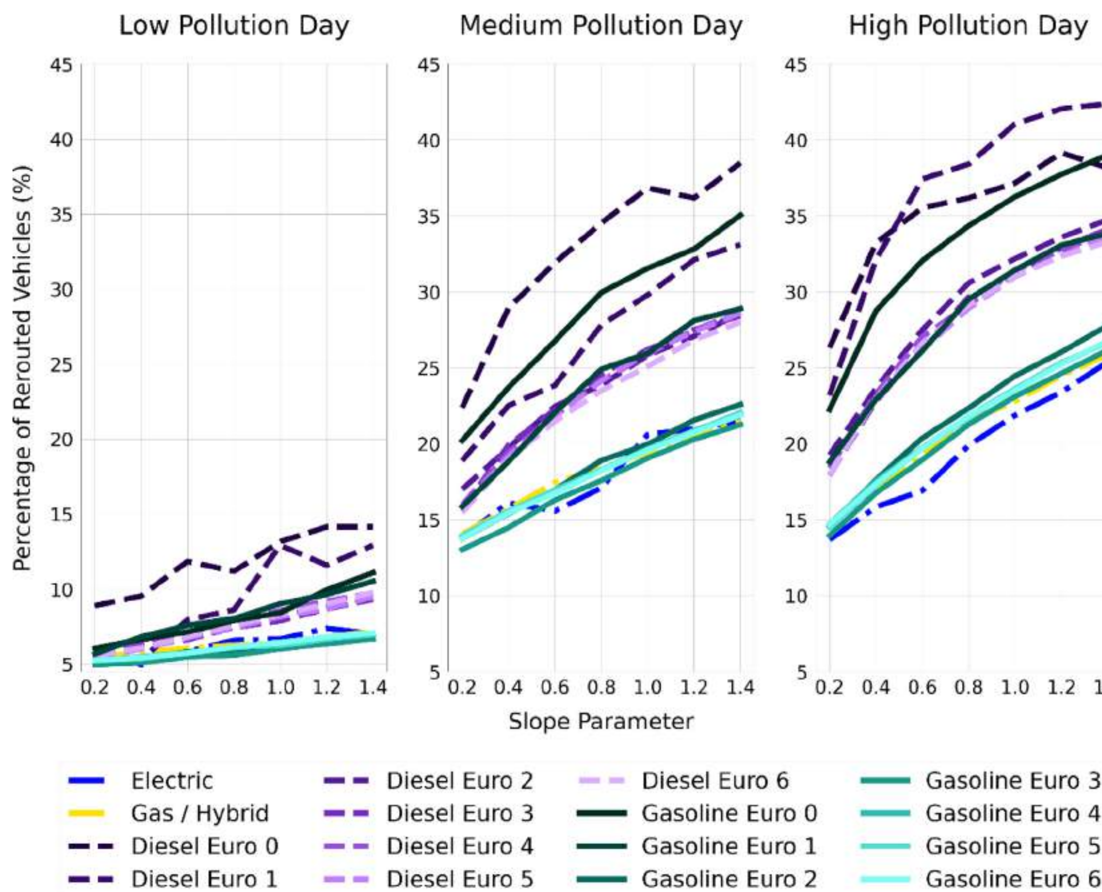

Fig. 8. Share of rerouted vehicles within each emission class for days with low, medium, and high air pollution.

