Activity Deliverable

Real-time pollution City mAp thRough cOLlaborative sensIng aNd Analysis

Collaborative and dynamic urban air pollution monitoring

EIT Urban Mobility - Mobility for more liveable urban spaces

EIT Urban Mobility

Lausanne | 30 November 2020

eiturbanmobility.eu

EIT Urban Mobility is supported by the EIT, a body of the European Union

Reporting year	2020
Activity code	20002
Deliverable No. Deliverable title	DEL04 Dynamic and collaborative urban air pollution monitoring methodology.

Document information

Author(s) and contributing partner(s) - if any

Name	Organisation	Contribution
Emmanouil Barmpounakis	EPFL	Technical contributions in the whole document and fitting with overall KAVA overview
Nikolaos Geroliminis	EPFL	Technical contributions in the whole document
Caio Beojone	EPFL	Technical contributions in the whole document
Patrick Stokking	EPFL	Technical contributions in Section 4
Raúl Urbano Escobar	CTAG	Check quality criteria of completeness, accuracy, relevance, appearance and structure
Esteban Ferro Santiago	CTAG	Technical contributions in the whole document
Yusuf Hacibekiroğlu	ISBAK	Technical contributions in Section 4
Ebru Akyol Ergüner	IMM	Technical contributions in Section 4

List of abbreviations

AQ	Air Quality
UAQMP	Urban Air Quality Management Plan
AQM	Air Quality Monitoring
AQMS	Air Quality Monitoring System
CSMN	Conventional Stationary Monitoring Network
SSN	Stationary Sensor Network

WSN	Wireless Sensor Network
CSN	Community Sensor Network
VSN	Vehicle Sensor Network
ML	Machine Learning
AI	Artificial Intelligence

Contents

1. Executive Summary

Air pollution is a global challenge and a major concern in major cities around the world. In order to set up and maintain an acceptable level of ambient Air Quality Monitoring System (AQMS) specific measures need to be taken. While networks of fixed measurement stations have been a quite accurate solution during the past years, the low spatial resolution of the collected data does not allow the assessment of the spatial variability of pollutants in detail while other drawbacks include their large size, high price and laborious maintenance.

It has been reported that an increase in network size of fixed stations can lead to increased complication, exponentially growing costs and effort for data analysis and visualization. Thus, engaging citizens into being part of a collaborative system of the emission monitoring infrastructure can contribute towards this direction, bringing different complexities, issues, challenges and opportunities than the static-based solution. This deliverable aims to explore the current state of the art in air quality monitoring approaches and consider the inclusion of citizens into an open and collaborative process for an enriched air quality monitoring system. Thus, in order for citizens to become a vital part of this system and contribute towards the reduction of urban air pollution, the motivation and the way to attract and engage them is explored. Finally, based on the discussion around current and past projects with similar scopes to CAROLINA from the city of Istanbul and the findings of the literature review, further opportunities and suggestions towards the deployment of such a system are provided.

The leading team from EPFL consisting of Emmanouil Barmpounakis, Nikolas Geroliminis and Caio Beojone conducted the initial literature review related to the direct scopes of the specific deliverable and the relative A2003 task of CAROLINA project. Due to the significant advances in sensors' technology and monitoring technology during the past two decades, the literature studied is for the past two decades (2000-2020) and since the literature on the subject of Air Quality Monitoring (AQM) is very broad, considerable effort was put in order to include high quality papers and identify papers with overlapping results and/or conclusions. In this deliverable, insightful findings regarding the different AQMSs, emphasizing on Vehicle Sensor Networks, Hybrid Systems, Open and Community-based approaches and motivation for citizens are reported. The first draft was distributed to the rest of the partners in September 2020 and comments by Raúl Urbano Escobar and Esteban Ferro Santiago (CTAG) were addressed while additional references were also included in the text. Following, the main section titled "Istanbul: An early adapter city" was formed by using input from the team of IMM and ISBAK. The experience from current and past projects was aligned with the findings of the literature review regarding the challenges and caveats during the deployment of a low-cost sensor system. In addition, after the formation of the specific section and the insightful comments from the experience from previous projects in the city of Istanbul, suggestions and advice regarding a future system to be adopted were included. For a more complete recommendation, Emmanouil Barmpounakis and Patrick Stokking from EPFL were collaborating to review and discuss case studies related to the A2005 task of CAROLINA that could be related to the scopes of the specific section of the deliverable. Then, the deliverable was being updated continuously based on new studies that were being published based publication alerts and literature review using specific keywords. Finally, the summarizing results of a success deployment methodology for an AQMS, the concluding remarks and the lessons learnt are discussed in the final sections of this deliverable.

The literature review has two important directions as discussed in the following sections. The first one describes the state-of-the-art and identifies the main issues that should be taken into consideration by policy makers, researchers and practitioners during the first stages of the design and deployment a network of sensors. It is an important guide that not only categorises challenges and caveats but also identifies substantial opportunities to maximize the success rate of such a system. Compared to earlier approaches, a hybrid system is suggested the ideal solution using the latest powerful data fusion techniques and technological advancements. Since the low-cost sensors are still not flawless in terms of accuracy, calibration and collection of high-quality data should be the primary goal. The second direction that is related to the engagement of the citizens to participate in an AQMS identified that some of the main concerns of the citizens' participation include privacy, data quality and energy efficiency issues. Additionally, it is important to maintaining their engagement and participation throughout the data collection process is of major importance and can be guaranteed by quality feedback, economic or other incentives and technological support. Finally, as communities have been demanding a greater role in decision-making that affects their lives it is vital to communicate the results of such participation in a clear way. The last part of the deliverable discusses how the findings of the literature review combined with the experience from current and past projects in the city of Istanbul, can be a unique opportunity for the successful deployment of a low-cost sensor system in a city like Istanbul.

2. Introduction

Air pollution is a major concern in many urban areas around the world. Human health is affected noticeably as while the air quality (AQ) of cities is decreasing, the risk of stroke, heart disease, lung cancer, and chronic and acute respiratory diseases, including asthma, increases for the people who live in them (WHO, 2018). The World Health Organization (WHO), that works with countries and cities to monitor air pollution and improve AQ, reports that 4.2 million people die every year as a result of exposure to ambient (outdoor) air pollution, while 91% of the world's population lives in places where AQ exceeds WHO guideline limits (WHO, 2020). The U.S. Environmental Protection Agency (EPA) has identified six "criteria pollutants" as pollutants of concern because of their impacts on health and the environment: ozone (O_3), particulate matter (PM), carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and lead (Pb) (Williams et al., 2014). The increased traffic volume has been reported as one of the most significant causes of ambient air pollution in 20 European cities (Gulia et al., 2015). The concentration of air pollutants is highly location-dependent and traffic junctions, urban canyons, industrial installations and topological structure can have an extensive effect on local air pollution (Vardoulakis et al., 2003).

Therefore, it is seen that specific measures need to be taken to maintain an acceptable level of ambient AQ. These actions can be summarized as an Urban Air Quality Management Plan (UAQMP). As reported in (Gulia et al., 2015), the basic components of an UAQMP are i) air quality objectives, ii) monitoring, iii) emission inventory, iv) prediction and forecasting tools, v) control strategies and vi) public participation.

2.1. Task Description

This task relates to two of the basic components of an UAQMP; these are monitoring and public participation. It should be noted that another component of an UAQMP is also examined in task A2004 of project CAROLINA, focusing on the predictions and forecasting tools, while a systematic review of different UAQMPs around the globe can be found in (Gulia et al., 2015).

When it comes to the first topic, nowadays air pollution can be monitored quite accurately by networks of fixed measurement stations. Hence, the gathered data have a low spatial resolution and cannot be used to assess the spatial variability of pollutants in detail while other drawbacks include their large size, high price and laborious maintenance (Hasenfratz, 2015). Apart from that, monitoring stations have been reported to be expensive in terms of both implementation and maintenance (Haiahem et al., 2016). In recent years several research groups started experimenting with mobile air pollution monitoring systems (Honicky et al., 2008) like handheld devices (Common Sense project) (Dutta et al., 2009), vehicle-based sensors (Devarakonda et al., 2013; Lo Re et al., 2014). However, in order to have a large spatial coverage, specific strategies should be introduced to engage citizens into being part of a collaborative system of the emission monitoring infrastructure, although it has been reported that increasing network size leads to increasing complexity and exponentially increasing costs and effort for data analysis and visualization (Clements et al., 2017).

Thus, the main objective of the specific task is to explore a new dimension of urban air pollution monitoring methodologies based on portable pollution-sensing devices deployed in the street. In addition, the collaborative dimension to expand the coverage of the system as part of the engagement of drivers and public transport vehicles should be examined.

Aims of the Specific task

The aims of the specific task can be summarized to:

- Exploration of the current state of the art in next generation monitoring techniques
- Consideration of the open collaboration approach for AQ modelling and monitoring
- Analysis on what should be the motivation, what should attract and how to engage citizens to actively contribute towards the reduction of urban air pollution
- Based on the findings the city of Istanbul is examined as a specific case study

2.2. Methodology

The literature review is divided into three research directions to fulfil the aims of the specific task: i) emission monitoring techniques, ii) transportation-related open collaborative approaches and iii) transportation-related motivation and engagement for citizens. The databases that are used are ScienceDirect (Elsevier) and Google Scholar (Google) for a wider set of resources. Due to the significant advances in sensors' technology and monitoring technology during the past two decades, the literature studied is for the past two decades (2000-2020). Specific keywords are identified for every different direction of the literature review.

For the first research direction, the following keywords and terms are selected for the inquiries:

- air quality monitoring
- mobile sensors
- sensor network
- emissions

The second direction including the open collaborative approaches and the motivation and engagement, are considered really close thematically and therefore are studied together with relative keywords:

- motivation
- collaborative
- gamification
- social

3. Literature Review

3.1. Monitoring technology

Monitoring the AQ is of crucial importance as not only does it provide all the necessary information regarding the current status of present AQ, but also contributes in the evaluation of existing policies and their effective implementation. In order to apply an efficient and effective UAQMP, the quantification of the different sources of ambient pollution is necessary as these data can support the decision-making process for additional measures or the update of the existing strategies. The necessity of an effective AQ monitoring (AQM) system is also reported in (Yang and Wang, 2017) integrated with an early warning system when the air pollution is becoming more hazardous.

Since the early 1950s, when the automobile exhaust emissions were first linked with the formation of urban ozone, the study of vehicle exhaust emissions has been in the centre of attention when it comes to assessing public health and AQ (Haagen-Smit et al., 1953; Haagen-Smit and Fox, 1954). Until a few years ago the sensors available for air pollution measurement, although very accurate, were unmanageably sizable and high-priced. With the latest advances in the new generation low-cost portable sensors new opportunities have been unfold with a wide range of applications, like deploying sensor networks easily and with very low cost (F. Karagulian et al., 2019; Williams et al., 2014; Xie et al., 2017). It should be noted that this kind of sensors is much less accurate and requires periodic calibration. Some of them are referenced below in Table 1:

Table 1: Potential applications of low-cost sensors (Williams et al., 2014)

Application	Description	Example
Research	Scientific studies aimed at discovering new information about air pollution	A network of air sensors is used to measure particulate matter variation across a city
Personal Exposure Monitoring	Monitoring the air quality that a single individual is exposed to while doing normal activities	An individual having a clinical condition increasing sensitivity to air pollution wears a sensor to identify when and where he or she is exposed to pollutants potentially impacting their health
Supplementing Existing Monitoring Data	Placing sensors within an existing state/local regulatory monitoring area to fill in coverage	A sensor is placed in an area between regulatory monitors to better characterize the concentration gradient between the different locations
Source Identification and characterization	Establishing possible emission sources by monitoring near the suspected source	A sensor is placed downwind of an industrial facility to monitor variations in air pollutant concentrations over time
Education	Using sensors in educational settings for science, technology, engineering and math lessons	Sensors are provided to students to monitor and understand air quality issues
Information/Awareness	Using sensors for informal air quality awareness	A sensor is used to compare air quality at people's home or work, in their car or at their child's school

An analytical survey of applications that utilize wireless sensor network (WSN) can be found in (Yi et al., 2015). In the specific review, the authors discuss in detail and categorize the applications based on the three different types of sensor networks i) Static Sensor Network (SSN), ii) Community Sensor Network (CSN) and iii) Vehicle Sensor Network (VSN). The advantages and disadvantages of each method are summarized and illustrated in Figure 1, compared to the Conventional Stationary Monitoring Network (CSMN). The same categorization is also followed in a later study in (Pavani and Rao, 2017). In the following section, while we will emphasize on VSNs, that offer high spatial resolution with reduced costs, some additional studies that utilize different types of sensors are also included.

