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Exploring the Financial Implications of Operating a Shared Autonomous Electric Vehicle Fleet in Zurich

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ABSTRACT

The introduction of shared autonomous electric vehicles (SAEVs) brings along many advantages. Most of these advantages can be achieved when SAEVs are offered as on demand services by fleet operators. However, autonomous mobility on demand (AMoD) will only be established if fleet operation is economically worthwhile. This paper proposes a macroscopic approach to modeling two implementation scenarios of an AMoD fleet, differing in the number of deployed SAEVs. The city of Zurich is used as a case study, with the results and findings being generalizable to other similar European and North American cities. The simulation builds on the traffic model of the canton of Zurich (*Gesamtverkehrsmodell des Kantons Zürich* (GVM-ZH)). Financial profitability is based on the simulation results which are combined with a comprehensive SAEV cost analysis. The results demonstrate that, depending on the scenario, journeys can be offered profitably to customers for CHF 0.66 or CHF 0.56 per kilometer. While larger fleets allow for lower price levels and increased profits in the long term, smaller fleets exhibit elevated efficiency levels and profit opportunities per day. The paper concludes with recommendations on how fleet operators can prepare themselves to maximize profit in the autonomous future.

1. Introduction

Autonomous electric vehicles will significantly change our cities and urban mobility. To date, however, it is uncertain whether they will be owned by individuals — and used as upgraded conventional vehicles — or used as shared autonomous electric vehicles (SAEVs) and offered as autonomous mobility on demand (AMoD). For city officials and policymakers, privately-owned vehicles, due to low occupancy rates and limited transport capacities, may not be desirable. Such vehicles lead to high traffic loads, which result in congestion (Wang et al., 2013), harmful pollution (Nieuwenhuijsen & Khreis, 2016), and an increasing number of traffic collisions (WHO, 2018). Cities such as Paris, Hamburg, Madrid, and Oslo have recognized these patterns and recently started to ban individual passanger in certain ares (Cathkart-Keays, 2015). Also, from the perspective of mobility users, vehicle ownership within cities is decreasing in last decades. Factors such as high acquisition costs (AAA, 2019; Becker et al., 2019) and low utilization (Bates & Leibling, 2012) make owning a vehicle unattractive.

Recently, the idea of the sharing economy has entered the transportation sector, fostering the reduced usage of privately owned vehicles (Barbu et al., 2018). Mobility on demand (MoD), as offered by transportation network companies such as Uber or Lyft, provides access to vehicle-based mobility, without the responsibility and financial burden of ownership (Boysen et al., 2019; Hamari et al., 2015; Hyland & Mahmassani, 2020). Over the next few years, however, SAEVs may further disrupt today's MoD concepts. Once SAEVs are introduced into the market, the sharing aspect will be amplified, enabling the transition from MoD to AMoD (Ciari & Becker, 2017, Meyer & Shaheen, 2017).

Overall, current research suggests that the use case for AMoD holds great potential for urban areas (Milakis et al., 2017). For example, Hamadneh & Esztergár-Kiss (2019) show that one SAEV can replace up to 8 conventional vehicles. Hence, SAEVs have the potential to decrease the number of cars necessary to meet our urban transportation needs. Further, Boesch et al. (2018) found a reduction in mobility cost of up to 80% due to the use of shared autonomous services. MacKenzie et al. (2014) predict a decrease in emission by up to 20% due to reduced ownership and autonomous taxi services. However, potential AMoD operators might face certain challenges: While the current business model of transportation network companies can be considered asset-light, as vehicles are owned by drivers, operating an AMoD fleet requires vehicle ownership. This results in a continuous financial commitment, including not only operational expenses but also major investments in the vehicle

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fleet (Chen et al, 2016, Fagnant & Kockelman, 2015). Hence, the question arises whether operating an AMoD system is viable for fleet operators (Gurumurthy et al., 2019; Loeb & Kockelman, 2019). This question remains crucial as such fleets will be rolled out — and thus benefit cities — only if operation is profitable (Spieser et al., 2014).

Some researchers have touched on the cost of SAEVs and their application within cities as AMoD systems (Becker et al., 2020, Chen et al., 2016). However, additional research is needed to fully understand how SAEV fleets might be operated from a financial perspective, as outlined below.

First, only few publications have comprehensively addressed the financial implications of AMoD systems from an operator perspective. Even fewer studies have taken into account whether fleet operation is financially worthwhile. Following the literature, Burns et al. (2012) and Spieser et al. (2014) have discussed the financial implications of the costs of SAEVs. However, these studies have not considered fleet operations. Fagnant and Kockelman (2018) contrasted the cost of an SAEV with its return on investment for SAEV operations in a shared context. Further, Farhan and Chen (2018), Chen et al. (2016), and Loeb and Kockelman (2019) focused on the fleet operator perspective to assess the impact on performance and the cost of different vehicle types. However, the mentioned studies assume a simplified cost structure and do not directly compare operating expenses and profit. While Boesch et al. (2018) pointed out inconsistencies and neglected cost buckets in previous studies, they only considered AMoD fleets as one of many potential modes. Hence, they did not explore profit opportunities in detail and their discussion of the strategic implications for potential fleet operators is limited.

Second, previous studies have often involved the same data sets, models, and cities. Hence, results have been biased toward certain geographic areas such as the commonly used Austin region in Texas, US (Fagnant & Kockelman, 2014; Farhan & Chen, 2018; Zhao & Kockelman, 2018; Loeb & Kockelman, 2019). Since cities may be assumed to differ significantly on the international level in terms of certain key characteristics (e.g., infrastructure design or vehicle-based travel patterns), the insights of previous studies may be transferred only to a limited extent. While several papers investigate various aspects around SAEV usage in Europe (Narayanan et al., 2020), only few have investigated the European cost perspective of SAEVs.

Third, the size of simulated fleets is often derived based on demand. This procedure allows drawing conclusions about the fleet sizes required to serve a certain number of passengers. However, this results in a significant number of SAEVs in the network. Chen et al. (2016), for example, simulated more than 57,000 SAEVs, while Spieser et al. (2014) modelled up to 300,000 SAEVs. Considering forecasted SAEV adoptions, such fleet sizes will only occur in far-distant scenarios and are generally only relevant to scenarios multiple decades in the future. This circumstance restricts the meaningfulness and practical relevance for fleet operators, as travel demand is likely to fundamentally change until then.

Finally, given the speed of development in the industry, most of the calculated values used in the studies reviewed above have changed since. For example, while Bösch et al. (2018) base their calculation on battery costs of $227 per kwh, prices are expected to undercut $100 in the next 5 years and go as low as $50 by 2030 (Lutsey & Nicholas, 2019).