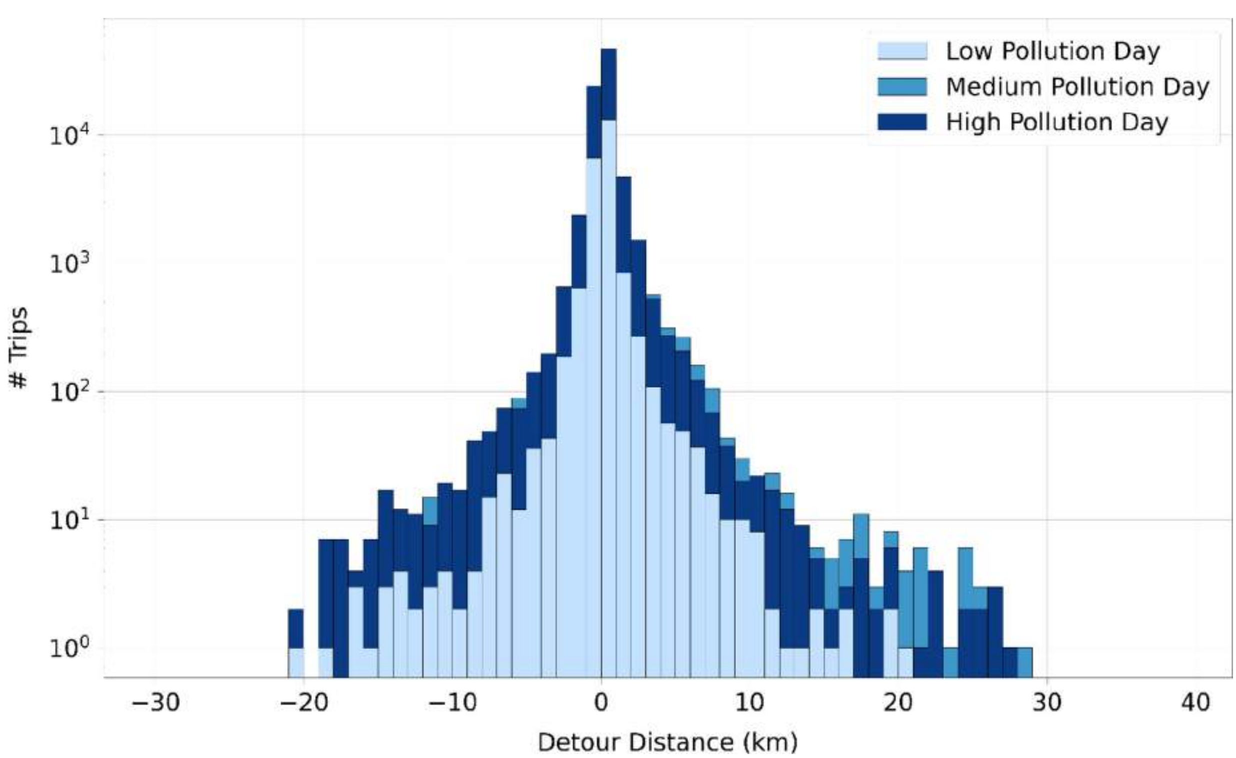

Fig. 9. Distribution of detour distance differences in comparison to the baseline. L1.4: Low pollution day, M1.4: Medium pollution day, and H1.4: High pollution day.