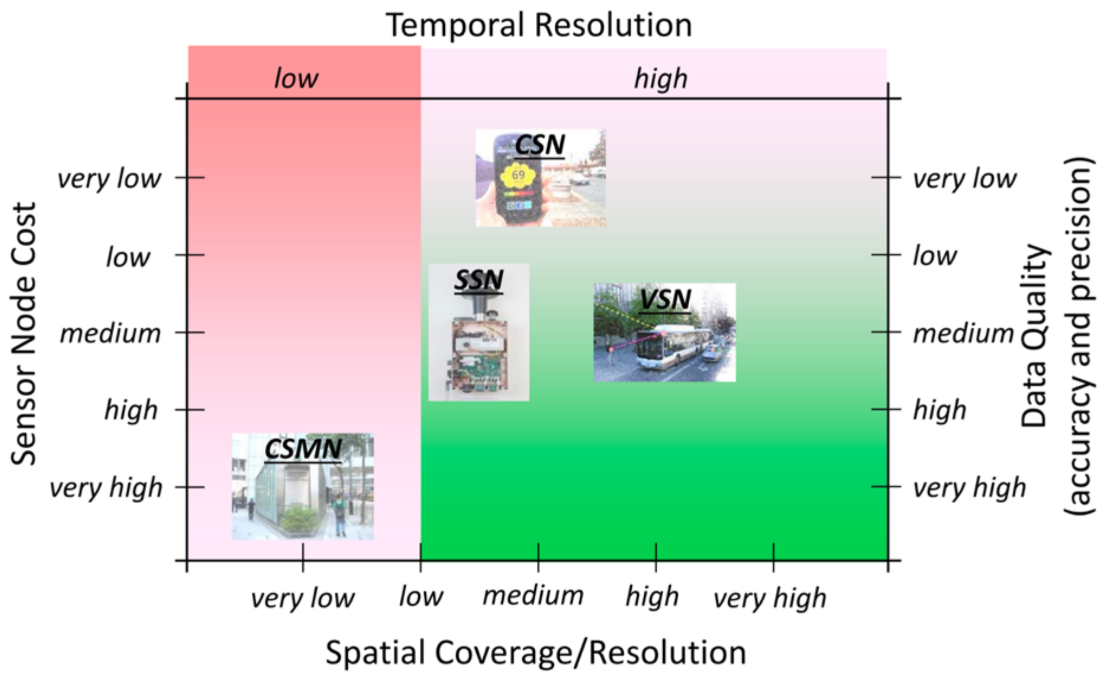


Figure 1: Trade-off for the different types of wireless sensor networks (Yi et al., 2015)

Static Sensor Networks (SSNs)

The first approaches of an AQMS included collecting data through permanent stations that would pe part of a CSMN. For example, in a highly industrialized area in Izmir, Turkey the monitoring network for SO_2 included four permanent stations (Elbir, 2003). Two different models compared their predictions with the data of the measured values from the monitoring network. As it has been previously mentioned, these sensors have a very low spatial coverage while their operational cost can be significantly high. Since the spatial representativeness of the sensors are crucial in terms of reducing and optimizing operational costs, (Stolz et al., 2020) propose clustering methods for the redundant stations as an effective and reliable solution. However, as proposed in (Anderson and Giddings, 2009; Arfire, 2016) there is usually a trade-off in the measurement quality during the transition from a CSMN to a different system consisting low-cost sensors.

One of the earliest experiments to collect data with expensive experimental mobile sensors took place in Zurich, Switzerland, where a mobile trailer with photoacoustic technology was placed at the exit of a tunnel to identify of ammonia (NH_3), ethylene (C_2H_4) and carbon dioxide (CO_2) concentrations (Marinov and Sigrist, 2003). A mobile laboratory in the same area was also used during project YOGAM (Year Of Gas phase and Aerosol Measurements) covering downtown, suburban and rural areas during different temporal and seasonal variations (Bukowiecki et al., 2002). The development of another mobile laboratory that measures on-road or real-world emissions from engines at the quality level specified in the U.S. Congress Code of Federal Regulations is described in (Cocker et al., 2004a, 2004b). The specific system can measure NO_x, methane (CH_4), total hydrocarbons (THC), CO, and CO_2 at a frequency of 10 Hz and were selected based on optimum response time and on-road stability. However, since the specific system is the size of a truck it's not easy to be used for congested urban areas. After the proposition of collecting on-road exhaust emission to study road emissions on the long them, more than 20M exhaust measurements of CO, hydrocarbons (HC), NO, vehicle information, speed, and acceleration were collected over the same location for regular intervals (Bishop and Stedman, 2008; Burgard et al., 2006). Other studies have also used instrumented vans with similar findings and challenges to face (Hagler et al., 2010; Zhu et al., 2008).

A recent study proposes to deal with the high cost of deploying dense SSNs by using downscaled sensor deployments (Cheng et al., 2020). Specifically, it is suggested that for the accurate monitoring of a large city like Beijing which has over 260 sensors deployed, 60 sensors can provide sufficiently accurate results by using the proposed downscaling method, while some issues might appear to specific sub-regions. In (Huang et al., 2020) driving emissions were measured by both AQ monitoring stations and on-road remote sensing systems, showing good correlation with each other and useful findings regarding the emission control programmes were provided.

Other approaches that have been used include the conduction of controlled tests in closed environments (laboratories) simulating different traffic and weather conditions for different scenario, such as the effect of the A/C on vehicle emissions (Weilenmann et al., 2005), or the potential of using satellite data in AQ monitoring and forecasting (Li et al., 2011), while several issues related to data availability and quality appeared.

Community Sensor Networks (CSNs)

On the later years, the CSMN approach was replaced by SSNs in order to increase coverage and reduce costs. A research and educational initiative from the U.S. EPA called as "Village Green Project" aimed to develop a self-powered, low-maintenance monitoring system to measure AQ (Jiao et al., 2015). The project was conducted from 2013 to 2019 and, while a pilot station was installed in Durham, North Carolina, which demonstrated the system's ability to monitor several common air pollutants in real-time the project expanded to other communities across the U.S. in order to further assess the operability of the system under different circumstances. Sensors were installed on park benches and citizens were able to learn more about air pollutants and pollution trends, in order to increase awareness of this new community-based AQMS (EPA, 2020). Two other examples of utilizing large-scale distributed wireless sensors for environmental monitoring are CitySense (Murty et al., 2008), which focused mostly on urban environments, and SensorScope (Barrenetxea et al., 2008), which focused on more harsh environments.

Such systems have also been used in later years, as a similar approach of using a simple WSN-based AQ monitoring system (WSN-AQMS) was proposed in (Mansour et al., 2014). Later, (Zheng et al., 2016) propose a system using portable sensors to collect the AQ information for increased coverage and then transmit the information efficiently through a low power wide area network. Then all the information is processed and analysed in the IoT cloud. Another portable device that uses microscopy and machine-learning labelled as c-Air was presented in (Wu et al., 2017). This specific device is described as cost-effective compared to other solutions while for the whole system to operate a smartphone app for device control and display of results and a remote server for automated processing are also required. A similar approach was followed (Dhingra et al., 2019) where the end-user can not only have access to real-time AQ information but also to forecasted information for a recommended route. In another study, data collected from a WSN-AQMS are being pre-processed before being sent, in order to reduce dimensionality and connect the nodes directly to the cloud computing system (Arroyo et al., 2019).

Especially with the rapid increase in the number of smartphones, some studies have suggested to allow people collect AQ measurements and share data for an enhanced UAQMP (Wang and Chen, 2017). For example, in (Nikzad et al., 2012) a system named CitiSense is proposed that utilized wearable mobile sensors that are used to directly measure AQ near the user. Each device includes three electrochemical gas sensors for monitoring exposure to carbon monoxide (CO), nitrogen dioxide (NO_2), and ozone (O_3). A phone that was equipped with AQ monitoring equipment is described in (Nyarku et al., 2018) and while several limitations are reported, authors suggest that it can be sufficiently used for comparative assessments. In a very recent study, a low-cost smartphone based solution was deployed in Seoul, South Korea (Lim et al., 2019). The advantages and potential data that are collected massively and with ease through mobile sampling with multiple low-cost sensors are emphasised to model and map street-level air pollution levels in urban locations. While the advantages of such approaches have been clearly documented in the abovementioned studies, the significant challenges that are associated with the use of mobile phones for AQ monitoring, such as privacy and security issues, unpredictable human behaviour in terms of spatial coverage, obstruction of air flow (due to placement of phones in pockets, bags etc.) were reported early during the project N-SMARTS that utilized sensors attached on GPS-enabled mobile phones (Honicky et al., 2008).

A client-cloud system consisting of low cost, custom-designed sensors and AQ analytics engine in the cloud was AirCloud (Cheng et al., 2014). In order to monitor AQ, except for data from these sensors, other data, (such as meteorological and location data) were collected to calibrate the algorithms in the analytics engine. When sensors are not available a Gaussian process is used to infer data or further improve accuracies of low confidence sensors. At the end of the process, the model can estimate the AQ in the deployment area and a heatmap is created that can be utilized for applications such as pollution tracking, trip planning, locating pollution sources etc. However it should be noted that in (Castell et al., 2017) results show that low-cost sensors' performance varies spatially and temporally. Authors note that not only it is determined by the atmospheric composition and the meteorological conditions but also changes from unit to unit. Although data quality is again noticed as a major concern especially for crowdsource applications, these sensors are still reported to provide significant information about AQ in a wider area (Castell et al., 2017). Data quality is also identified in (Rai et al., 2017) as a major concern, although the deployment of low-cost sensors allows high density monitoring of the pollutants. Therefore, these sensors' frequent calibration, aging and manufacturing details should be taken into account when used for air-quality monitoring (F. Karagulian et al., 2019; Federico Karagulian et al., 2019; Pavani and Rao, 2016; Rai et al., 2017; Williams et al., 2014; Zimmerman et al., 2018), sometimes needed before and after their deployment (Maag et al., 2018). Similar findings are reported in (Lee, 2020; Morawska et al., 2018; Pares et al., 2020; Penza et al., 2017; Schneider et al., 2017). Authors in (Cavaliere et al., 2018) calibrated their sensors in the laboratory and later they validated their readings on the field. They report better scores than the ones reported already in the literature and emphasize on the robustness of the developed station as a further key point. (Ali et al., 2020) discuss the development of a low-cost sensor node that can be powered by either solar-recharged battery or mains supply and uses public or private LoRaWAN IoT network for long-range communication and short-range high data rate communication over Wi-Fi. Authors compared the readings from this node to an accurate reference sensor and while their readings are relative to the reference's data, they emphasize on the calibration methods to further improve the accuracy. Different approaches for calibration modelling, such as reference-based, semi-blind and blind approaches are presented in (Marinov, 2020) and the associated challenges and directions are discussed. The same study notes that the main aspects for a successful calibration which are:

- costs
- duration
- duration of interruption of the normal operation of the sensors
- easy access to sensors
- ability for in-field calibration of a large number of sensors

The results of almost a one-year field study that is described in (Bauerova et al., 2020) showed that except for the reduced sensors' measurement accuracy, the early detection of defective units and the effect of meteorological conditions (such as air temperature and humidity) and different pollutants' interference is of crucial importance for the success of a similar monitoring system and therefore a comparative measurement prior to each sensor's field applications is advised. Moreover, two other commonly neglected issues regarding the deployment of such systems are reported in (Yi et al., 2018). First, in order to dramatically reduce costs and save time, except for system architecture and data quality issues, other practical issues should be taken into account, such as the frequent recalibration or replacing misfunctioning parts of sensors. Secondly, sensors nodes should be easy to use and easily adaptive and flexible to reconfigurations to modify and further develop their sensing capabilities. Other practical issues include the choice of the location of the sensors so that they can capture the spatial variability of the air pollutants in an optimal way, that can be tackled by developing a site suitability analysis (Fattoruso et al., 2020).

(Bach et al., 2020) propose a layered network where one of the layers is used for data analytics and another one for visualisation. They emphasize that for facilitated and automated decision making, the results from the Machine Learning (ML) and Artificial Intelligence (AI) models should be visualized in an easily explainable way. Authors also conducted a traffic simulation study using the SUMO (Sumilation for Urban Mobility) to present the value of their method (Behrisch et al., 2011).