To date, a study which considers the costs, prices, and potential profits of an AMoD fleet in a comprehensive, yet up to date manner is missing. Nor has any study yet examined the financial perspective based on a realistic and relevant AMoD simulation — i.e., first, with fleet sizes that are likely to occur in the near future and second, in a European hub (which would enable transferring the findings and implications across multiple cities). Our study is, therefore, the first to explore in a relevant, setting how an SAEV implementation strategy affects operator profit. This aspect remains crucial as it determines whether the advantages of SAEVs as shared fleets might eventually become economically and politically viable. As the performance of SAEVs is strongly correlated with the fleet size (Vosooghi et al., 2019), we modeled two scenarios differing in number of vehicles, following various SAEV market share predictions (Archambault et al., 2015; McKinsey & Company, 2016). We apply dynamic ride-sharing mechanisms that allow not only sharing the vehicles but also the rides. The algorithm identifies partially overlapping trip requests in real time and considers a set of predefined matching criteria (e.g., maximum detour factor). We comprehensively derived the SAEV cost structure for both scenarios as well as adapted and updated the assumptions of previous research to produce the most relevant results.

Our overarching research question is: *How does fleet size affect the profit of AMoD fleet operators?* We raise two specific research questions:

1 At which price level can an AMoD service be offered viably based on a per passenger kilometer view?
2 What are the strategic implications of the fleet size for operators?

From a managerial perspective, our approach provides an ideal starting point for exploring the financial implications of a realistic AMoD deployment in a representative European hub. The remainder of this article is structured as follows. Section 2 illustrates our methodological procedure. It addresses the underlying traffic simulation and highlights the relevant aspects of our cost derivation. Section 3 presents the results of the simulation and cost derivation. Section 4 discusses the results and implications while Section 5 draws conclusions and considers avenues for future research.

2. Methodological approach

This study involves a traffic simulation of an AMoD fleet across the city of Zurich and its metropolitan area in order to perform a financial analysis. Our methodology comprises two approaches: 1) Simulating demand to gain insights into SAEV usage and load factors; 2) comprehensively deriving the costs of operating an SAEV within an AMoD fleet. We assumed a business-to-consumer service model in which the operator is also the fleet owner (Stocker & Shaheen, 2017).

2.1. Simulation-based determination of operational parameters

The method used in our work combines two elements: the first element is a macroscopic traffic model, which is widely used in the literature for evaluation the impact of autonomous driving. For example, see prominent worksy by Crisan & Filip (2015), or Stathopoulous & Sener (2017). We use PTV Visum, which is a commen tool for scientifc studies (as example see Jacyna et al., 2017), as well as leading tool used by transport planners analysts throughout the world (PTV Group, 2021). The second element is the PTV MaaS Modeller which is an add-on to PTV Visum that enables the simulation of on-demand ride pooling fleets to determine operational performance (PTV Group, 2017). Instead of using an agent-based simulation system, in which independent entities determine the outcome by making decisions based on a set of predefined rules (Bonabeau, 2002), the PTV MaaS Modeller encompasses a procedure that allows for the generation of individual trip requests, based on the aggregated demand of the traffic model.

The network in our study is an adapted version of the calibrated and comprehensive traffic model of the canton of Zurich (Kanton Zuerich Volkswirtschaftsdirektion Amt für Verkehr, 2011). Input parameters were fed into the model, and demand calculation and mode choice of the model were iteratively matched with route planning and traffic allocation, in order to determine an equilibrium over the course of the simulated timeframe. Once an equilibrium is reached, the output parameters (in terms of vehicle, passenger, and further network data) can be retrieved (see Figure 1).

Simulation of exogenous parameter:

In general, input variables are based on reasoned assumptions. The most important factors are the advance booking time (15 minutes), the operating time of 24 hours and the passenger change time (1 minute).

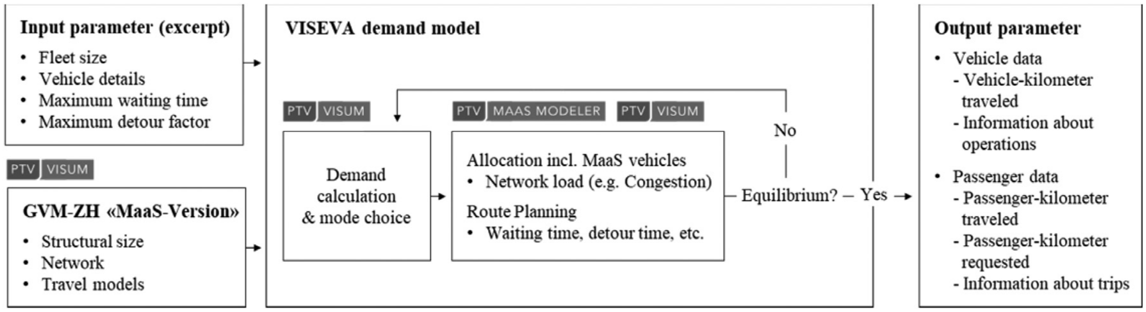

Fig. 1. PTV MaaS Modeller Workflow showing input and output parameters as well as providing an overview of the demand model approach.

Since ride-pooling is accepted in the study, the parameters for the waiting time, the maximum accepted time that could be added to the travel time by demand pooling, and the maximum diversions factor of a trip are added (Nökel & Schäfer, 2018). In previous studies, the waiting time varies between five and ten minutes (Bischoff & Maciejewski, 2016; Dia & Javanshour, 2017; Loeb & Kockelman, 2019; Martinez, 2015). Since it is assumed that traffic jams can occur frequently in the city of Zurich, the maximum waiting time was set at ten minutes. The maximum diversions time to be accepted was based on the Lisbon study (Martinez, 2015). Hence, we define the maximum diversions time as 20% of the travel time, but only a maximum of ten minutes if longer distances are covered. The diversions factor was also based on the study by Martiznez (2015). The value is defined as 20% of the distance between the departure and arrival points and set to a maximum of two kilometres.

The fleet size corresponds to a real-life implementation scenario for an autonomous fleet. In this study, two scenarios were formed. Scenario 1 representing a fleet of 500 vehicles, corresponding to an early market entry, and Scenario 2 describing an established market scenario with 10,000 vehicles (see chapter 3.1).

Vehicle details: In previously conducted studies, the SAEV with ride-sharing was assumed to be a car of medium size and capacity of four to five seats (Bösch et al., 2018; Dia & Javanshour, 2017; Loeb & Kockelman, 2019; Martinez, 2017). The Audi e-tron serves as the reference vehicle and the number of seats per vehicle was set at five.