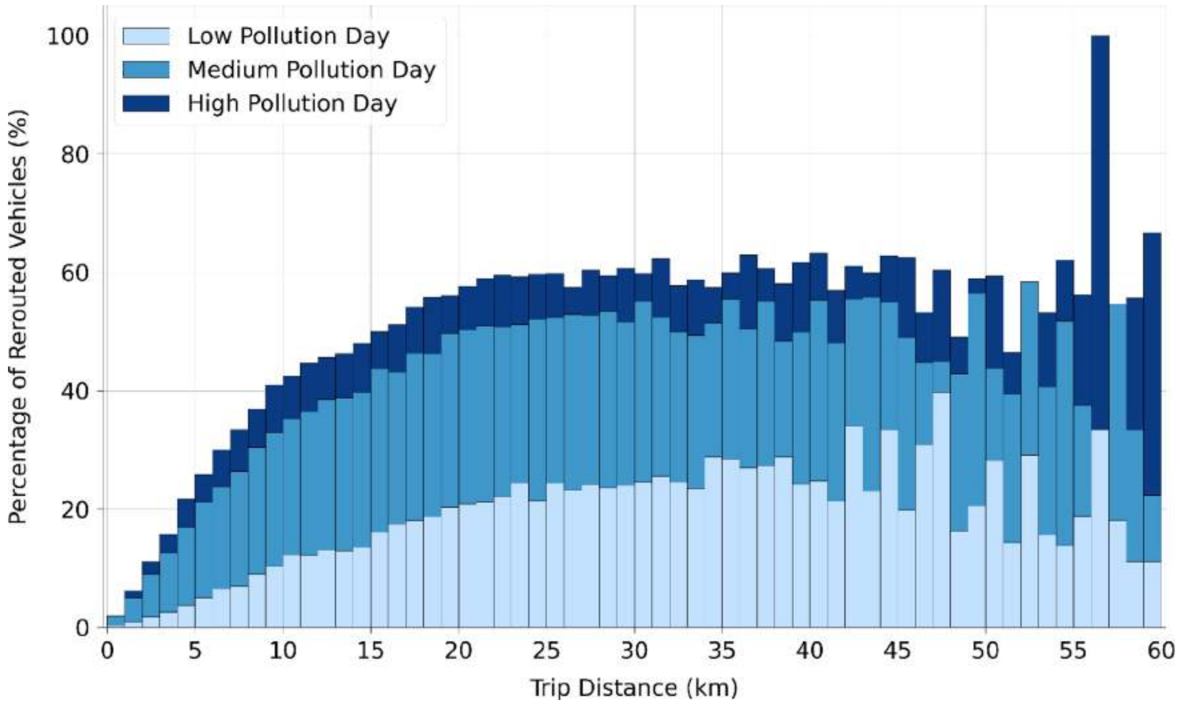

Fig. 10. Share of rerouted trips with slope 1.4 at days with low, medium, and high air pollution and grouped by trip distances.

vehicle covers the same or a longer distance, but a shorter one instead, it is necessary to investigate which additional vehicle emissions can be expected (**RQ5**). SUMO uses the databases provided by the Handbook Emission Factors for Road Transport (HBEFA)[10] in version 3.1 to model the exhaust emissions of passenger and light delivery emission classes. Non-exhaust emissions such as particulate matter caused by brake, tire, and road surface wear are not supported in HBEFA version 3.1. The simulated emissions depend upon the kilometers driven, the vehicle speed and the vehicle emission class. Fig. 11 shows the relative increase of vehicle emissions with an increasing slope with respect to all trips, including trips without rerouting. The relative increase due to detouring remains below 1.5% even with a high slope on the day with medium air pollution. Surprisingly, on days with high air pollution, there is only a 1.3% increase in fine dust pollution, although about 28.5% of drivers choose to bypass. These are the additional emissions from vehicles only and it does not even consider wind and weather conditions. Since detouring causes additional emissions in zones with lower air pollution and relieves zones with high air pollution from further emissions, the overall air pollution should get more evenly distributed across a toll area. Unfortunately, this may lead side roads to experience a higher traffic load with additional negative consequences such as increased noise and air pollution and traffic risks.

So, if the road charging scheme would be deployed, how would the road network utilization in Berlin change (**RQ6**)? Fig. 12 plots the absolute traffic increase and decrease (additional and lesser number of vehicles per edge) at a slope of 1.4 in contrast to the baseline for each day under investigation. It shows, contrary to the assumption above, that main roads are mostly affected by the detours through an increase or decrease of the traffic, even at the day with high air pollution. Roads used for detours and their counterparts are clearly visible for all days because the increase at an alternative main road of a detour with similar distance leads to a decrease at the main road at the original route. The traffic at a few notoriously overcrowded sections of the inner-city freeway (clearly visible as a semicircular red line in the baseline plot) gets even worse at days with medium and high air pollution while most of the sections experience either no effect or lesser traffic. Some detours are frequently used detours even without the hypothetical charging scheme in place. It remains to be investigated which situation factor contributed most to the decision of the driver to detour: actual travel time based on traffic load or upcoming road charges for the rest of the original route?

A change of the traffic behavior has also an effect on the amount of AQI zone transits since cost-conscious drivers try to avoid costly routes. Hence, this leads to a change of the overall toll volume to be expected by a toll operator or collector, as investigated with respect to **RQ1**. Fig. 13 shows the absolute increases and decreases of the amount of AQI zone transits with an increasing slope for the days under investigation. On the day with high air pollution, cost-conscious drivers cause a significant decrease of transits through AQI zones of level 3 and at the same time an increase of transits through AQI zones of level 1 and 2. The overall effect culminates at a difference of approx. 52,000 km for transits of AQI zones with level 3. Drivers at a day with high air pollution have no options to avoid tolled zones. At the day with low air pollution, in contrary, detours are conducted to avoid tolled zones in general and to drive through non-polluted areas (AQI zone with level 0). The decreases of transits through AQI zones of levels 1 to 3 are thus not compensated by tolled trips.