Vehicle Sensor Networks (VSNs)

Since, in general, vehicles can cover bigger areas than pedestrians the idea of installing sensors on vehicles has widely been proposed as an effective alternative (Haiahem et al., 2016; Morselli et al., 2018; Wong et al., 2009). One of the early studies that used sensor nodes mounted on cars is SensorMap (Völgyesi et al., 2008). Specifically, the device sampled the sensors (measuring ozone, CO, and NO_2 concentrations) every minute (when the car is in motion) or every hour (when the car was stationary) and stored the results tagged with a location and timestamp. Given a sufficient number of nodes and diverse mobility patterns, a detailed picture of the AQ in a large area will be obtained at a low cost. While the advantages of the system are identified it is clear and that this methodology can provide a detailed record regarding AQ and pollutant dispersion within the region, no meteorological information is included and it cannot send the monitoring data back in real time as noted in (Liu et al., 2011). Therefore, authors propose the use of multiple wireless sensors spread outdoors. In (Apte et al., 2017), two Google Street View vehicles were equipped with pollution measurement equipment with promising results for detailed pollution maps. Authors suggest the evaluation of their method in different cases while emphasize that the deployment on public vehicles (buses, taxis, etc.) can have even greater potential and impact. In (Anjomshoaa et al., 2018) it is suggested that although taxis and buses can offer a quite high and frequent sample rate in busy areas of a city, the spatial coverage of a city is not complete. Therefore, the use of trash-trucks is suggested by the authors as an alternative, that although they operate only specific hours, they offer complete spatial coverage. As a following study, the results and highlights of a monitoring experiment using two trash-trucks in Cambridge, Massachusetts, USA are described in (DeSouza et al., 2020). Among the findings is that the spatial coverage of the trash-trucks is not adequate and therefore additional sensors should be installed on a limited number of public vehicles. Additionally, the calibration of the sensors' measurements from nearby fixed sensors is of great importance in order to avoid misestimations of emissions and to treat issues such as self-pollution.

(Tudose et al., 2011) suggested that a sensor embedded onto a vehicle would take readings of the pollutant agents and using the readings of a temperature sensor, measured values are corrected accordingly. Moreover, a GPS module would assign geographical coordinates to the values. The specific system was tested by installing the Mobile Unit prototype on a privately-owned car and driving around a predetermined path in the city of Bucharest, for different times of day, traffic conditions etc.

A vehicular-based mobile approach for measuring fine-grained AQ in real-time was also presented in (Devarakonda et al., 2013) in which two cost effective data collection methods are described i) deployed on public transportation and ii) deployed on a personal sensing device. Authors emphasize on the importance of real time information and how this can be associated with driving patterns, as better driving habits will lead to reduced pollution. These driving patterns can be related both to alternate "healthy" routes based on the pollution information or eco-driving. Other studies have also used the concept of a vehicular wireless sensor network with embedded sensors on cars or buses aiming to monitor CO_2 concentrations in the areas of interest, without reporting different findings or challenges (Al-Ali et al., 2010; Hu et al., 2011, 2009). Another project which included the deployment of sensors on buses is described in (Gao et al., 2016). One of the innovations of the specific study, is its construction which allows a better airflow-disturbance design with a good cost/coverage trade-off. The study also includes a POI-oriented bus selection algorithm to optimize the bus lines and the number of buses that the sensors will be deployed. However, since many issues could appear relating to the communication protocols, attention should also be given to how fast the data are produced and the no limitation on buffer size (Wang and Chen, 2019).

(Lee et al., 2017) describe a system in which a mobile sensor was installed on the roof of a vehicle to measure CO_2 emission. They also report promising results regarding the deployment of a fleet of such sensors to calculate emissions. Authors in (Kolumban-Antal et al., 2020; Kumar et al., 2015) report that the current trend is the use of mobile and micro-scale sensing accurate sensors instead of massive, costly sensing stations. In (Kolumban-Antal et al., 2020, 2019) a low-cost mobile sensor network is utilizing public transport fleet due the large spatial coverage in the city of Timisoara, Romania which, among others, focuses on the secure transmission of data. Finally, in a very recent experiment that took place in Uppsala, Sweden, authors report the importance of route planning to increase coverage while being operational as much time as possible without maintenance (Kaivonen and Ngai, 2020). While the connectivity issues were overcome and accuracy of the CO sensor was satisfying, the same does not apply for the NO_2 sensor, due to its low sensitivity. Then, authors suggest that in the future other factors that may affect sensors measurement should be examined such as the bus moving speed, the wind speed and the effect of the bus cooling system.

Hybrid Systems

As described earlier, it is seen that the different approaches have different opportunities and challenges. Thus, an effective alternative to using a specific type of sensor networks is the use of hybrid system. Such cases can use different combinations of sensor networks (for example, a VSN can be a CSN at the same time) for more effective and broader AQM. For example, in (Ma et al., 2008), a two layer network was proposed where the mobile sub-network would be formed by public vehicles (including buses, service vehicles, taxis and commercial vehicles as the first layer) carrying sensors and information would be fused data from stationary sensors – the second layer of the network.

One of the first projects that such an approach was implemented is the "OpenSense" project, that focuses on the idea of an open community sensing system (Aberer, 2012; Aberer et al., 2010). In the specific project, sensors were deployed around the city of Lausanne, Switzerland on mobile vehicles (buses) and stationary monitoring stations (bus stops) in collaboration with the public transport authority of Lausanne. Additionally, a prototypical participatory AQ monitoring platform using an off-the-shelf smartphone was introduced, which allows anyone to collect AQ data. For the same project, in (Hasenfratz, 2015) it is reported that since the aim was to obtain a high spatial measurement resolution in an urban area, the noise in data from these sensors can be quite challenging. Therefore, algorithms were developed to treat it by exploiting sensor readings near governmental measurement stations to keep sensors updated (Hasenfratz et al., 2012) and maps with a high spatial and temporal resolution were developed to monitor air-pollution. Finally, the author proposes a novel route planning service, which helps urban dwellers to reduce their exposure to airborne pollutants.

Another hybrid system is described in the project "HazeWatch", which aimed to collect spatial measurements of air pollution in Sydney by crowdsourcing and to engage users in managing their pollution exposure via personalized tools (Sivaraman et al., 2013). A prototype low-cost and portable system for users' vehicles to collect air pollution data was designed, together with a smartphone app for data annotation and sharing. The crowdsourced data would be analysed to show personal exposure of the users and propose low pollution travel routes, emphasizing the potential benefits between pollution exposure and health.

The use of a hybrid system was also utilized in (Lo Re et al., 2014). However the system could not provide real-time measurements as the data would be transmitted when the bus would approach specific stations. (Song and Han, 2019) also describe a hybrid system for AQ monitoring using 28 fixed locations stations and 15 vehicles. ML approaches are also proposed for cases where data are not available and significant findings are discussed (i.e. combining fixed and mobile data for training), and grid based $PM_{2.5}$ maps are created for this large urban space. It is stated that while fixed location data can provide good spatial resolution and accurate results, the need for mobile sensors emerges. However, it should be noted that inherent inconsistencies are reported between fixed and mobile sensors and are dealt with by i) either treating them as two different sources or ii) assuming the fixed-location data as correct and changing the mobile data accordingly. In (Yuan et al., 2019) a similar methodology to accurately estimate data in areas that are not monitored is used and is validated using real data from taxis and AQ in Beijing, China. The prediction of AQ in different areas of China is also examined in (Mao et al., 2020) in which data from 65 AQM stations and meteorological data were collected. A deep learning framework is proposed that can predict quite accurate the long time series and can have great potential in making atmospheric management decisions. The combination of ML approaches with VSN is also described in (Le and Tham, 2018), showing that such systems can achieve a similar accuracy to static networks while significantly reducing costs in communication and equipment. In a very recent study the performance of LUR models and ML techniques was compared to predict traffic-related air pollution (Wang et al., 2020). Data were used from sensors installed on rooftops of a moving vehicle, while a dashboard camera and a GPS device would collect data related to the traffic conditions and the position and speed of the vehicle respectively. Promising results to air pollution monitoring and prediction with the use of deep learning techniques are also reported in (Kalajdjieski et al., 2020).

In (Zhang and Woo, 2020), authors propose a system that adopts both fixed and mobile sensors. Specifically, 3 fixed and 3 mobile sensors on top of cars were deployed in Songdo area, South Korea. While authors report promising results in both monitoring and predicting air pollution, the need for more data coming from more sensors is also described, specifically by utilizing taxis or buses for increased coverage.

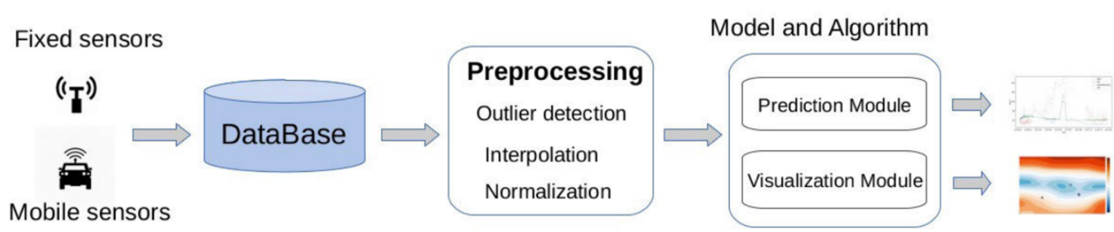


Figure 2: The structure of the system proposed in (Zhang and Woo, 2020)

A very recent project where low-cost sensors were installed in the city of Nantes, France and deployed on different kinds of public vehicles (driving school cars, ambulances and service vehicles) is described in (Gressent et al., 2020). In this project, the methodology that is illustrated in Figure 2 is applied. Results show that considering including the low-cost sensors' observations reduces the bias to 2.5%. However, fusing the data from the two different sources smooths the peaks in the pollution graphs but provides better average estimations of the pollutant levels. Also, the importance to estimate precisely the error of the devices is highlighted and spatial interpolation of the sensors to ensure better performance.

Another recent study from Lisbon, Portugal provides promising results in terms of the measured particles concentrations and emphasizes on the need for additional tests to compare the low-cost VSN to the fixed reference stations (Santana et al., 2020). In the specific study, significant information is provided regarding both the hardware solution (sensors, power supply, shape etc.) and the software solution (system architecture, filtering techniques, server and visualisation). However, apart from the calibration of the sensors, authors identify challenges such as the attachment of the sensor on the vehicle or the vibrations that can cause issue to the measurements.

As a cost-effective and sustainable alternative, sensors that are installed on bicycles have also been proposed (Vagnoli et al., 2014). The specific system is composed of three main parts i) an opensource Arduino-based mobile platform equipped with sensors for AQM, ii) an urban GeoDatabase and iii) a Web application for visualization of data. Another similar system was UbiAir, a mobile crowdsensing system, that utilized the mobility of sharing bikes attached with customized IoT sensing devices to monitor large areas with high spatial resolution (Wu et al., 2020). Cyclists had the role of the "crowd workers", while with advanced models and calibration methods the recovery accuracy was improved. While different challenges arise, such as error calibration, coverage etc., UbiAir is described by the authors as "a low-cost, accurate and scalable system, presenting promising performance and usability on combining mobile crowdsensing".

Bicycle-based sensors were also utilized in (Elen et al., 2013; Samad et al., 2018; Samad and Vogt, 2021; Velasco et al., 2016) and in (Hankey and Marshall, 2015) together with Land Use Regression (LUR) models. While the bicycle sensors can provide good accuracy in terms of data quality and spatial coverage, authors report that their models do not perform well when there is not traffic congestion, meteorological conditions, measurement location, etc. Therefore, it is suggested that for specific combinations of pollutant, time-of-day and urban areas, VSNs and CSNs may offer some significant benefits over fixed-site monitoring solutions and further work is required for the effective use of LUR models. Similar findings are reported in (Shi et al., 2016), in which authors developed LUR models using data from sensors on a specific vehicle covering a large area of downtown Hong Kong. While the advantages of mobile sensors combined with LUR are also, identified authors suggest that specific attention should be given to data aggregation. In addition, when it comes to the transferability of such methods to different study areas, adjustments might be necessary in both the experimental design and the data processing methods. In (Penza et al., 2017) a hybrid network is described, including 10 stationary on public buildings like offices, schools, airport, port etc. and 1 sensor mounted on a bus. The system was deployed in Bari, Italy and researchers aimed to raise citizens' environmental awareness and to demonstrate the competitive advantages of cost-effective sensors at high spatial and temporal resolution compared to the existing outdated and expensive SSN.

The community-based project CamMobSens was a hybrid system that included sensors mounted on pedestrians' mobile phones and cyclists to monitor pollution ("Cambridge Mobile Urban Sensing (CamMobSens)," 2008). The researchers from Cambridge University connected these sensors with the phones via Bluetooth and the information collected would be sent to an open server as soon as it was gathered. The project aimed to develop and demonstrate the capabilities of low-cost sensors to provide data for planning, management and control of the transportation sector's effect.

The aims of the recent project MONICA (an acronym for cooperative air quality monitoring) are really close to the aims of CAROLINA project. Specifically, in (Vito et al., 2020) authors describe a hybrid system that uses mobile devices to measure AQ, that can be easily attached to bicycles or backpacks. The device allows citizens to monitor their personal exposure to pollutants and by sharing their data, high-resolution spatiotemporal air-quality maps can be created, after analysis using geostatistical and AI technologies.