Network model GVM-ZH: The network model is based on the multimodal transport model of the canton of Zurich (Gesamtverkehrsmodell des Kantons Zürich (GVM-ZH)) from the reference year 2013 (Kanton Zuerich Volkswirtschaftsdirektion Amt für Verkehr, 2011), which constitutes the most recent version provided by the canton. Furthermore, it can be assumed that this model can be transferred to the year 2021, since both traffic does not change significantly and private car ownership in Zurich has remained constant. The GVM-ZH depicts traffic in its large-scale context (Greater Zurich) and presents its manifestations and interdependencies (demand, capacity utilisation, travel times, etc.). It also includes settlement and structural data (inhabitants, working, sales areas, etc.) and different transport modes (Swiss Federal Statistical Office (BFS), 2006). As such, the model represents personal transportation modes and public transport in a single network and also takes into account bicycle and foot traffic in the choice of transport. The GVM-ZH incorporates the transport services of all public transport systems in the agglomeration of Zurich. Consequently, public transit lines with all routes (and their spatial course), as well as stops, transfer points, transport times, and course intervals are recorded. Regarding individual mobility, the model also takes into account the availability of parking spaces at destinations (Vrtric, et al. 2015). To adjust the existing model to the instance of hailing shared rides, around 7,000 routing points were defined to build on the route creating feature within the software. These Pick-Up and Drop-off points (PUDOs) are located according to specific guidelines along key nodes, such as crossroads, of the network area and act as virtual stops (potential start or ending locations of the ride) (Figure 2). On average, PUDOs are located roughly 100 to 300 meters apart from each other. This procedure allows for faster pickups by avoiding major detours. The traffic demand is preadapted to the PUDOs, so that there is a realistic distribution of the demand to the nodes.

VISEVA demand model:

The simulation runs on PTV Visum, a macroscopic travel-demand simulation software (Noekel & Schaefer, 2018). The PTV Group incorporates algorithms from the logistics industry through PTV X-Server, a logistical and geospatial software for optimizing logistics processes (Noekel & Schaefer, 2018; Barceló et al. 2018). The trip generation, trip distribution and mode choice is applied simultaneously by an EVA algorithm developed by Lohse (1997) and PTV (2021). The VISEVA demand model is used as a large class of different model expressions of a relatively consistent and clearly formulable transport demand modeling theory, which is associated with the Bayesian axiom of probability theory, minimisation of information gain, and the solution procedures of n-linear systems of equations with constraints and close ties to the discrete stochastic ties to discrete stochastic choice theory (c.f,. among others Ben-Akivea et al. (1985), Lohse et al. (1997), Lohse et al. (2006a)).

The basis of the traffic distribution is an n-linear activity purpose pair approach. It is assumed that the traffic volumes of a traffic flow matrix are known from the traffic decomposition. The choice of a destination traffic district j and a means of transport k by a road user for a change of location starting from the source traffic district i is assumed with a conditional a priori probability BW_{ijk} (evaluation probability of the relationship ijk with regard to the effort from the road user's point of view) and rejected with the probability (1-BW_{ijk}) (Lohse, 2006b). This conditional probability is:

$$BW_{ijk} = p\left(W \mid A_i \cap E_j \cap M_k\right),$$

where A_i is the origin zone, E_j is the destination zone, M_k is the mode of transit for trip W.

The MaaS Modeller translates the macroscopic demand to a macroscopic level. The exact time of origin and the exact place of destination within the respective cell is randomly selected for each zone. In order to counteract the random component, different starting numbers (random seed) are used (PTV Goup, 2017). Weighting factors can be used for the time of origin as well as the place of origin. We do not have a weighting factor for the place of origin, but for the time of origin indirectly through the demand hydrograph per hour.

2.2. Derivation of the comprehensive costs for a vehicle in the AMoD fleet

Overall costs were determined to establish the costs and profits of the fleet within the simulation. This procedure was primarily based on the cost structure derived by Boesch et al. (2018). However, given the speed of change in the industry, most values were adapted and updated to reflect a more recent perspective and allow for the most realistic and relevant results regarding our research questions. Following a bottom-up approach, cost components were comprehensively derived based on reference values from practice and academia. The costs considered refer

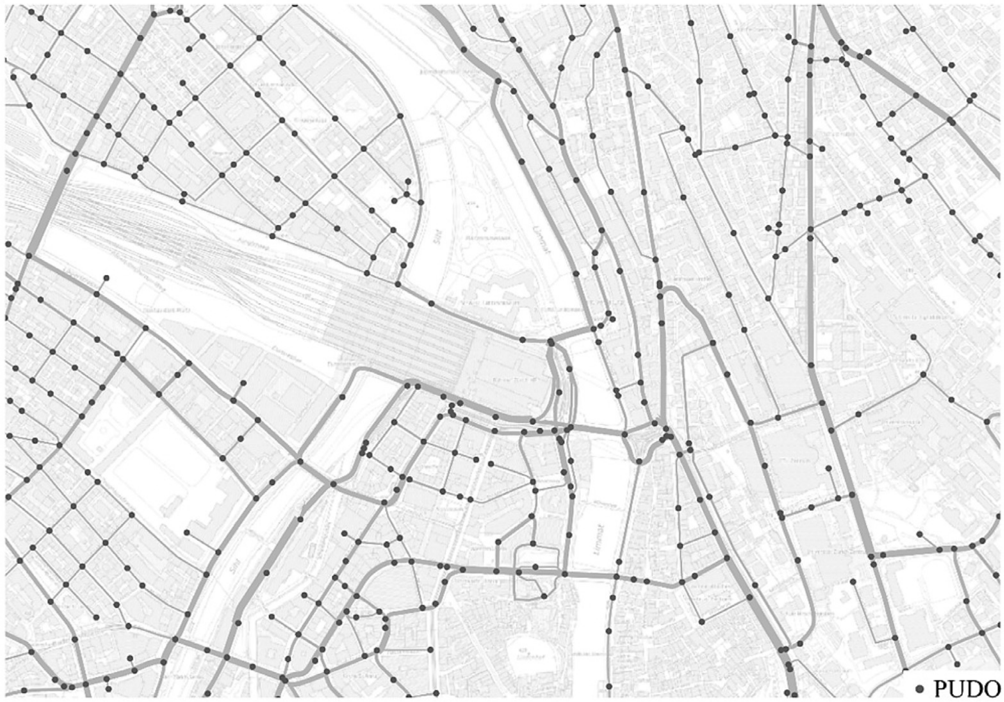

Fig. 2. Extract of the network model including the added PUDOs for determining the stopping points of SAEVs.

to an AMoD application in the city of Zurich and are stated in Swiss Francs (CHF). Following the approach of Boesch et al., (2018), as some product and service prices are gross, Swiss VAT of 7.7% (ESTV, 2020) was deducted whenever applicable.