Discussion

For a proper interpretation of the results, it is necessary to summarize the assumptions and limitations of the conducted simulations and put them in relation to the findings. A major limitation is to simulate only 10% of trips that Berlin usually experiences during a weekday. The traffic for weekends were not simulated at all. With only 10% of traffic, a traffic network (not scaled) that is designed to cope with order of magnitudes higher traffic demand will hardly present any sections where traffic congestions occur. The actual travel time, as used in the determination of the effort, thus might play only a minor role for the routing decision. This would mean, on the other hand, that the rerouting happened mostly to reduce the overall road charges for a trip. A non-scaled network allows therefore to investigate the effects in an isolated manner. If even alternative main roads would get congested, vehicles might

[10] https://www.hbefa.net/e/index.html

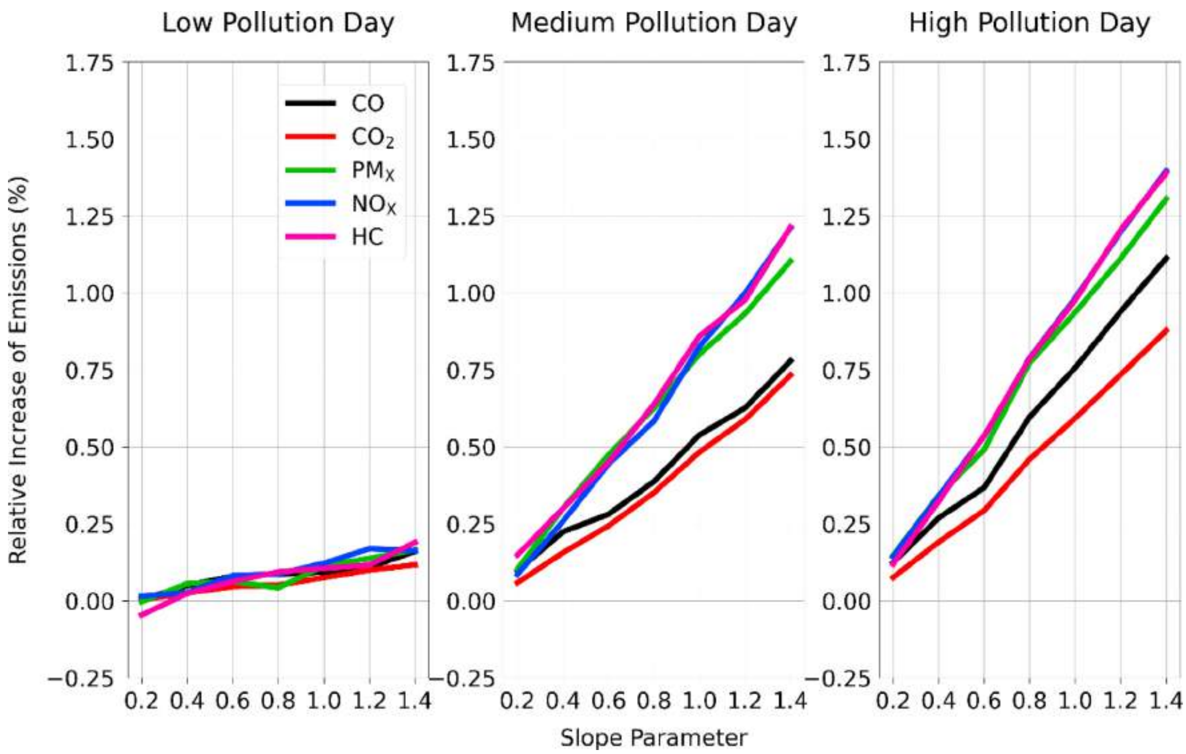

Fig. 11. Relative increase of vehicle emissions depending on the slope parameter. CO: Carbon Monoxide, CO_2: Carbon Dioxide, PM_x: Particulate Matter, NO: Nitrogen monoxide, HC: Hydrocarbons.