Authors emphasize on the significance of calibrating these sensors with the existing static sensors in the city of Portici, Naples, Italy. The advantages of a hybrid systems are also discussed in (Bardoutsos et al., 2020) where a hybrid, holistic system is proposed to collect, monitor and analyze air pollutants and noise indicators. They emphasize on the contribution of the human factor to increase coverage, by using engagement and crowdsourcing methods. Among others, some of the means they refer to are social media analytics or citizen questionnaires

Lately, Unmanned Aerial Vehicles (UAVs or simply "drones") have found applications in many areas (agriculture, search and rescue missions, infrastructure inspection), especially with the latest advances in their technology and the related sensor technologies (Barmpounakis et al., 2016). Drones have also drawn the attention in the AQM related research (Hodgkinson et al., 2014). The idea of using UAVs to collect more spatially sparse data is also reported in (Morawska et al., 2018), noting their advantage against other methods to collect data in different altitudes. The lack of 3-dimensional data and the opportunities that rise with the use of UAVs are also reported in (Xiaojun et al., 2020; Yi et al., 2015). However, results from studies that deployed sensors on UAVs suggest that further improvements should be imposed to these kind of sensors for the efficient and accurate collection of data (Alvarado et al., 2015; Koval and Irigoyen, 2016). The spatiotemporal distributions of air pollutants next to an urban road in Shanghai were studied in (Zheng et al., 2020). (Long et al., 2020), although they do not refer to urban environments but open-pit coal mines, describe another good case study where drones are the main part of an AQMS providing very detailed results. Another possible direction is to use drones as an eye-in-the-sky solution and the estimation of the traffic conditions using machine vision techniques (Barmpounakis and Geroliminis, 2020). Drones can provide a great level of detail when it comes to vehicle trajectories and by using the appropriate microscopic models, data fusion techniques and advanced statistical measures, the emissions of the vehicles can be accurately estimated for large urban road network, while the quantified relation between macroscopic traffic measures and emissions can provide significant insight for policy makers regarding the traffic restrictions of congested urban areas (Montesinos et al., 2021). The above is further discussed in the deliverable of activities A2004 of CAROLINA project.

3.2. Open and Community Approaches: How citizens are motivated

From the results from the abovementioned studies, it is already established that air pollution can be monitored quite accurately given that all good practices are followed. Hence, the gathered data sometimes may have a low spatial resolution and cannot be used to assess the spatial variability of pollutants in detail while the cost is not negligible (Hasenfratz, 2015; Zheng et al., 2016). The idea of an open community sensing system for AQM has been proposed in different projects. The main characteristics of an open community sensing system is the bidirectional relationship between the those who collect and those who utilize the data. Specifically, the data collectors need to have an incentive for contributing in sensing which could either be the feedback of how the produced data are used or monetary and other incentives. Additionally, privacy, energy efficiency and low costs are also in the basic requirements for a continuous and sustainable data collection process. When these are guaranteed, the data utilizers can increase the incoming data in terms of quantity and quality, while also increasing the spatial and temporal coverage.

Except for the data quality related issues, communities have been demanding a greater role in decision-making that affects their lives (Clements et al., 2017). Citizens realize more and more that air pollution not only impacts their communities, where they live, work or entertain, but also threatens their health, thus they are searching of ways to document these exposures and environmental health dangers. Apart from that, education and involvement of citizens builds awareness about the sources of air pollution, exposure pathways, and the association between contaminants and health endpoints.

A project that emphasizes on the citizens' role was SmartSantander (Sanchez et al., 2014, 2013, 2011). Although SmartSantander is not directly connected to solely AQM it aims in bringing citizens and the technology together, with cities being the meeting point. This provides an additional aspect that can be utilised for various crowd-sourced scenarios. Authors use the term of "societal innovation" to describe how citizens "can be immersed in a context which stimulates the conception of new ideas and quickly engages them with solutions addressing the problems related to their ecosystem".

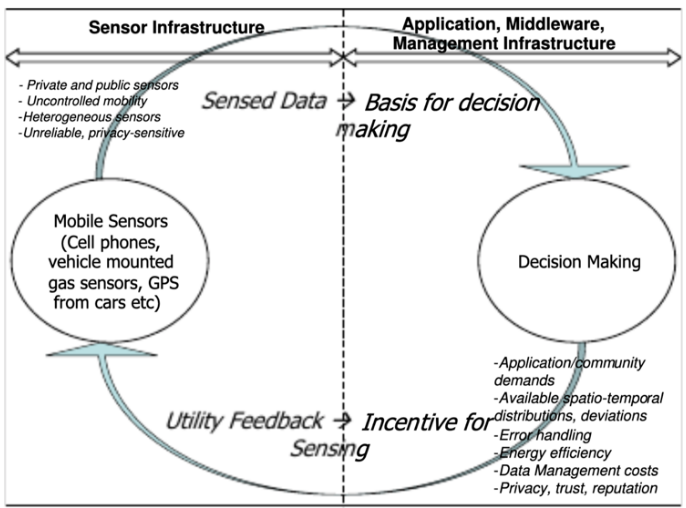


Figure 3: The cycle of production and consumption of community sensing data according to OpenSense (Aberer et al., 2010)

One of the projects that based its sustainability and success on an open community sensing system is the previously mentioned project "OpenSense" (Aberer, 2012; Aberer et al., 2010). One of main conclusions is the bidirectional connection between consumers (applications or communities) and producers of the sensing data.

However, as reported in (Thompson, 2016) although many independent projects have attempted to "crowd-sense" environmental data, the technology for low-cost sensors is not sensitive or reliable enough to meet market demands. Therefore, in order to be an effective tool of data collection, specific advances in analytical chemistry and collaboration withing multiple disciplines are required for crowd-sensing to be an effective tool. Collaboration between multiple disciplines is also a requirement for success.

Similar concerns are raised in (Clements et al., 2017). For example, one of the most important requirements for long-term deployment is treating sensor failures and their replacement. Especially when it comes to new low-cost sensors, evaluation efforts have noted significant variation in their operability, such as pre-mature failures and indications of short sensor lifetimes with declining performance within the first year of use. Some other important issues to consider include data standardization, AQ data platform etc.

In (Camprodon et al., 2019), authors report that the use of low cost sensors has been approached mainly by either educational activities, engaging activities and raising awareness for citizens or by a more sophisticated and scientific way to examine their potential in an AQM system. Thus, they propose a system that can fulfil both goals, by providing a complete tool that can i) act as a solution of citizen engagement and awareness, ii) promote open-source solutions for scientific development and iii) provide an all-in-one, open-source and low-cost educational tool. The potential of "open data" sources that could be applied to generate a large volume of data is also highlighted in (Lim et al., 2019). Then, with the appropriate models, maps with fine spatial granularity and the power of ML and artificial intelligence, the AQM could be significantly improved. The potential of ML methods to improve data quality is also reported in (Loglisci et al., 2020) as when data is collected by non-expert practitioners data can become unusable or even lead to wrong conclusions. In (Kristiani et al., 2020), an updated deep learning model is developed to monitor and analyse the changing AQ data in terms of time and space as soon as they become available, while the reports are visualized on interactive maps. (Xie et al., 2020) also report that technical improvements such as improved Bluetooth connectivity, increased portability and more efficient data transfer would simplify the engagement of a broader audience.

In (Cicutto et al., 2020) an open system is described, in which community residents would use wearable PM2.5 sensors to monitor their indoor and ambient air to understand personal exposures. One of the significant findings is that the users' confidence in using these wearables was improved over time with the support of coaching that occurred during home visits. It is also reported that self-monitoring of AQ allows individuals to identify exposures of their concern and develop personalized action plans. Of course, when the sensors do not require any specialized knowledge to be deployed and operated, citizens are also more easily encouraged to participate in such a system (Paulos et al., 2008). The "HazeWatch" project, that was also referred in the previous section, utilizes crowdsourcing techniques to engage users in managing their pollution exposure via personalized tools (Sivaraman et al., 2013). The main tools of the system are a prototype low-cost portable to data and a smartphone application for data annotation and information sharing.

In (Castell et al., 2015) it is reported that all the positive features related to open and collaborative approaches may lead to the effective use of low-cost sensors in different environmental and human health fields. Especially when sensors are used in crowd sensing, citizens can take it into account when taking decisions to improve their quality of life. For example, (Nyarku et al., 2018) report that citizens can greatly benefit by knowing their proximity to vehicle emissions, either for social purposes (e.g. street cafes) or exercising (e.g. walking or jogging along busy roads) or indoor environments affected by combustion emissions (smoking, candle burning, open fire). Moreover, the involvement of citizens in the information and decision policies regarding the air they breathe, not only rises public awareness but also encourages them to develop sustainably toward different directions (Hasenfratz, 2015).

However, there are also significant challenges in order to get the general public in participating in AQM. For example, the crucial parameter of user privacy is discussed in (Kolumban-Antal et al., 2020) as such solutions may require high-priced cryptographic processes. There have been examples however that data collectors stated they would use a personal air pollution sensor, if they were small and light, while they were generally not concerned about privacy or sharing their GPS location especially if the data collected would be used for educational actions or actionable alert, with only two stating they would not share their GPS location under any circumstances (Xie et al., 2020). In addition, the challenges of involving from communities in environmental health research are discussed in (Rickenbacker et al., 2019). It is suggested that the first step for researchers should be understanding the citizens' perception before setting any goals. Additionally, community-based research can not only build trust but can also contribute in transforming culturally sensitive issues at a community-level. Authors also suggest that bottom-up principles should be followed, and local residents should be involved in trainings and workshops to promote environmental justice issues.

(Hasenfratz, 2015) reports that "obtaining and retaining the critical mass of participants to get a coherent picture of the exposure situation in an area of interest is a formidable challenge and may require hundreds to thousands of contributors." Since collaboration between citizens and scientists is crucial for the success of a crowdsourced system, it is vital that all parties understand both the advantages and limitations of low-cost sensing (Clements et al., 2017). Additionally, while citizens who participate in such processes can educate themselves about scientific methods and potential links between AQ and their health, they should also be prepared for different research outcomes, such as negative or no results at all (Clements et al., 2017). Moreover, authors report that in the case of real-time data, the distinction between short-term high exposures versus daily or weekly averages in pollutant levels should be clearly communicated for better decision making. The participation of citizens in the decision making process regarding the environmental issues and the inclusion of their perception of the AQ is discussed in (Grossberndt et al., 2020). They argue that by giving citizens the opportunity to express their views and concerns, urban planning will certainly benefit by better understanding socio-cultural dimensions. In the same work, they compare the citizens' AQ perceptions compared to AQ measurements in the greater Oslo area, showing that the perception data have the potential to indicate local AQ.

As reported in (Bonney et al., 2009; Dickinson et al., 2012) science education and participatory democracy should be among the major outcomes projects that include and promote citizen participation. (Gulia et al., 2015) reports that public participation should include active response from citizens and stakeholders. Different techniques for effective dissemination of AQ information to the public include mobile applications, street panels, mass media, websites, publications or newsletters. As (Kumar et al., 2015) reports AQ information can allow the general public, especially those at risk, to make better decisions regarding their health by avoiding highly polluted areas. Such a service is already operating in London, and although it is not related to a sensor-based programme, similar services are suggested to operate in highly polluted cities (Kumar et al., 2013; Molina et al., 2004; Peng et al., 2014). In a recent study, the potential of higher education institutions as learning campuses of a smart city was examined and the results showed that students can be trained to become more sustainable and care about the impact of urban mobility in AQ by becoming part of a smart and learning environment (Mazutti et al., 2020).

As reported in (Hasenfratz et al., 2012) the low-cost sensors deployed should be designed for mobile measurements, using unobstructive and user-friendly methods while high-quality data are being collected. Also, data collectors welcome feedback on the collected information as reward or incentives, thus an effective gamification design could massively contribute in user-engagement.

Gamification, or else the use of game-like concepts to non-game environments, is seen as the third pillar of process innovation, along with big data analytics and crowdsourcing to gather data and solve problems, which reflect the essence of a smart/connected city. The usefulness of gamification is established on the concept that all traffic and transportation activities may be seen as a game, where the user is to execute a series of actions and make a series of decisions in order to reach a certain goal (Montola, 2005; Vlahogianni and Barmpounakis, 2017).

Such a framework is described in (Mahajan et al., 2020) where the use of interactive air quality quizzes, offline questionnaires and low-cost air quality monitoring sensors are integrated. Results showed that such methods can contribute greatly in understanding people's perception about AQ but also to provide significant insights regarding their exposure levels. In the same work, the way community engagement in AQM can be a significant initiator for collaboration between different aspect of a community and researchers. A similar framework, based on gamification, is also discussed in (Bosello et al., 2020) where the use of bicycles and a Web application, enriched with gamification elements, that communicates with a portable low-cost sensor are the basic elements of a crowdsensing system. The user interface and the gamification mechanisms have been designed with the aim of meeting users' preferences and needs, and, thus engaging better in the data collection process. Another project nicknamed SensorWebBike was developed on similar concepts in order to "augment" urban social interactions to increase citizens' awareness (Vagnoli et al., 2014), involving the local Police of Siracusa as a first step towards.