Investment costs: The most crucial cost factor of an AMoD service is the SAEV acquisition. Given that, to date, no fully autonomous car is commercially available, the vehicle price in our study is composed of an electric vehicle and an automation premium that incorporates the technology to make the vehicle drive by itself. In our study, the Audi e-tron served as a reference point, with a base price of around CHF 70,000 (ADAC, 2019) and the automation premium set at CHF 10,000 (Fagnant & Kockelman, 2015; Jones & Leibowicz, 2019). As SAEV technology will become cheaper due to learning and scale effects, a 10% learning rate per annum was factored in and the technology was assumed to have been on the market for three years at the time of investigation (Wadud, 2017). A fleet discount of 21% was considered for the 500-vehicle fleet (Blens, 2015) and 40% for the 10,000-vehicle fleet (eFahrer, 2020). Vehicles were assumed to be financed with a loan. Given the confidentiality of corporate interest rates, we performed a multi-step approximation, which considered capital market rates, corporate bonds from fleet operators, and private annuity loans. Credit terms were assumed to be flexible and based on vehicle lifetime (in years). Thus, interest rates were set at 3.5% for Scenario 1 and 2.5% for Scenario 2 (compounded annually). Based on Deloitte (2019), we assumed that SAEVs have a life expectancy of 300,000 km and that the vehicle price is written-off linearly over the kilometer-based life expectancy. Potential processing fees and cash-flow relevant repayments were neglected. In the case of the canton of Zurich, municipal taxes were waived (BFE, 2020). Since the warranty of the electric battery of most electric vehicles is limited to a maximum of 160,000 km (Autogazette, 2020), and following Chen et al (2016), the SAEV battery must be replaced once in a lifetime. According to the ADAC (2019), the battery capacity of the Audi e-tron amounts to 71 kWh. With battery packs becoming significantly cheaper every year (Loeb & Kockelman, 2019), the mean values of battery cost predictions for 2025 were adopted and rounded to CHF 110 per kWh (Lutsey & Nicholas. 2019). A fleet discount was granted as stated above, and battery installation was calculated with CHF 100. Vehicle registration, including the registration certificate and number plate was rounded to CHF 100 to allow for potential administrative compensation (STVA, 2020). As great uncertainty exists about SAEV insurance premiums (Loeb & Kockelman, 2019), vehicle insurance was set at CHF 800 per year (Comparis.ch, 2018). Given that further savings may be expected due to SAEV crash avoidance (MacKenzie et al., 2014; Wadud, 2017), the insurance premium was reduced by 25%. Moreover, fleet discounts of an additional 10% and 20% respectively were granted. Boesch et al. (2018) established overhead and operations costs by determining potential indirect costs (e.g., development and provision of booking infrastructure, real estate, the management team and other personnel, as well as advertising expenses or customer discounts). The values of CHF 14 and CHF 10 per SAEV per day were adapted for Scenario 1. For Scenario 2, we assumed that marginal indirect costs per SAEV decrease with increasing fleet sizes. Due to fleet automation and economies of scale this effect leads to a 75% indirect cost reduction, as observed for other transportation network providers that quickly scale up their operations without significantly increasing their workforce or legacy systems.

Operating costs: While new automation technology will make cars more prone to system failures, service intervals will be significantly reduced in the future due to the electric drivetrain (Firmenauto, 2019). In our study, therefore, the car was serviced and maintained every 30,000 km at a cost of CHF 300 for Scenario 1 (Repcheck, 2020). While a potential learning curve might bring down maintenance costs in the foreseeable future, it is not taken into account given the limited time-span of this work and high level of uncertainty. For Scenario 2, we assumed that vehicle service could be conducted in-house and that the accruing costs could be reduced by 25%. Furthermore, costs for tires must be considered (Boesch et al., 2018). According to Pneuexperte (2020), an all-season tire costs around CHF 55 and lasts 50,000 km (Lange, 2020). Volume discounts of 10% and 20% were granted for the two scenarios. To calculate the required electricity to power the vehicles, the fuel consumption of the Audi e-tron with 25.8 kWh per 100 km served as a benchmark (ADAC, 2019). According to Swisscharge (2020), the variable charging costs in the urban area of Zurich amount to around CHF 0.30 per kWh. The variable time tariff and a fixed entry fee were neglected in our calculation to offset potential savings

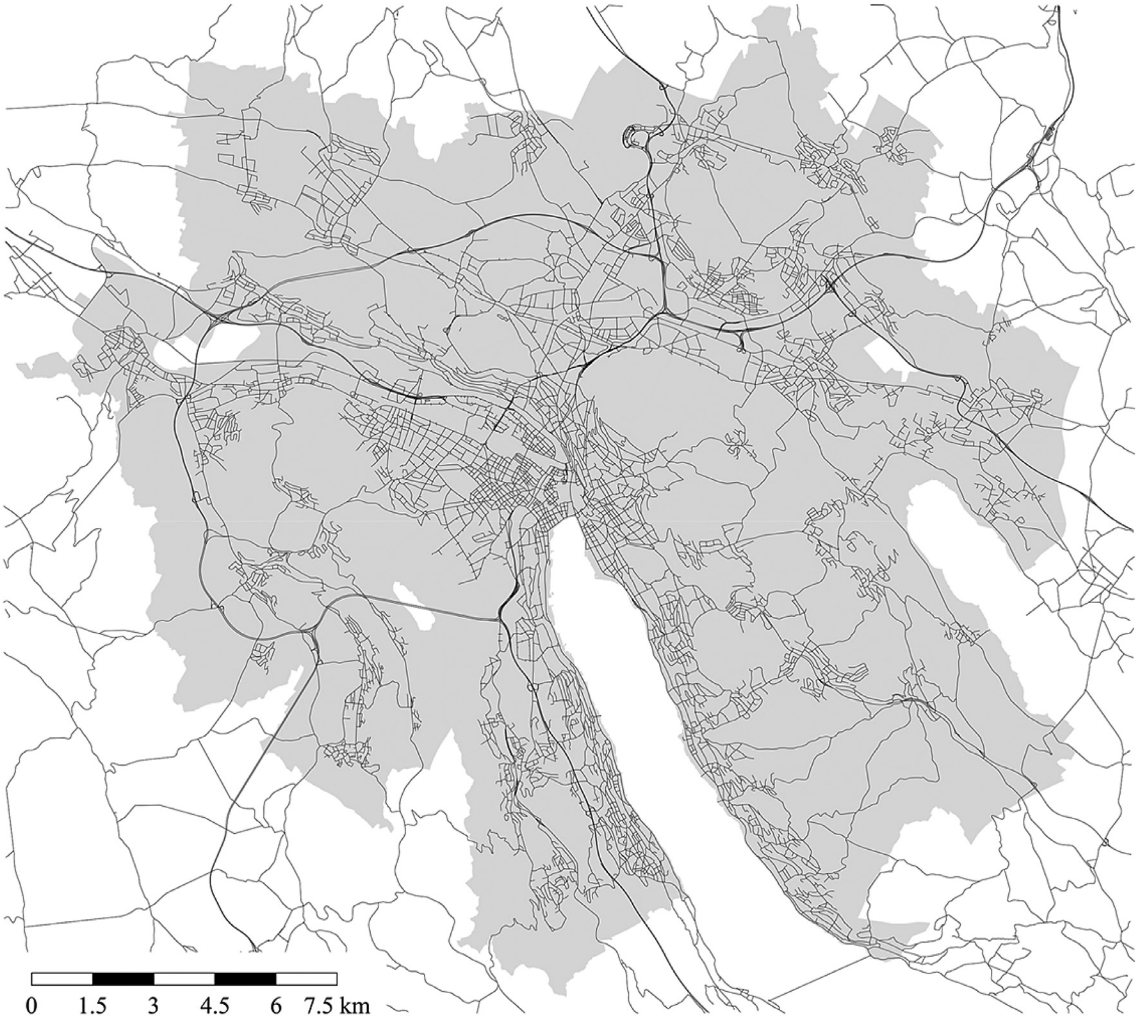

Fig. 3. Geo-fenced area of Greater Zurich that determined the scope of the AMoD service (shaded grey).