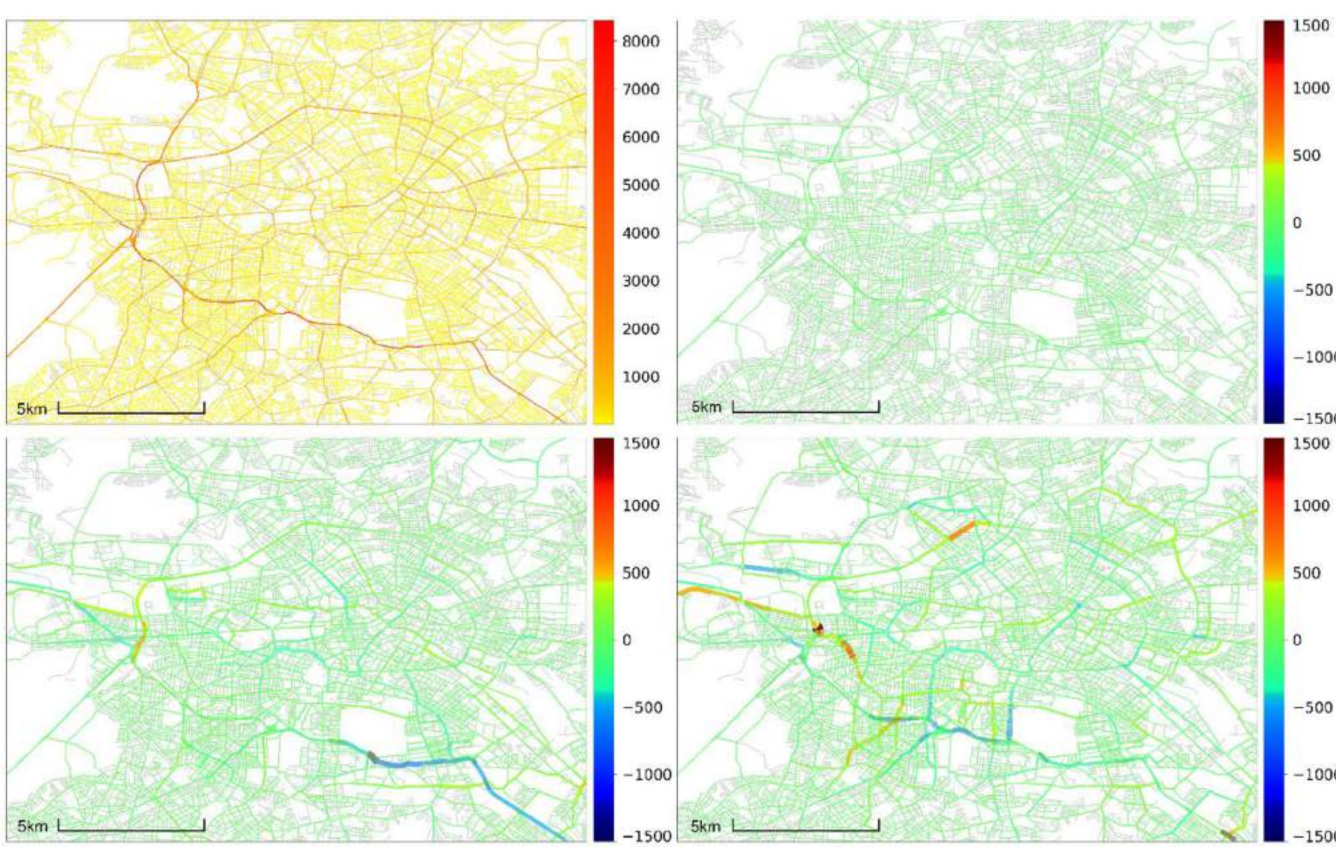

Fig. 12. Absolute increase and decrease of trips per edge of the traffic network within the downtown of Berlin at slope 1.4. Top left: baseline; top right: low pollution day; bottom left: medium pollution day; bottom right: high pollution day.