(Wang and Chen, 2017) suggest giving a higher reward to encourage drivers to collect data on locations where pollutant concentration changes drastically, while lower the reward when cars report sensing data with little variation. Special cases should be treated like when many drivers are collecting data from the same area in order to increase the reward, as this may increase traffic congestion in that area. The potential of this system should be examined by real experiments to estimate the effect of the rewarding policies. Although a strong gamified framework is not described in (Rickenbacker et al., 2020), each household that participated in seasonal monitoring periods received two debit cards (to total $80.00).

Authors in (Tao and Hafid, 2020) propose a framework that utilizes a deep reinforcement learning (DRL) method to optimally assign sensing tasks to crowdsourcing users for large-scale sensing. As they report in their study, the whole framework described includes six stages: i) registration of sensing tasks, ii) announcement of reward rule, iii) collection of users' information, iv) task allocation, v) execution of sensing activities and vi) distribution of data and rewards. Hence, the DRL aims to maximize the platform's profit by allocating the correct sensing tasks to the mobile users.

4. Istanbul: an early adapter city

Introduction

Since the 1980s the air pollution problem in Istanbul has received global attention and the problem has been intensified from the late 1980s and beginning of 1990s as reported in the study of (Incecik and Im, 2012). Istanbul is a megacity with more than 15 million inhabitants and has an area of 5343 km^2 covering 39 districts. Istanbul is one of the most important cities in Turkey that straddles Europe and Asia across the Bosphorus Strait, that connects the sea of Marmara to the Black Sea. The city is a centre of industry, economics, finance and culture with its Old City reflecting cultural influences of the many empires that once ruled here. Many historical areas of the city have recently been added to the list of UNESCO World Heritage. In the European part, the city is built on seven hills and is surrounded by historical city walls.

As reported in (Incecik and Im, 2012) the main emission sources in Istanbul are traffic, industrial processes, domestic heating, road dust and biogenic emissions. The rapid urbanization and development of the society and economy after the 1970s is among the causes of the increase in pollution. Traffic was the secondary source in the 1980s showing increasing trends even after the 2010s. As the study of (Incecik and Im, 2012) is quite detailed in terms of describing the situation of AQ in Istanbul, in this deliverable we will mostly focus on the aspects directly related to the CAROLINA project.

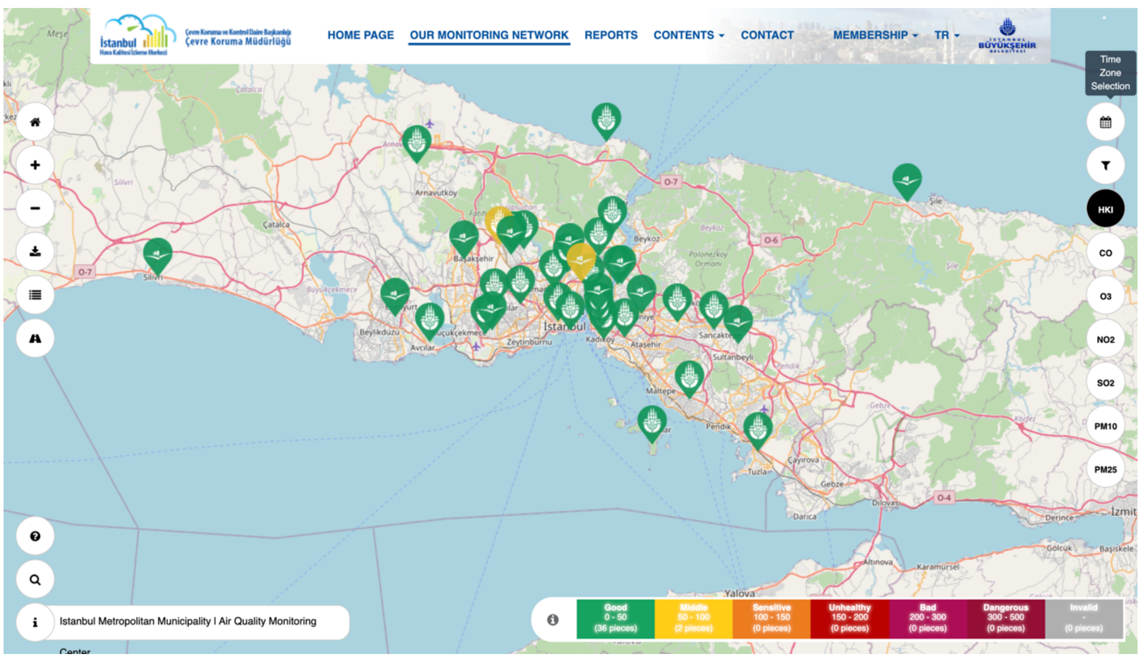


Figure 4: A map of Istanbul with air quality measurement stations (https://havakalitesi.ibb.gov.tr/Pages/AirQuality)

Although Istanbul has a dense AQ network (Figure 4) not all particulate matters and pollutants are measured everywhere (Table 2). The monitoring network that has been developed and can be visualized in https://havakalitesi.ibb.gov.tr/Pages/AirQuality describe the AQ in Istanbul in 6 different categories, i) Good, ii) Medium, iii) Sensitive, iv) Unhealthy, v) Poor and vi) Dangerous, as can be seen in Figure 5, while other visualizations can include i) the land use, ii) population density and iii) traffic conditions etc.

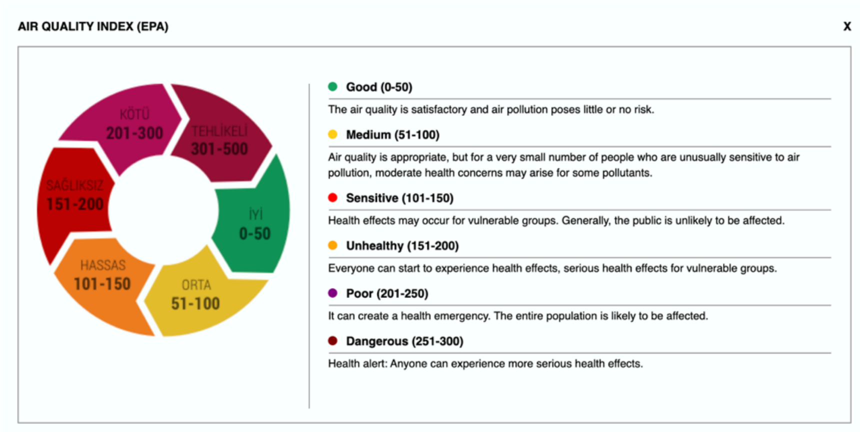
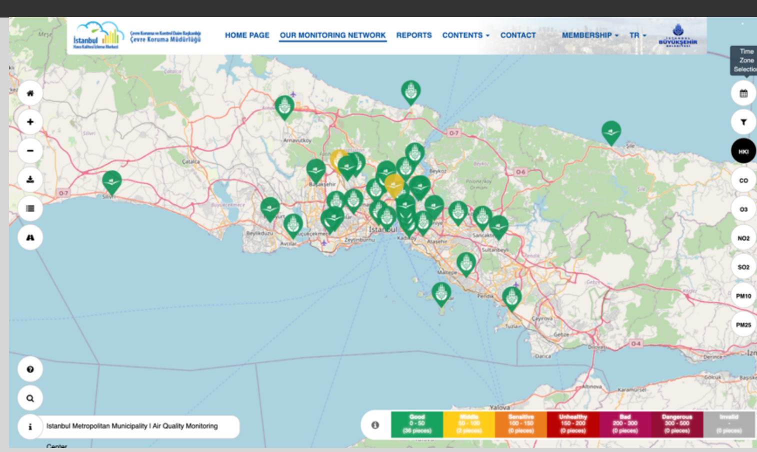
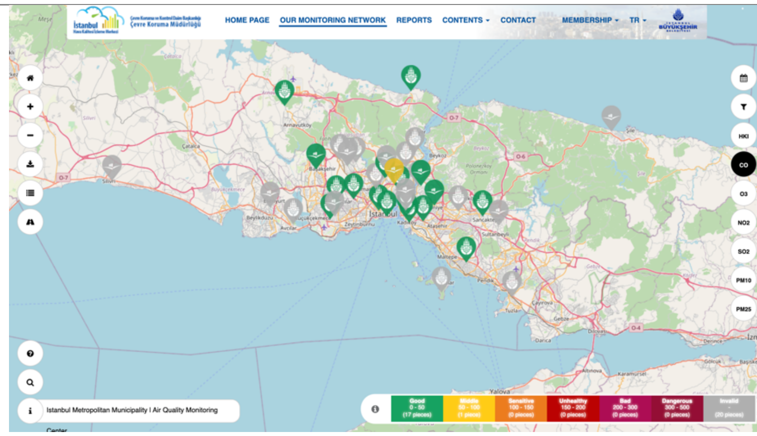
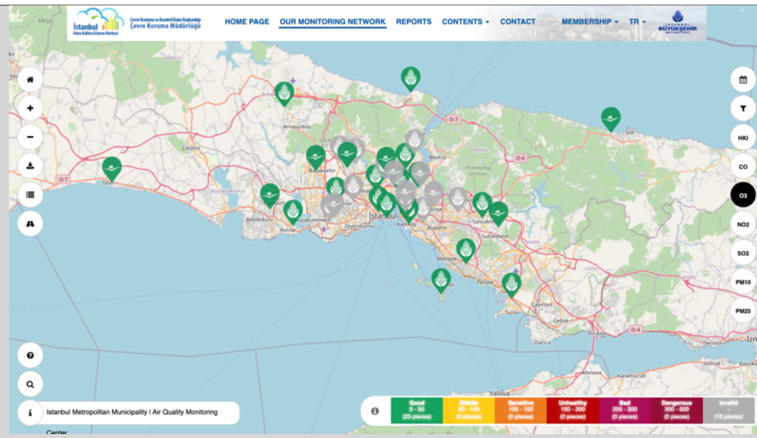
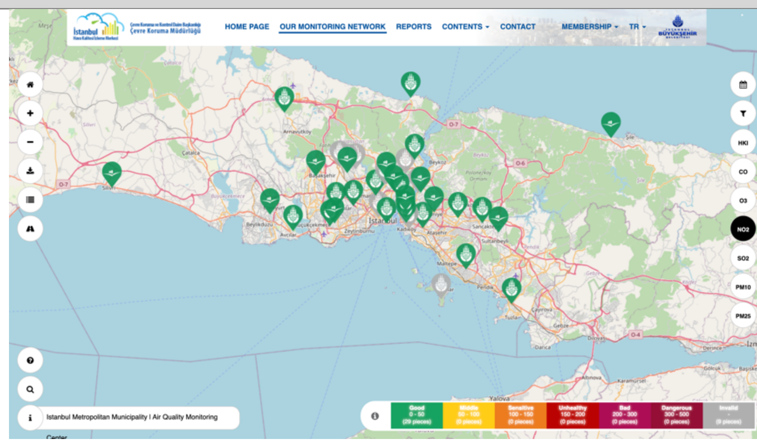