from agreements with station providers. Furthermore, we assumed that no further infrastructure investments (e.g., private charging stations) were necessary. This assumption was supported by the fact that Zurich City Council actively supports setting up charging infrastructure for both Level 2 and Level 3 charging (City of Zurich, 2019). To address potential parking expenses while the SAEV is idle, the yearly parking costs of a Drive-Now vehicle of CHF 1,000 were adopted for Scenario 1 (Frankfurter Rundschau, 2017). A 50% parking discount was assumed for Scenario 2, as cities are actively incentivizing the potential reduction of privately owned vehicles (BCS, 2019). Considering that cleaning intervals are highly subjective (Loeb & Kockelman, 2019), a total cleaning time of 10 minutes every 30 passenger trips was factored in and a minimum of one cleaning procedure per day was stipulated. The hourly wage of vehicle cleaners was set at CHF 35 (Quitt, 2020) so as to include the (potential) costs of machinery and cleaning utensils. As vehicle trips were limited to urban space, toll fees were neglected.

3. Case Study Zurich

3.1. Case study and scenario description

To answer the research question, at which price level the AMoD service can be offered viably based on a per passenger kilometer view, we perform a case study in the city of Zurich. Figure 3 shows the geo-fenced area within Greater Zurich in which the simulated vehicles were operated during our study. At the time, this area comprised 788 thousand inhabitants and 373 sqm. An assumption was made that everyone who uses the service is willing to share the vehicle with other passengers. According to Gurumurthy and Kockelmann (2020) and Lavieri and Bhat (2019) sharing a trip does not influence the willingnes to pay given a person is willing to share its ride.

Within the geofenced area, we simulate two scenarios that only vary in the size of the fleet. These scenarios reflect a realistic implementation of a fleet from the operator's point of view. As Vosooghi et al. (2019) state, bigger fleet sizes do not necessarily translate into optimized operations. Furthermore, it will likely take many decades until high modal shares will be realized. Therefore, a comparably small number of SAEVs was used. The fleet size was set to 500 shared shared autonomous electric vehicles in Scenario 1 and to 10,000 shared SAEVs in Scenario 2. This approach aimed to explore how potential implementation strategies impact financial considerations. For both scenarios, we assumed that the whole fleet was operated by one transportation company and that corresponding demand for AMoD was met only by this supplier. Scenario 1, therefore, depicts a slow implementation strategy, with a moderate number of SAEVs in the network. Scenario 2, on the other hand, follows a rapid growth and scale approach. Most recently adopted by various scooter-sharing services, the latter approach results in a significant number of transportation units in the network within a short time frame (Schellong et al., 2019).

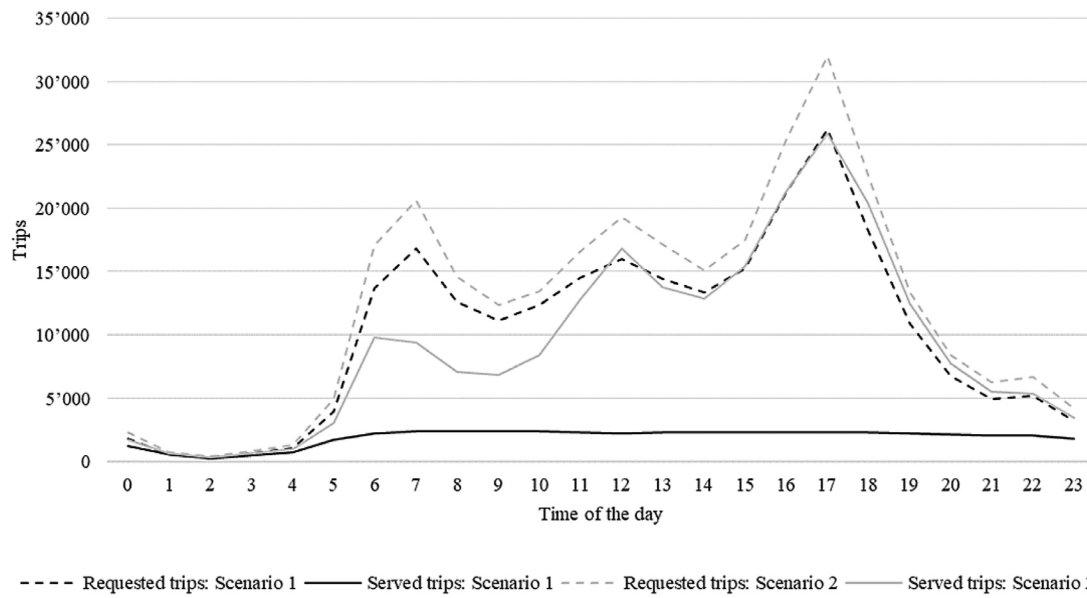

Fig. 4. Requested and served trips for both scenarios over the course of the day.

3.2. Simulation results

The traffic simulation model in our study determines the input parameters for our financial analysis. Regarding a fleet operator's implementation strategy, it is crucial to understand the demand that arises within a city. The demand for Scenario 1 was recorded at 244,832 requested trips, while that for Scenario 2 increased by 19% due to improved service availability. The small fleet size in Scenario 1, however, meant that only 18% of all requested trips were served by the AMoD fleet, while the majority of requests were denied due to lacking transport capacity. In Scenario 2, however, about 76% of all requests trip were served (see Figure 4). The deviation can be explained by a mismatch of demand and supply, which results in no empty SAEV being available at the time some of the requests were registered. This was particularly the case during morning hours as the vehicles were not sufficiently positioned where the requests were registered. Demand followed a typical pattern, peaking in the mornings and afternoons (Zhang et al., 2018). The total vehicle-kilometers traveled per day for the 500-vehicle fleet amounted to 310,172 km (Scenario 1) compared to 1,737,937 km for the entire fleet (Scenario 2).

Average vehicle occupancy for all occupied vehicle trips was 1.5 people for both scenarios, which matches the value of other researchers (Gurumurthy et al., 2019). The relatively low utilization of dynamic ride-sharing can be attributed to the relatively short waiting time and limited detour factor as stated above. The average trip length for Scenario 1 was 6.3 km, compared to an average of 7.8 km in Scenario 2. The increase in trip length for Scenario 2 resulted from more vehicles being available to serve passengers with longer trip requests that did not end in high density areas. In Scenario 1, by contrast, the relative shortage of SAEVs led to longer-distance trips with a higher fraction of empty kilometers being forgone in favor of shorter trips in the denser city core.