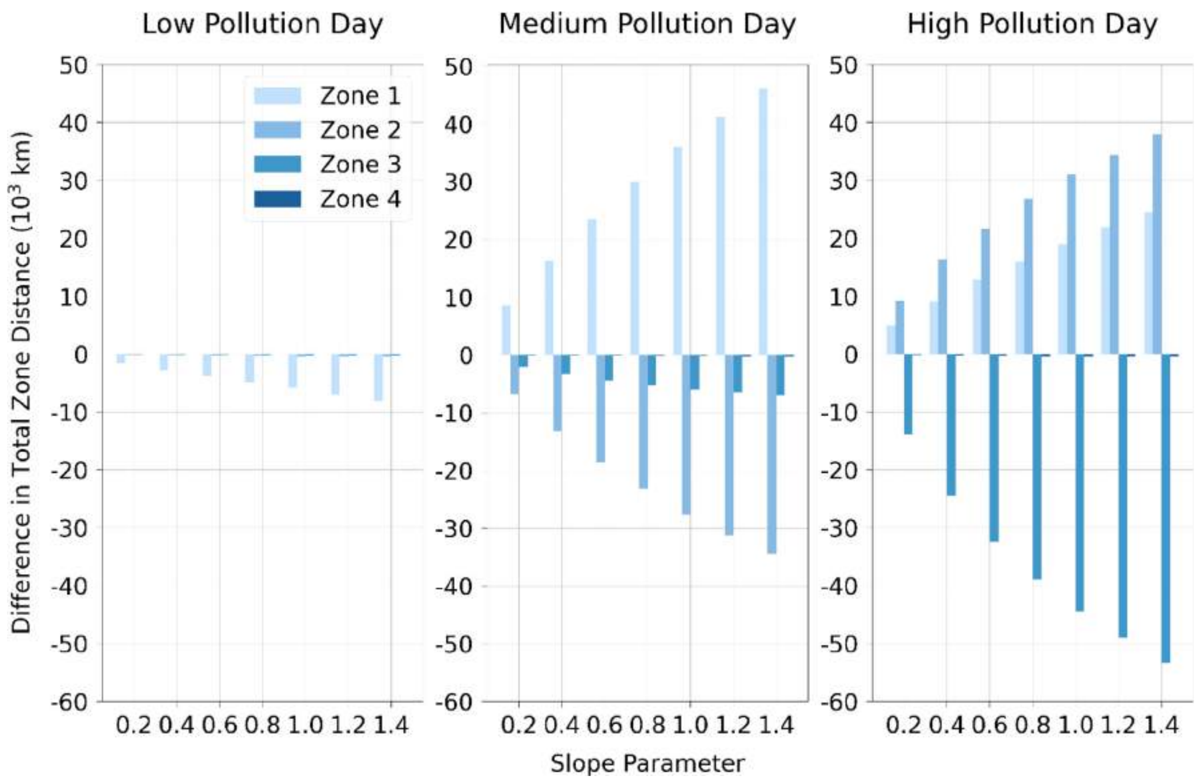

Fig. 13. Absolute difference of AQI zone transits depending on the slope and day of investigation.

switch onto side roads. Which side road to switch to, might then be as well influenced by the road charges. A closely related assumption is to take the rerouting decision only at the beginning of the trip. During a trip, as can be inferred from the tariff changes per trip, AQI zones might change. A routing decision taken at the start of a trip might turn out to be not optimal with respect to road charges. For proper investigation it needs to be empirically determined how often drivers are willing to change their route based on, for example, recommendations by an air pollution-aware navigation system. In general, the decision process to take a detour is quite complex and depends on several context factors such as day of the week, time of the day, personal preferences, etc. (Ziebart, Maas, Dey & Bagnell, 2008). For the simulations, the driver was assumed to reroute only based on travel time. The travel time encompasses the actual travel time and the additional travel time resulting from the road charges. A driver might even decide to leave the car and take the public transport or to change the destination instead. Another option would be to advance or postpone the trip in order to avoid the rush hours with their longer trip durations and higher road charges. However, this requires forecast mechanisms to be in place or decision making based on experience. Hence, another limitation is the focus on a few factors in decision making and the limited number of choices. Especially, because taking alternative means of transport or rescheduling the trip will most probably have a significant impact on the resulting amount of AQI zone transits and overall emissions. But not every driver evaluates the route to the destination. Some might follow their preferred routes independent of hypothetical road charges. In this work, 100% of the drivers were simulated to evaluate their route at the start of the trip to investigate an edge case. If the share of cost-conscious drivers among all drivers would be lower, then the amount of AQI zone transits would most probably rise. The results with respect to the AQI zone transits should therefore be interpreted as a lower bound while the amount or rerouted trips should be considered as the upper bound. It would also be possible to restrict access to AQI zones with particular AQI levels for vehicles with specific emissions classes as done within today's LEZs in Germany. This would probably have a significant impact on the lower bound of AQI transits and upper bound for the amount or rerouted vehicles. However, adjusting the extent of restricted zones in a temporal and spatial manner makes it, on the one hand, difficult for drivers to predict whether an envisioned route is permitted and, on the other hand, likely to accidentally drive in a zone that is not supposed to be crossed due to rather spontaneous tariff changes.