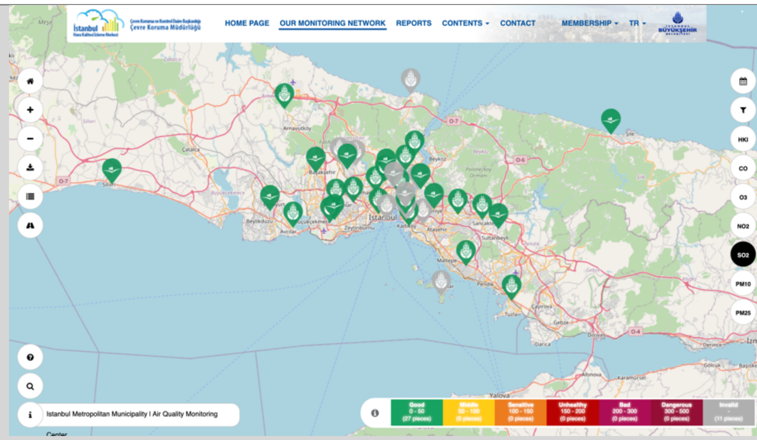
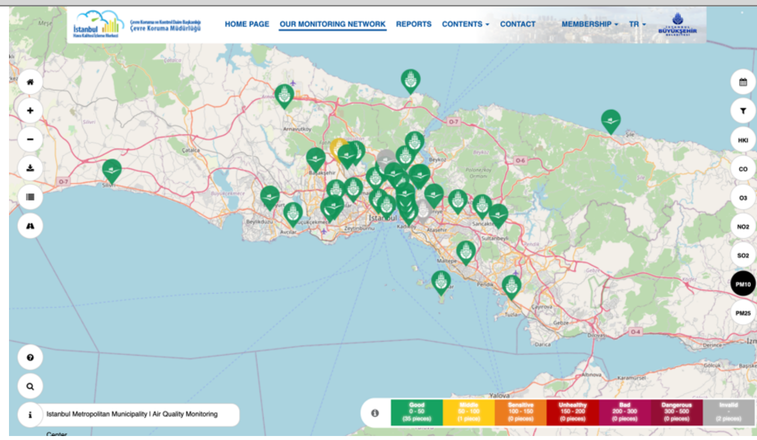
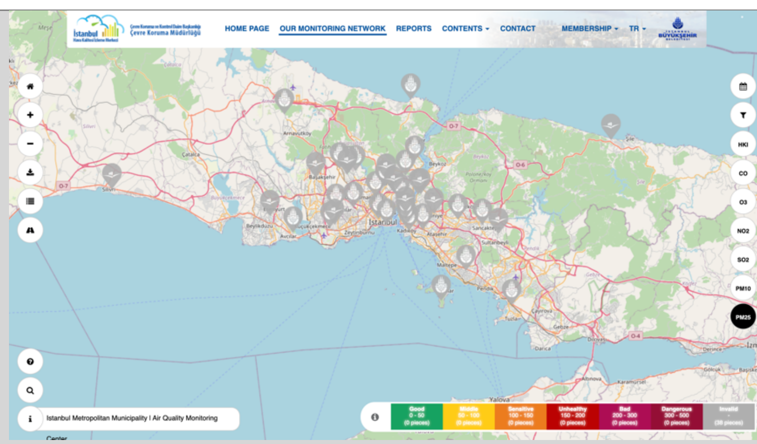
Figure 5: The 6 different categories of AQ in Istanbul (https://havakalitesi.ibb.gov.tr/Pages/AirQuality)

Thus, in order to understand the factors that affect the AQ in a city of such a size and provide solutions high spatial and temporal resolution is necessary. Studies that have been conducted related to the AQ of Istanbul emphasize on the hourly or seasonal variations in the measurements due to both natural processes such as weather conditions or the Sahara dust transport and human activities, such as traffic or domestic heating (Celebi et al., 2010; U. Im et al., 2011; Ulas Im et al., 2011; Koçak et al., 2011; Theodosi et al., 2010). The necessity of increasing the spatial and temporal resolution is discussed in all these studies, however due to technical limitations when they were conducted it has been seen that the situation has not changed drastically since then.

Table 2: SSN measurement availability in Istanbul (https://havakalitesi.ibb.gov.tr/Pages/AirQuality)

Pollutants	Number of Sensors	Figure
ALL	38	

CO	18	
O3	23	
NO2	29	

SO2	27	
PM10	36	
PM25	0	

Current projects and challenges

TaxiCap project

One of the projects carried out to contribute to Istanbul's Smart City journey, which is led by Istanbul Metropolitan Municipality (IMM) was implementing a dynamical air quality measuring and monitoring system into the taxi caps in Istanbul. With the TaxiCap project, the taxi caps were planned to have a modern and functional design and equipped with an embedded board connected with various sensors. Due to facing various challenges, the project is still in the prototype phase and has not been implemented around the city of Istanbul. There are no official reports or websites referncing to this specific project, thus the description is based on our discussions and interviews with the members of the IMM.

A prototype static station (prototype device) was mounted near the IBB Aksaray AQM Station in order to compare outcomes between the official station's (fixed station) readings and readings of ISBAK's AQ Sensor. The other prototype (vehicle application) was mounted on a mobile EDS (Electronic Detection System) vehicle to collect data from the environment in real-time around the city of Istanbul. The measured parameters from the ISBAK's AQ Sensor are, NO_2, SO_2, O_3, CO, PM 2.5, PM 10.

As a result of the comparison between ISBAK's AQ Sensor (static application) and İBB Aksaray Air Quality Measuring Station data, PM10, NO_2, Temperature, and Humidity values are close to each other. Besides, PM2.5 and Sound Noise Level data, which are not provided by the station are within the expected values. On the other hand, there are high differences between the station and ISBAK's AQ Sensor (static application) in CO, SO_2, and O_3 gas values. By evaluating Istabul's AQ measurements, it is concluded that the NO_2 and PM values are the main pollutants of the city. In this context; it has been concluded that NO_2 and PM measurements from ISBAK's AQ Sensor are reliable compared to the fixed station.

On the other hand, regarding the vehicle application of ISBAK's AQ Sensor some additional issues were noticed due to the differences between the application techniques; static and vehicle. Since the ISBAK's AQ Sensor (vehicle application) mounted to the mobile EDS vehicle works connected to the ignition; it only measures air quality while the ignition remain engaged. Once the unit power supplied, the obtained measured data is out of range and then it takes a while for the data to reach realistic values. For this reason, significant differences have been observed between static and vehicle prototype data. This process revealed the demand for solving the energy problem of the device. In order to eliminate this problem, a battery has been integrated into the vehicle prototype. The battery supplies the prototype and enables it to measure air quality constantly. With the help of the constant energy supply, peak measurements have been avoided. ISBAK's AQ Sensor takes air samples at a certain period of times using the integrated air pump. The functionality of air pump requires at least five minutes between each run which causes a decrease in the resolution of the collected data. To overcome such a problem the air pumps were cancelled and replaced with the use of the ventilation holes. After getting rid of the restictions caused by the pumps, the collected measured data's resolution were increased in order to capture a better picture of the air quality while the vehicle is on move. As a result of this modification, the sensors became more sensitive to the pressure, airflow, and movements.

In this project, it is observed that the pollutants measured via gas sensors increase the complexity of the system and requires additional electrical and mechanical works. The sensors measure the pollutant in the air by performing a small chemical process. This chemical process takes a minimum of 35-40 seconds. The pollutants in the air must also be constant and not variable. The system inside the ISBAK's AQ Sensor takes air into the circuit boards and the sensors, which are located inside an IP65 box, via an air pump to provide a sample from the outside air to the sensors. For each air sample sucked by the pump, approximately one minute is needed for the sensors to complete the measurement process.

The main concern is to create a filtering mechanism in order to prevent from unwanted items such as dust, water, etc. Although filtering can be applied in various ways, it is important that the filtering should not change the pollutant to be measured, especially when measuring particulate matter. Regarding the vehicle application of ISBAK's AQ Sensor, because of direct sunlight exposure it is very difficult to provide convenient conditions for the working environment of the gas sensors, yielding to decreasing lifespan of the sensors.

In addition, it has been foreseen that the device mounted on the vehicle exposed to vibration and high strikes due to deformations or holes on the roads will have some negative impacts on the lifespan and calibration of the sensors. It has not been foreseen yet what kind of situations and issues the system will cause in various regions and various weather conditions in long term. Long-term tests and observations are required to be made in order to measure pollutant in an environment which is dynamic and directly exposed by external influences. Other challenges that were reported are related to higher than expected cost and low quality of the data collected.

Istanbul and Bicycle

Istanbul is establishing "Bicycle Home" aimed to train the citizens on riding a bicycle while the works have been completed on including Istanbul into the "Eurovelo Route". The engagement and education of the citizens to urban mobility is among the basic aims of these works.

ISTANBUL ALIGNED BICYCLE ROADS

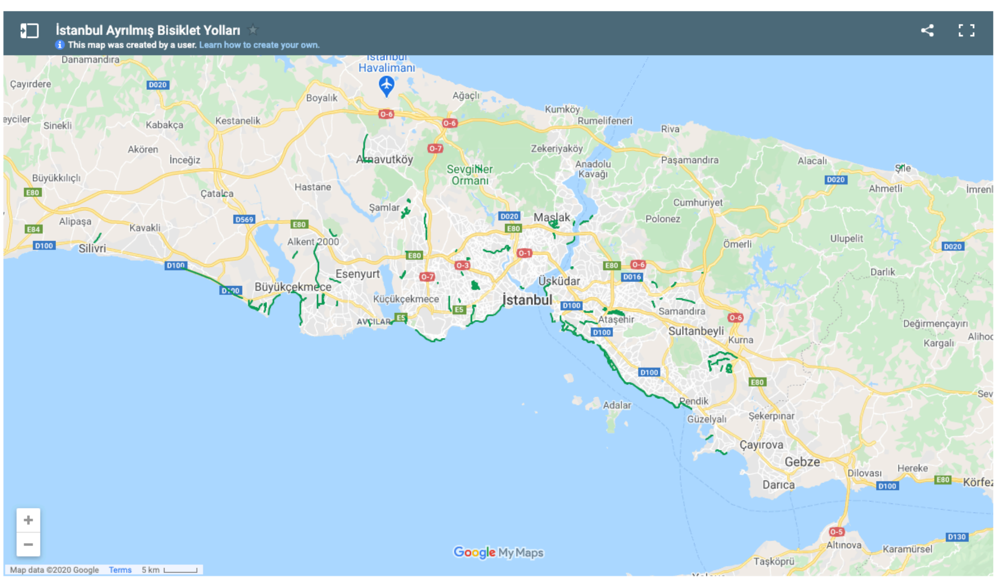


Figure 6: Istanbul aligned bicycle roads (https://bisiklet.ibb.istanbul/)

Although more information is not yet openly available for the specific works, the department of transportation of the IMM has lately updated released a website regarding the use of bicycles in Istanbul (https://bisiklet.ibb.istanbul/). Their vision is "making the bicycle network a visible component of the urban transportation system in line with the goal of sustainable transportation in Istanbul". Also their scope includes the integration of a the public transport system with an established continuous bicycle system Figure 6).

The economic, environmental, social and health benefits of cycling in order to raise awareness about cycling. Especially when it comes the environmental benefits, bikes are emphasized as viable solution for not causing air pollution and not consuming fossil fuels. As they state, each car generates 26.5 tons of waste while bikes on the other hand require much less maintenance, repair and infrastructure than cars. European CO of a bicycle according to the study conducted by the Federation of cycling the second swing amount of 210 gr. In addition, they report that cycling provides more opportunities for interpersonal interaction, since pedestrians and cyclists move at a certain speed, social interaction and perception of the environment is higher than other types of transportation. In the same website one can find information and maps regarding the different bicycle roads in Istanbul.

Additionaly, in 07.02.2020 in order to organize and develop the bicycle road network in Istanbul, the problems and suggestions related to the integrated bicycle path network and infrastructure with the urban public transportation system were discussed in the workshop organized by the Transportation Planning Directorate of the Istanbul Metropolitan Municipality Department of Transportation. Other topics included the "Istanbul Bicycle Master Plan" and "Bicycle Paths Design Guide". District municipalities, non-governmental organizations, media organs, companies, non-provincial municipalities, relevant directorates from Istanbul Metropolitan Municipality, trade associations, academicians and bicycle users participated and they were given the right to speak under the 11 topics determined within the program, and the opinions of the participants regarding the problems and solution proposals collected under 7 topics were taken. The bike roadmap has been determined with the demands collected at the end of the workshop, the identified problems and solution suggestions, and our work continues.

In the opening speech of the Head of Transportation Department Utku Cihan, which included the vision, goals and strategies regarding the development of bicycle transportation in Istanbul, it was stated that pedestrian, bicycle and public transportation will be supported in the future projects, and the continuity of the existing projects will be evaluated in line with this goal. He mentioned that a supervisory mechanism will be established.

Suggestions and Further Steps

Topics on type of the low-cost sensor system deployment

One of the main findings from the literature review that is aligned with the experience from the IMM's project suggests is that further examination regarding the installation of sensors on vehicles should be conducted. Especially when it comes to newly developed sensors, the position of the sensor is related to the type of vehicle among other factors. Specifically, it was seen that the position of the sensors in the caps of the taxis, although it could solve many issues related to energy efficiency, was not accurate enough for all the particulate matters. Thus, more experimental tests should take place in order to define the optimal position of the sensor per type of vehicle to collect accurate measurements while not being affected by self-pollution, air flow, weather condition, dust etc. It should be emphasized that since sensors can be installed in different types of vehicles (typical vehicles, taxis, buses and trams as discussed in the next paragraphs) it should be ensured that the type of sensor should also be examined that is optimal for the different types of vehicles. Additionally, as road surface anomalies can lead to problematic measurements and calibration of the sensors, the environment of the vehicle should be examined and taken into account.

In addition, one of the good practices that was followed according to the literature is the calibration of the sensors by using data from the static sensors that are already deployed in the city. The evaluation of the accuracy of the low-cost sensor compared to the static sensors was successful and showcased the potential of such a method. However, this practice could be enhanced by using more than one static sensor as different topological and traffic characteristic could affect the measurements of the sensors. Therefore, future approaches should include the calibration of the low-cost sensors spatially and temporally distributed to ensure that the sensor collects accurate data throughout the day and for different locations and is thus not affected by externalities. As also discussed in the DEL05 of CAROLINA, the calibration of the sensors by utilizing novel technologies such as drones should not be abandoned, as different technologies can cover different technological gaps and thus massively improve the quality of the collected data.