Considering the simulation results on a per-vehicle basis, the results suggest that an SAEV in Scenario 1 drives an average of 620 km, compared to almost 174 km per day in Scenario 2. This translates into average active vehicle times, including transport of passengers, empty travel and charging, of 22:55 and 8:55 hours, respectively. For the purpose of this study, we assume ubiquitous charging infrastructure which allows vehicles to charge for short amounts of time between trips. While, due to excess demand, the 500 SAEVs in the network are close to full utilization over the course of the day, the 10,000 SAEVs demonstrate significant downtimes, as vehicles are idling while waiting for new trip requests to be served. Nevertheless, vehicle efficiency in terms of distance driven increased in Scenario 2, as the empty vehicle-kilometers (9,9%) were lower than in Scenario 1 (10,1%).

Figure 5 shows that, in both scenarios, most traffic occurs in downtown Zurich and leads to a higher traffic load in the city center. Consequently, increasing AMoD fleet size does not significantly impact users' route choice or travel patterns. This finding is highly favorable from an operator's business perspective, as trips to more remote areas potentially increase empty driving, as vehicles need to relocate themselves back to areas with more demand in order to serve the next trip requests.

3.3. Financial analysis

3.3.1. Determination of cost per vehicle-kilometer

To consider costs on a per vehicle-kilometer basis, fixed costs (incurred only once in an SAEV's lifetime) were standardized by the vehicle lifetime of 300,000 km. Costs recurring after a certain distance driven (e.g., vehicle and tire maintenance) were first accumulated for the entire vehicle lifetime before being divided by kilometer-based life expectancy. Daily costs were broken down by the simulated daily vehicle-kilometers as stated above. Regarding annual costs (e.g., insurance or interest), daily vehicle-kilometers per SAEV and kilometer-based life expectancy were both considered. Since, according to the Swiss BFS (2019), the daily travel distance per person is relatively constant across all days of the week, daily usage patterns can be extrapolated to the year (Fagnant et al., 2015). Therefore, fleet operating time was first calculated in years using daily vehicle-kilometers and SAEV life expectancy, before yearly costs were added up and divided by 300,000 km. Table 1–3.

Table 4 shows the resulting breakdown of the corresponding costs per vehicle-kilometer. Based on the analysis, an SAEV may be expected to operate at CHF 0.37 in Scenario 1, compared to CHF 0.33 in Scenario 2. These figures incorporate potential detours and unoccupied trips. Under our simulated conditions, this figure translates into average operator costs of CHF 231.77 (Scenario 1) and CHF 56.77 (Scenario 2) per vehicle per day, based on daily vehicle-kilometers (see Table 5).

3.3.2. Determination of price levels

Analyzing potential price levels requires converting costs to a per passenger-kilometer basis. Therefore, we first considered accruing vehicle costs on a per-day basis and subsequently broke these down ac-

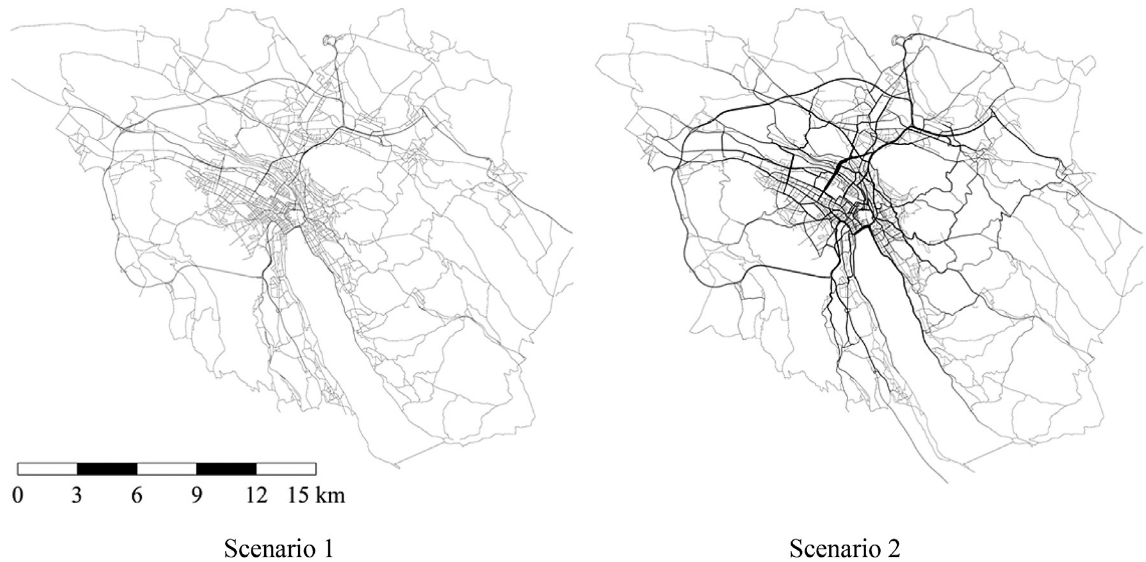

Fig. 5. Network utilization due to AMoD fleet traffic for both scenarios.

cording to the simulated requested passenger-kilometers. This approach implies that possible detours occurring due to the nature of ridesharing are not charged to the user. Furthermore, we considered revenues by the number of journeys rather than by the number of passengers. This strategy is also adopted by leading MoD services such as Uber Juntos (Uber, 2020) or common taxis in Zurich (City of Zurich, 2015), according to which a supplementary charge is only required from three or four passengers per journey request. The price per passenger-kilometer, P_{pkm}, calculation was performed analogously to Boesch et al. (2018) and by taking into account the Swiss payment transaction fee (p) of 0.44% (WEKO, 2014), VAT, and the cost per passenger-kilometer C_{pkm}, as stated above. To allow for viability, the current take rate that serves as profit margin (r) for platform providers like Uber of 25% (Egg, 2020) was applied. In addition, demand in terms of passenger-kilometers requested was assumed to be fixed. The overall system of demand is inelastic. Referring to Krueger et al. (2016), the preferences for the choice of a SAEV are based only to a small extent on the travel costs. Factors which we applied as inelastic factors such as waiting time and travel time are much more decisive. Furthermore, no fixed fee (e.g., per ride) was considered; the price level was expressed in terms of a variable kilometer-based fee (Boesch et al., 2018).

$$P_{pkm} = \frac{C_{pkm}}{(1-r)(1-p)}(1+VAT)$$

As a result, feasible price levels of CHF 0.66 per passenger-kilometer were derived for Scenario 1 and CHF 0.56 for Scenario 2. Correspondingly, AMoD can be offered viably at the aforementioned price level while capturing an industry-average profit and considering empty vehicle travel.

Under the simulated conditions and assuming inelastic demand, the fleet operator can break even with a price level of between CHF 0.49 (Scenario 1) and CHF 0.42 (Scenario 2). The lower price for Scenario 2 is primarily caused by fleet discounts, yet is also impacted by longer fleet life expectancy due to fewer trips served per day.