It was not intended to define a concrete price per kilometer, AQI zone and emission class and to investigate the effects, but only to observe the development of traffic with increasing relative prices per emission class. Mapping the relative prices to additional virtual driving time without defining a budget limit or upper limit for the expected driving duration bears the justified risk of taking detours that take many times longer, but in reality, are not driven due to higher fuel costs or lack of time. Due to the limited extent of the investigated area, only a few alternative trips were identified, whose tracks proved to be unrealistic. 50 out of 289,207 trips experienced a trip duration increase of over 50% and 2 trips over 100% on a day with medium air pollution and slope 1.4.

To model the air pollution in Berlin, crowdsourced air quality measurements were taken. Privately-owned and operated air quality sensors integrate mostly low-cost sensors. Low-cost sensors, such as the one mainly used in the Luftdaten.info initiative, bear the risk of unprecise measurements (Budde et al., 2018). Moreover, they can be placed at arbitrary locations, for example, in the garden, on the roof top, or close to windows. Without considerable expert knowledge, it cannot be guaranteed that they will be placed at locations that allow representative measurements of the urban air quality. Their measurements might be biased by cooking or heating smoke or emissions at highly frequented roads. Community-operated sensors might also be faulty or broken (Wan et al., 2016). . Despite the conducted removal of outliers prior to the modeling of the urban air quality, the measurements should always be interpreted as approximations. For the urban air pollution modeling it is assumed that the density of sensors in Berlin is sufficiently high to properly interpolate the traffic-related air pollution at places lacking a sensor. However, an arbitrarily distributed air quality sensor network, such as the one in Berlin, should - in general - be thoroughly investigated with respect to its suitability to properly represent traffic emissions (Sun, Li, Lam & Leslie, 2019). Hence, not only the microscopic placement at a building but also the placement out of a macroscopic perspective within an urban environment needs to be considered.

Whether AQI zone snapshots should be determined based on the measurement of the last 30 min. and updated every 10 min. as done within the simulation must be decided upon by the toll operator or collector. An activation interval of 10 min. was chosen to keep a fair balance between the accuracy of representing the current air pollution distribution and the price stability for the driver. A lower interval might not increase the accuracy significantly because the air quality must be measured anyhow by taking multiple sensor readings into consideration. Since air pollution might even arise at places without air pollution sources (Dedoussi et al., 2020), cross-street, cross-quarter, or cross-district air movements needs to be taken into consideration for a proper interpretation of sensor readings (Taseiko, Mikhailuta, Pitt, Lezhenin & Zakharov, 2009). As weather conditions play a major role for the urban air pollution dispersion (Holzworth, 1969), days with similar weather conditions were compared to each other. It remains to be investigated how the air pollution dispersion characteristics in Berlin evolve under different weather conditions, for example, with heavy rain and higher wind speeds.