Figure 7: Istanbul Tramway network

Moreover, the experience from previous project should not be neglected as significant lessons can be learnt. For example, a project that is considered as successful and can contribute with good practises is OpenSense. Specifically, in this project the bus stops were equipped with sensors that would be then used to calibrate the VSNs. As can be seen in Figure 7, Istanbul has a wide network of tram transit system. As parts of the tramway are close (or even similar) to the roads that other vehicles use and to pedestrian areas, the installation of sensors on the rail vehicle could be considered. The energy efficiency of both the vehicle and the infrastructure can solve many issues related to connectivity and privacy, as existing networks can be used. Additionally, due to the proximity of the stops to both pedestrians and vehicles, they can be used as hotspots for calibration, data transmission and/or communication for a system of CSNs. Moreover, by using vehicles that do not move directly to the same road network as typical vehicles, but on rails that are in general in better condition and more effective maintenance, the sensors' measurements will be less affected by bumps and vibrations. Even if some vibration still exists on railway systems, it is more easily trackable and thus such noise can be massively reduced.

Together with the metrobus bus rapid transit system (Figure 8), Istanbul has a very dense Bus Route Network (Figure 9) that covers more than 6100 kilometres and more than 4000 buses (Gerçek and Demir, 2008). Therefore, it clearly seen that the existing fleet can be a significant size in terms of spatial and temporal coverage. As discussed in the next section, citizens' vehicles should also be part of the AQMS in order to cover parts of the city that are not well monitored from the abovementioned types.

It should be noted that while bicycles can contribute both as a viable sustainable solution for everyday commuting and increase spatial coverage if they become part of a potential system, there are significant caveats that should be taken into account before integrating them in the data collection system. The technical requirements for a sensor to be installed on a bike are significantly different than the requirements for a conventional or rail vehicle and thus a different strategy should be followed.

By implementing the above, some crucial steps towards a system with great spatial and temporal coverage can be established. At the same time, the quality of the data collected by the sensors is continuously calibrated and tested for increased consistency and quality assurance. As it was discussed previously, it is vital not only to deploy the sensors in a large area but to introduce a system regarding their technical operability and calibration through preventing inaccuracies and defects that make the results unreliable, unusable or misleading.

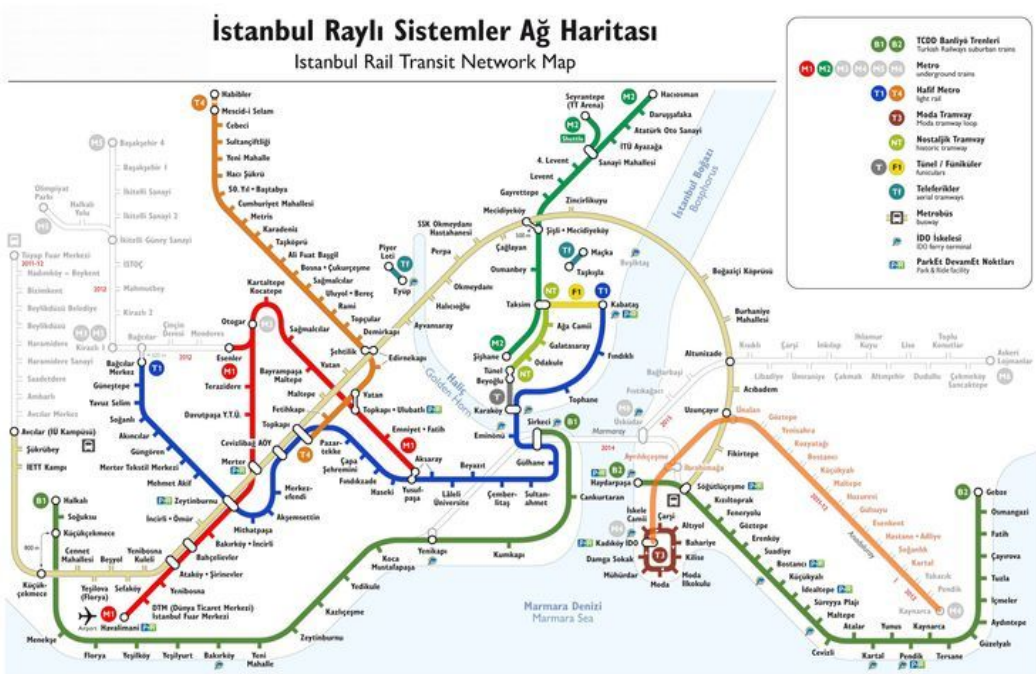


Figure 8: Istanbul Metro and Metrobus Bus Rapid Transit System network

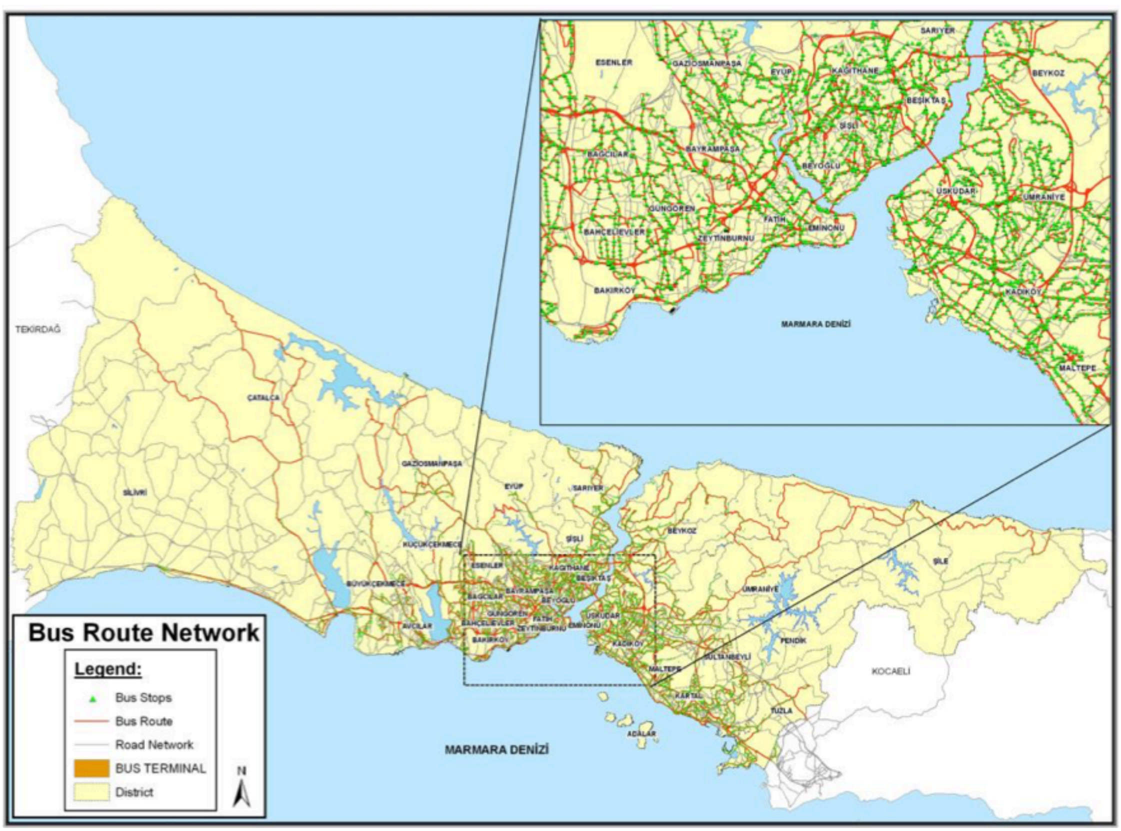


Figure 9: Istanbul Bus Route Network

Topics on open collaborative data collection and citizens' motivation

One of the issues that is not clear in the Istanbul projects that have taken place so far is the way in which the findings from the data collection were communicated to the citizens. As it was discussed in the previous sections, citizens need to feel and actually be part of a system that is directly related to their health and quality of life. It is clear therefore that any future attempt should establish communication channels that will distribute information about the AQ in different areas of city and at the same time educate and motivate citizens to follow the principles of sustainability.

As smartphone ownership is growing rapidly around the globe and the similar trend is appearing in Istanbul, they can be a game-changer in delivering AQ information to their users. For example, instead of using a browser to search for something that a user is interested in, specific smartphone applications can prominently display all of the info one needs based on his/her interests and behaviour. Similar apps have been proved to be successful in contributing to behavioural change techniques, such as the increase of physical activity (Middelweerd et al., 2014; Schoeppe et al., 2017). Personalized statistics regarding the user's ecological footprint or mobility patterns can be a first basic step. Thus, the development of a smartphone application which uses gamification elements to increase the users' participation and engagement is suggested to be developed. The design of this app could also be integrated to the platform that is discussed in DEL04 of CAROLINA. For example, the user will be able to see predictions of AQ in the area of interest and to get significant insights regarding their exposure levels.

At the same time, it can be the communication platform between the data collector (citizen) and the proper authority, corporation or institution. Through this secure and direct communication channel, technical support will be provided in case it is required while the user will also be able to ask questions and express his/her views and concerns for a more effective integration in the decision-making process. The support of an official recognized institution can also tackle any privacy concerns that the users might have.

Additionally, in the case of installing sensors on private vehicles or taxis to act as data collectors, it is of vital significance to incentivise the drivers to collect the appropriate quantity and quality of data. The idea of proposing alternative routes to collect data from areas with reduced coverage can improve the efficiency of the system, but it is clear that in order for a driver to deviate from his/her usual route and possibly increasing his/her commuting time, meaningful reasons should be proposed. The incentives could promote sustainable mobility while be associated with the reduction in user's ecological footprint to further communicate the importance of AQ monitoring. For example, when citizens or taxi drivers change their route to cover areas with reduced coverage, they could have reductions in their fuel costs, reduced parking fees or other similar economic incentives. It should be noted that while this kind of incentives might seem counterintuitive as drivers would increase their driving time, in the long term they contribute in the improvement of a system that promotes an eco-friendlier behaviour. Thus, the citizen becomes part of the AQMS while personalized feedback is communicated to assist in the long-lasting engagement.

Finally, while the proposed smartphone app can be a useful tool in terms of communicating personalized information like feedback and incentives, using it as part of the hardware of the sensor system is challenging. Specifically, the low-cost sensor should be in a specific position on the vehicle and is not suggested to be attached to the smartphone. However, the sensor could connect via Bluetooth (or similar wireless technologies) with the smartphone in order to transmit all necessary information packages. In this way, the user should not be responsible of any complex hardware procedures, but the user involvement should be limited to already known and simple procedures, like connecting to a Bluetooth-enabled car or a Bluetooth headset.

5. Results

The findings from the two directions of the literature review are multidirectional and different aspects of them were examined that are related to the deployment of a sensor network. The technical issues that can affect its success or not depend mainly on the different types of sensors have different advantages and disadvantages. The literature review was categorized by the type of sensor network, including Static, Community and Vehicle sensor networks. A summary of what was discussed in the previous sections has been successfully illustrated in (Yi et al., 2015), where a thorough comparison between the different types is provided and including a "final grade" of each comparison property of SSN, CSN and VSN systems Figure 10.

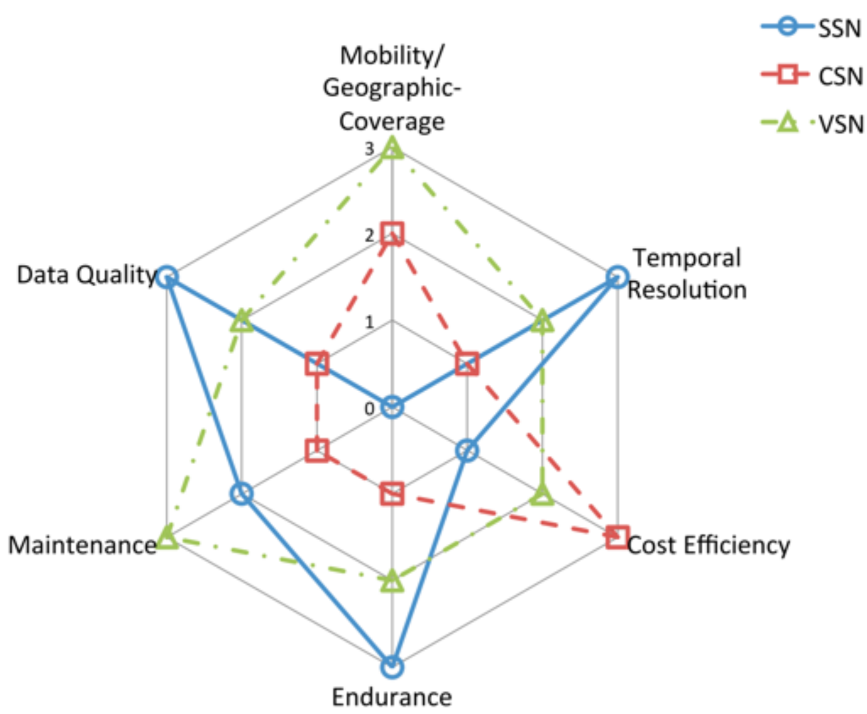


Figure 10: Grading result of the six major comparison properties in SSN, CSN and VSN (Yi et al., 2015)

It is clearly seen that there is not a single type of sensor network that outranks the others. For example, as it has been established, there is a massive difference between SSN in terms of spatial coverage and cost efficiency, which is also one of the main factors that the CAROLINA project was initiated. Indeed, it was seen that rarely a case has been documented where an SSN was successfully deployed without identifying its drawbacks. Additionally, while the VSN have a more average score, it is seen that the cost efficiency of the CSN cannot be neglected.