4. Discussion

4.1. How does the fleet size of an AMoD fleet affect profit of a fleet operator?

To evaluate profit in absolute terms, we calculated daily costs by multiplying the costs per vehicle-kilometer with the daily vehicle-kilometers traveled. Analogously, we calculated daily revenue using the feasible price per passenger-kilometer and the passenger-kilometers requested per day, as stated above. We calculated profit by subtracting daily costs and transaction fees from daily revenue.

$$Cost_{day} = D_{vkm} C_{vkm}$$

$$Revenue_{day} = \frac{P_{pkm}}{1+VAT} R_{pkm}$$

$$Profit_{day} = Revenue_{day}(1-p) - Cost_{day}$$

$Cost_{day}$ are the total daily operating costs, D_{vkm} represents the daily vehicle-kilometers traveled, $Revenue_{day}$ is the expected daily revenue, R_{pkm} illustrates the initially requested vehicle kilometers without potential detours, and $Profit_{day}$ is the expected daily profit.

Under the simulated conditions and assuming a feasible price level (see above), operating an AMoD fleet enables generating a profit of CHF 77.26 and CHF 18.92 per SAEV per day, depending on fleet size and daily kilometers. As, according to Fagnant et al. (2015), mobility usage patterns in terms of passenger-kilometers are relatively constant across all days of the year, daily profit can be extrapolated and results in a yearly profit of up to CHF 28,198 per SAEV Scenario 1. While the number of vehicles in Scenario 2 is 20 times that of Scenario 1, the costs and the corresponding profit for Scenario 2 are only about 5 times higher. This results from the high deviation in servable trip requests per day per SAEV. As each SAEV in Scenario 1 accumulates about 3.6 times as many vehicle kilometers and 4 times as many passenger trips per day compared to the 10,000 SAEV fleet, the costs and revenues are "accelerated" and vehicle lifetime in terms of years is significantly reduced. While SAEVs in Scenario 1 will most likely reach their 300,000 km life expectancy within the first two years, SAEVs in Scenario 2 are expected to be in the market for around five years before reaching their kilometer-based life expectancy. Consequently, while costs on a daily or yearly basis for Scenario 2 will most likely be much lower, they will occur over a much longer time period. An additional factor to consider are potential congestion-fees that may be charged by authorities to circumscribe empty travel. This instance will drive down profits.

4.2. Strategic implications for fleet operators

When determining the size of their AMoD fleet, operators must weigh up achieving cost saving potential and ensuring service quality. Larger

Table 1
Overview of cost derivation parameter.

	Scenario 1	Scenario 2
Investment costs		
Vehicle lifetime[1]	300,000 km	300,000 km
Base vehicle[2]	CHF 70,000	CHF 70,000
Automation premium[3]	CHF 7,290	CHF 7,290
Vehicle fleet discount[4]	21%	40%
Interest rate[6]	3.5%	2.5%
Battery capacity[2]	71 kWh	71 kWh
Cost per kWh[5]	CHF 110	CHF 110
Replacement cost[6]	CHF 100	CHF 100
Battery fleet discount[6]	21%	40%
Registration[7]	CHF 100	CHF 100
Insurance (per year)[8]	CHF 800	CHF 800
Insurance automation discount[9]	25%	25%
Insurance fleet discount[6]	10%	20%
Overhead (per day)[10]	CHF 14	CHF 3.5
Operations (per day)[10]	CHF 10	CHF 2.5
Operating costs		
Maintenance & service[6,12]	CHF 300	CHF 225
Service interval[11]	30,000 km	30,000 km
Tire-set[14]	CHF 210	CHF 210
Tire lifetime[13]	50,000 km	50,000 km
Tire fleet discount[6]	10%	20%
Electricity (per kWh)[15]	CHF 0.3	CHF 0.3
Consumption (kWh / 100 km)[2]	25.8	25.8
Parking (per year)[16]	CHF 1,000	CHF 500
Cleaning interval[6]	30 trips	30 trips
Hourly cleaning wage[17]	CHF 35	CHF 35
Time per cleaning[6]	10 minutes	10 minutes

1 Deloitte, 2019
2 ADAC, 2019
3 Fagnant & Kockelman, 2015; Jones & Leibowicz, 2019; Wadud, 2017
4 Blens, 2015; eFahrer, 2020
5 Lutsey & Nicholas, 2019
6 Expert interview
7 STVA, 2020
8 Comparis.ch, 2018
9 MacKenzie et al., 2014; Wadud, 2017
10 Boesch et al., 2018
11 Firmenauto, 2019
12 Repcheck, 2020
13 Pneuexperte, 2020
14 Lange, 2020
15 Swisscharge, 2020
16 Frankfurter Rundschau, 2017; BCS 2019
17 Quitt, 2020

Table 2
Demand-based output parameters from the simulation for the entire network.

	Scenario 1	Scenario 2
Passenger-kilometers travelled (incl. detour) [km]	283,145	1,607,722
Passenger-kilometers requested (excl. detour) [km]	253,558	1,466,481
Number of served trips [trips]	44,667	223,007
Number of requested trips [trips]	244,832	292,525
Average passenger-trip length [km]	6.34	7.79
Number of passengers [pax]	62,356	313,063

Table 3
Supply-based output parameter from simulation for the entire network.

	Scenario 1	Scenario 2
Vehicle-kilometers travelled [km]	620.34	173.79
– Occupied vehicle-kilometers [km]	559.06	155.85
– Empty vehicle-kilometers [km]	61.28	17.94
Active Operating Time [hh:mm]	22:55	8:55
Share of empty kilometers driven [%]	10.12	9.88

fleets result in major discounts, which in turn lower price levels and potentially increase operator profit. In contrast, smaller fleets hold cost saving potential as, due to learning and scale rates, certain cost components are expected to steadily decrease over time. As small fleets reach much higher turnover and thus can be replaced much more frequently, operational assets become much cheaper. On the other hand, the rejection of about 82% of all trip requests in Scenario 1 poses a major problem. While this finding does not affect the present business case, it is highly unfavorable from the customer point of view. As a result, the high level of unreliability may cause a decline in willingness to use the service in the long term. Particularly during peak times (mornings and afternoons), excess demand means many trips are not served. The resulting unreliability might lead to other modes of transport being preferred over AMoD. Consequently, fleet operators are advised to determine fleet size whilst keeping both the customer and the operational-efficiency perspective in mind.

Our simulation also shows that given high demand levels, the larger the fleet, the more inefficient the service becomes in terms of served trips per day. This finding stresses the need for ride-sharing to avoid empty vehicle travel, which accounted for about 10% of the driven distance in both scenarios. Consequently, fleet operators are advised to incentivize potential users to share, i.e., pool rides (Martinez et al., 2014). Operators can improve matchmaking algorithms by granting discounts to users who book rides in advance or to those who are willing to wait

Table 4
Costs per vehicle-kilometer.