The major risk of the proposed charging scheme is that drivers will take detours to save costs. Detours can cause additional emissions, pollute residential side streets, and lead to congestions on alternative routes. As can be seen in the results, emissions are in fact rising, but not with the same amount as the number of rerouted vehicles. This can be attributed to detours which are short on average compared to the length of the route and which sometimes even lead more directly to the destination and are therefore shorter in total. Since rerouted vehicles take alternative routes, the overall vehicle-caused emissions get more evenly distributed across the toll area. Side roads are hardly or only marginally used for detours, while some sections of alternative main roads show an increase of a maximum of 1000 vehicles per day at the day with medium air pollution. However, it is not possible to determine whether there may even be a reduction in overall emissions with the simulation setup because the drivers' scope for deciding whether to advance or postpone the start of the trip or to switch to alternative means of transport was not modeled. Another important finding is that the number of detours depends not only on the average pollution levels along the route, but also on the spatial distribution of the air pollution. The smaller the zones with higher or lower air pollution along or close to the route are, the more detours are beneficial for the driver. Due to the different characteristics of the distributions, it is difficult to compare the results between the day with the medium and the days with the low and high air pollution. To achieve a general applicability of the findings, the specific characteristics of spatial distributions of urban air pollution must be identified and their impact on driving behavior be investigated, together with a concrete pricing model.

Conclusion

This article presented an explorative analysis of an air quality and distance-based charging scheme for the metropolitan region of Berlin. As the first of its kind, it investigated the effects of adjusting the extend of LEZs dynamically without human interaction, according to the spatial and temporal distribution of the urban air pollution. By simulating 10% of the daily traffic volume on a working day in Berlin for days with different particulate matter concentrations, it was examined, how many trips are likely to be eligible for road usage charges and how the trip charges are composed of transit costs through LEZs with different PM_{10} concentrations. The impact of the charging scheme on the traffic and vehicle emissions was investigated by varying the relative price tag per temporary LEZ and by allowing cost-conscious drivers to decide on the preferred route before departure. A key finding, beside others, is the moderate increase of the overall emissions with the increasing number of rerouted vehicles. Detours are on average short compared to the trip length and sometimes even shorter than the original route. Major roads are affected mostly by an increase or decrease of traffic while side streets experience no significant changes in traffic volume. It turned out that the spatial characteristics of the PM_{10} concentrations within a toll area - besides the price tags - had a significant impact on the number of drivers that decided to take an alternative route. Hence, not only the AQI level and the associated price per kilometer but also the sizes, shapes, and placements of AQI zones influence the characteristics and number of detours with their additional emissions. Further investigations are necessary to identify recurring air pollution patterns, generalize their distribution characteristics, and examine their impact on the mobility behavior of motorized drivers. Although particulate matter was considered only in this investigation, further considerations, for short to medium term solutions, could also include emission gasses such as carbon dioxide.

However, the results of the simulations gave first valuable insights into the expected overall road usage charges per day and the potential consequences for the road network infrastructure. Whether the main objectives of the charging scheme have been achieved, namely, to better distribute or even reduce the overall emissions and to relieve critical areas in the city from further traffic and thus emissions, remains to be examined. To do so, transport mode switches, rescheduled departure times, local air dispersion models, and a scaled transport network need to be considered as well within the simulations. But the insights can at least be used as a starting point for toll collectors and municipalities to further investigate whether it's worthwhile to control the urban air pollution through temporarily and spatially varying LEZs. This also raises the crucial question of whether citizens would accept a toll system in which the price for the passage of a road section can change after each activation period. Road usage costs for trips become, therefore, difficult to predict although the average number of tariff changes per trip is rather low with 0 to 3 for 50% of the simulated trips.

Although the dynamic charging scheme was considered in isolation, it could also be part of a more complex charging scheme that also considers other context parameters, e.g., such as current traffic volume, road type, time of day, vehicle occupancy, and assimilative capacity of the environment. The latter could help to set the price range for the dynamic air pollution-dependent portion of the total charges, while the prices per time of day, road type, and vehicle occupancy are fixed by tariffs similar to the emission class. Electric vehicles could also be considered to contribute to additional emissions due to their comparable or even higher particulate matter emissions. The flexible air pollution-based LEZs could - besides road charging - also be used by hybrid vehicles to automatically switch between combustion and electric engines to directly influence vehicle emissions within the toll area. Overall, ITSs with the proposed charging scheme put in place are excellent applications of the new monitoring and control mechanisms for urban traffic and the associated urban air pollution that can be used in modern smart cities, due to the technical possibilities such as distributed city-wide sensor networks and precisely localizable and connected vehicles, to meet the growing demand for mobility while raising the awareness for sustainable urban living.

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