	Scenario 1		Scenario 2	
	Cost [CHF]	Share of Cost	Cost [CHF]	Share of Cost
Investment Costs				
Vehicle Depreciation	0.189	51%	0.144	44%
Interest	0.006	2%	0.003	1%
Replacement Battery	0.019	5%	0.015	4%
Registration	0.000	0%	0.000	0%
Insurance	0.003	1%	0.007	2%
Overhead	0.023	6%	0.020	6%
Operations	0.016	4%	0.014	4%
Operating Costs				
Maintenance & Service	0.009	2%	0.007	2%
Tires	0.004	1%	0.003	1%
Electricity	0.072	19%	0.072	22%
Parking	0.004	1%	0.007	2%
Cleaning	0.028	7%	0.034	10%
Costs per vehicle-kilometer	0.374	100%	0.327	100%

Table 5
Overview cost, revenue, and profit.

	Scenario 1 per SAEV	Scenario 2 per SAEV
Cost per day [CHF]	231.77	56.77
Revenue per day [CHF]	310.40	76.03
Profit per day [CHF]	77.26	18.92

longer for the SAEV to arrive. Both actions would enable the system to combine individual journeys more effectively as it gives the technology a time buffer. Moreover, Figure 4 highlights the concentration of traffic in central areas that might not only result in further congestion but potentially cannibalize public transport. This instance will apply particularly when considering competitive AMoD price levels: If customers used AMoD as their sole mode of transportation for the Swiss average daily travel distance of 36.8 km (BFS, 2019), the price of CHF 24.3 and CHF 20.6 for the two scenarios would surpass the price of CHF 13.6 for a three-zone public transport ticket in the city of Zurich (City of Zurich, 2020) by 50%, while offering higher levels of convenience. Whereas a conventional taxi would charge more than CHF 200 for this distance (City of Zurich, 2015), AMoD offers vehicle-based mobility at a fraction of the costs. Nevertheless, in terms of an annual or monthly subscription, public transport remains more favorable. The annual season ticket costs slightly more than CHF 3 per day and the monthly season ticket CHF 4 per day (City of Zurich, 2021).

However, the low prices of AMoD might lead to conflicts of interest with policymakers and urban planners, who are likely to introduce countermeasures so that people do not switch from public transport to individual transport. Thus, fleet operators should aim to improve efficiency on a system level. To ensure financially worthwhile operations, they are advised to cooperate with policymakers, to jointly decide where to introduce the geo-fenced area and also to ensure mobility in less-dense transit areas that lack transportation alternatives. Integrating AMOD into the existing network accordingly to ensure better connectivity on a system level would allow for routes to be subsidized by cities and ensures sustainable operations in the short and long term for fleet operators.

The initial investment of around CHF 28 million (Scenario 1) or over 430 million (Scenario 2) merely to acquire the fleet might challenge many operators. In order to increase profitability and accelerate breaking even, fleet operators are advised to improve operational efficiency. This, however, can only be accomplished profitably if the AMoD service is well used and accepted by customers. Operators are therefore recommended to carry out pilot projects, to invest in acceptance and trust-building measures, and to create awareness among the population, city governments, and regulators.

Other business opportunities arise beside fare-based revenue. Selling moving patterns, offering in-vehicle experiences, or running advertisements on or inside vehicles provide further means for increasing profitability. Other complementary business models include, for example, delivery of goods or a contribution to supporting the energy grid as ancillary service (Hude et al., 2018) and determine an additional profit opportunity. Moreover, even a comparably small fleet size of 500 SAEVs experiences high inefficiencies during low-demand times, particularly from around midnight to around 6 am in the morning. Instead of having SAEVs parked or cruising around empty, fleet operators are advised to utilize vehicles for non-passenger purposes. These might include last-mile goods delivery. Thus, fleet operators ensure they control in-vehicle experience and explore value-creation opportunities with potential stakeholders. Horizontal collaborative transport offers great potential for making freight transport more sustainable (Pan et al., 2019). Integrating SAEVs in this context also makes sense from the fleet operator's point of view. Following this proposal, higher fleet efficiencies throughout low-demand times could be maintained and revenue could be further incremented.

5. Conclusion

We used a case study in a major European city (Zurich, Switzerland) to analyze the financial implications of operating an AMoD service and to draw generalized conclusions about the profitability of such system based on the simulation results. We have adapted, updated, and enlarged Boesch et al. (2018)'s cost analysis of SAEVs to derive an SAEV's level of cost per kilometer. We have also applied a comprehensive cost analysis to an AMoD fleet operation based on a macroscopic traffic simulation. Our aim was to establish whether, from a fleet operator's point of view, operating an AMoD fleet is economically viable. Scenario 1 simulated a fleet of 500 SAEVs compared to a fleet of 10,000 SAEVs in Scenario 2. These scenarios represent a realistic fleet size within the next five to 10 years in which SAEV s will expand and complement the existing transport network instead of replacing it completely.

The results show that operating an AMoD fleet of 500 and 10,000 SAEVs within the city of Zurich is profitable even at low price levels. With an industry-average cut rate, each SAEV simulated in Scenario 1 could generate a profit of up to CHF 77.3 per day. In addition, vehicles could perform other services if they are not actively transporting passengers. Considering high SAEV utilization, AMoD vehicles are replaced roughly every 1.5 years in Scenario 1 compared to every five years in Scenario 2. Therefore, the learning rate, which reduces the cost of manufacturing SAEVs, plays a crucial role. Consequently, fleet costs will become increasingly cheaper in the following years. We also put the user costs incurred for average daily use of mobility services in relation to other means of transport. The costs of AMoD cannot compete with public transport, i.e., a monthly or annual ticket. They are, however, cheaper than using traditional taxi services. Based on these results, we recommend various measures for fleet operators, including cost saving, increasing operational efficiency, and pursuing long-term sustainable fleet deployment in collaboration with policymakers.

It must also be acknowledged that our simulation approach has various limitations. These include not sufficiently taking into account psychological factors (e.g., lack of acceptance of or trust in SAEV, which would influence mode choice). Further limitations stem from the cost derivation. While the analysis shows that operating an SAEV fleet may be highly profitable, it only considers the fare-based revenue from variable kilometer-based prices. Thus, actual profit will ultimately depend on the chosen price level. Although this study has involved comprehensive research, a certain degree of uncertainty remains about some of the cost components, as it is not clear how exactly the system will play out once being launched. This, for example, applies to parking costs or overhead and operational expenses. Also, effects on congestion were not particularly considered and quantified. Likewise, potential fees that might be introduced by city authorities to restrict empty travel were not included.

Due to the rapidly developing market, the cost structure of AMoD fleets should be continuously updated in the future. Further research should also include real-world experiments to further evaluate the effect of psychological adoption barriers and price sensitivity on different price functions and on the profit levels of fleet providers.

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