Thus, a hybrid system can take advantage of all the strengths of each system by fusing data from different sources and is proposed as the most appropriate solution for an innovative, modern and efficient AQMS. One of the most significant advantages of this system, as seen in different studies, would be the calibration and outlier detection is very important for adequate data quality. Of course, when an SSN is already functioning and is available, its endurance, temporal resolution and increased data quality can be a key part to any successful parallel deployment of a VSN and/or CSN. Although different ways to calibrate sensors can been found in the literature, corelation of mobile sensors with nearby static sensors is still an essential best practice (Clements et al., 2017), while the periodic calibration of such sensors is of vital importance to retain a high measurement accuracy (Hasenfratz, 2015). Since the low-cost sensors are still not flawless in terms of accuracy, calibration and collecting high quality data should be the primary goal and should be taken into consideration by policy makers, researchers and practitioners during the first stages of the design and deployment a network of sensors. It is also important to note that multiple disciplines need to cooperate for the fine-tuning of the data, including modelers and machine learning engineers to hardware experts and meteorologists.

Additionally, as it was also discussed in the section related to the deployment of the city of Istanbul, **the position of the sensors should be examined in great detail depending on the different conditions that are present to the study area.** These conditions are related to the weather conditions, traffic conditions, road environment, type of vehicle etc. Again, another requirement for success is the collaboration between multiple disciplines in order to maximize accuracy and efficiency in such a multifactorial system.

Similarly, **the use of vehicles to deploy community-based sensors, fuses the advantages of VSNs and CSNs.** For example, the VSN's high mobility and coverage, well-calibrated and maintained sensors, loose constraint on energy consumption and automatic gathering properties, can overcome some of the challenges that have been identified in CSNs, like the size and weight of sensors, privacy issues and operability. Of course, the one should always take into account the caveats of uncontrolled or semi-controlled mobility when specific types of vehicles are utilized (for example certain bus lines, vehicles fleets or trash-trucks) and the spatial-to-temporal resolution trade-off. It is essential to note that the position of the sensor should also be examined per different type of vehicle as the different size and shape of these vehicles, but also the environment they are moving on (trailway or roads) can greatly affect the sensors' measurement.

The use of novel technologies should also not be neglected in a future system. Particularly, the utilization of drones as part of an AQMS was also identified as a potential research direction that could also be implemented immediately under the right conditions. Their advantage against other methods to collect data in different altitudes, their ability to cover big areas in small time intervals and their flexibility as a portable sensor could transform drones into a game changer in a potential AQMS. Additionaly, drones as an eye-in-the-sky solution can contribute in the estimation of emissions in a city.

The second direction that is related to the engagement of the citizens' participation identified that some of the **main concerns of the citizens' participation include privacy, data quality and energy efficiency**

issues. However, it should also be noted that it is important not only to tackle these issues before the deployment of a sensor network but also to **keep the citizens engaged and participating throughout the data collection process**. Thus, quality feedback, technological support, economic or other incentives should be solicited as communities have been demanding a greater role in decision-making. Especially in the case of citizens taking also the role of data collectors, they need to have a stronger motivation to fully become a viable part of the system. The more satisfying the data collection process is for the citizens, the more the incoming data to be utilized in terms both of quantity, quality and spatial and temporal coverage.

It was reviewed that both scientists and communities can benefit by community-driven research, but a basic requirement is to build trust and communication between the different parts that are associated. The technical expertise alone is not always enough. Hence, citizens can become more motivated when the health risks are communicated and experience has shown that they have a significant part in defining the problems, supplying local knowledge and interpreting the results in the context of the local reality while at the same time improving the relevance of the research questions that are formed.

Finally, it is seen from the discussion regarding the experience from current and past projects in the city of Istanbul, **that the literature has systematically pointed out some of the forewarnings during the early deployment of such a system.** The experience gained from the deployment during the TaxiCap project together with the experience from similar projects around the world led to the suggestion of some first steps that should be foreseen in the deployment of a similar system. It was also identified that solving solely the technical issues is not adequate for a successful system, as its efficiency can be improved dramatically with the inclusion of citizens in the process through a collaborative approach. The case of Istanbul is described in the following section in more detail.

Use case in Istanbul

It was seen in Figure 4, that although Istanbul has a dense AQ network, not all particulate matters and pollutants are measured everywhere (Table 2). Therefore, a hybrid methodology that is identified as the proposed methodology for Istanbul should include compounds from different systems. The way this could be implemented practically is described in more detail in the following Table 3.

Table 3: Summary of the proposed Hybrid System

Type of Sensor Network	Installation	Description
SSN	Different parts of the city	38 Static Sensors for the 6 different pollutants (5 currently being measured), as described in Figure 4 and Table 2 The upgrade of existing sensors is suggested to measure all pollutants. The installation of more sensors is suggested to enhance the cailbration of VSNs and CSNs, for example on Bus Stops, Tram Stops etc.

VSN	Taxis	Further development based on the existing experience from the TaxiCap project. Engagement and incentives for more taxi drivers to participate in the program.
	Public Transport Fleet	Development of sensor for different type of public vehicles
	Private Vehicles and Vehicles Fleet	Development of sensor for different type of private vehicles (conventional, electric vehicles, automated vehicles etc.) and/or for different fleets (trash trucks, delivery vehicles etc.) Engagement and incentives for drivers to participate in the program
CSN	Bicycles	Development of sensor for bicycles and e-bikes Participation of shared bikes Engagement and incentives for more cyclists to participate in the program

Evaluation of results

As discussed in the Introduction, the aims that were set for the specific deliverable are related to i) the exploration of the current state of the art in next generation monitoring techniques, ii) consideration of the open collaboration approach for AQ modelling and monitoring, iii) analysis on what should be the motivation, what should attract and how to engage citizens to actively contribute towards the reduction of urban air pollution and iv) based on the findings the city of Istanbul is examined as a specific case study. After the completion of the literature review with the means that were described in the previous paragraphs and the discussion between the different partners of the project, the assessment for all the different aims is considered **successful**. The main conclusions are discussed in the following section.

6. Conclusions and Lessons learnt

The knowledge gained through reviewing the state-of-the-art in AQMS is the one of the core parts of the CAROLINA project as the know-how that was obtained during the reviewing process is necessary for a successful deployment of a low-cost AQMS. The main conclusions of the specific deliverable can be summarized into:

- **New knowledge was uncovered, both expected and unexpected**. The existing systems were reviewed to reveal their advantages and disadvantages. The hybrid system was selected as the most efficient solution, that takes into advantage novel technologies and the existing infrastructure. The potential of innovative technologies was identified that are still in experimental stage.
- **High-potential links between different sensor systems**. The potential advantages, opportunities and challenges of a hybrid system were identified and suggested as the appropriate methodology for the development of a future, modern and efficient low-cost AQMS.
- **Connections between the existing technology and open approaches.** The way the proposed system can be integrated into an open and collaborative approach was proposed by including sensors both on public and private vehicles, identifying potential risks and providing proper solutions.
- **Specific incentives and good practises to engage citizens.** The latest trends and good practises related to ways to incentivise citizens into a collaborative AQMS were identified. The important factors that can increase the possibility of success were acknowledged.

Specific suggestions for the city of Istanbul. A system that includes both public and private citizens was proposed. Incentives to citizens should be communicated prior and during the deployment of the system with the development of a smartphone application.

It should be noted that a literature review is a time-consuming process, however it is crucial in order to justify the efficiency, viability and possibility of a successful deployment of the proposed methodology. Through this process, the originality of this methodology was discovered and how it is related or not to previous projects. Significant gaps were discovered in previous researchers or projects that were pointed out in order to be avoided and demonstrate the preparedness of a future system.

However, as research attempts and projects in the generalized discipline of AQM and specifically the area of low-cost sensors is a very hot topic, the literature review should be a continuous non-stopping process. For example, many works that were reviewed were still in starting phase, so in the next years the results of these works should be studied and carefully be taken into consideration. The use of keywords for the regular update on the literature review can lead to targeted and consistent results and help in identifying the high-quality papers.

We should also emphasize that collaboration between researchers, practitioners and authorities is of major important during the stage of reviewing the state of the art. As it was discovered during the preparation of this deliverable, the collaboration between the different partners of CAROLINA and the experience shared between them contributed massively for the completeness of this report. The feedback and different opinions, the sharing of knowledge and experience, finding out how the different partners approach CAROLINA from their side are the major factors of the comprehensiveness of this deliverable, which can be a valuable guide during the design and the implementation stage for any similar project.

7. References

Aberer, K., 2012. Keynote: OpenSense: Open sensor networks for air quality monitoring. 2012 IEEE Int. Conf. Pervasive Comput. Commun. Work. 1–1. https://doi.org/10.1109/percomw.2012.6197478

Aberer, K., Sathe, S., Chakraborty, D., Martinoli, A., Barrenetxea, G., Faltings, B., Thiele, L., 2010. OpenSense: Open community driven sensing of environment, in: Proceedings of the ACM SIGSPATIAL International Workshop on GeoStreaming, IWGS 2010. https://doi.org/10.1145/1878500.1878509

Al-Ali, A.R., Zualkernan, I., Aloul, F., 2010. A mobile GPRS-sensors array for air pollution monitoring. IEEE Sens. J. https://doi.org/10.1109/JSEN.2010.2045890

Ali, S., Member, G.S., Glass, T., Parr, B., Potgieter, J., 2020. Low Cost Sensor with IoT LoRaWAN Connectivity and Machine Learning Based Calibration for Air Pollution Monitoring. IEEE Trans. Instrum. Meas. 9456. https://doi.org/10.1109/TIM.2020.3034109

Alvarado, M., Gonzalez, F., Fletcher, A., Doshi, A., 2015. Towards the development of a low cost airborne sensing system to monitor dust particles after blasting at open-pit mine sites. Sensors (Switzerland). https://doi.org/10.3390/s150819667

Anderson, R., Giddings, J., 2009. Message. Mobile Environmental Sensing System Across Grid Environments, Message. Mobile Environmental Sensing System Across Grid Environments.

Anjomshoaa, A., Duarte, F., Rennings, D., Matarazzo, T.J., Desouza, P., Ratti, C., 2018. City Scanner: Building and Scheduling a Mobile Sensing Platform for Smart City Services. IEEE Internet Things J. https://doi.org/10.1109/JIOT.2018.2839058

Apte, J.S., Messier, K.P., Gani, S., Brauer, M., Kirchstetter, T.W., Lunden, M.M., Marshall, J.D., Portier, C.J., Vermeulen, R.C.H., Hamburg, S.P., 2017. High-Resolution Air Pollution Mapping with Google Street View Cars: Exploiting Big Data. Environ. Sci. Technol. 51, 6999–7008. https://doi.org/10.1021/acs.est.7b00891

Arfire, A., 2016. Mobile Sensor Networks for Air Quality Monitoring in Urban Settings. EPFL.

Arroyo, P., Herrero, J.L., Suárez, J.I., Lozano, J., 2019. Wireless sensor network combined with cloud computing for air quality monitoring. Sensors (Switzerland) 19. https://doi.org/10.3390/s19030691

Bach, K., Akselsen, S., Veiga, T., Kalamaras, I., 2020. On the Use of Air Quality Microsensors for Supporting Decision Makers, in: 10th International Conference on the Internet of Things Companion. pp. 1–4.

Bardoutsos, A., Filios, G., Katsidimas, I., Krousarlis, T., Nikoletseas, S., Tzamalis, P., 2020. A multidimensional human-centric framework for environmental intelligence: Air pollution and noise in smart cities, in: Proceedings - 16th Annual International Conference on Distributed Computing in Sensor Systems, DCOSS 2020. https://doi.org/10.1109/DCOSS49796.2020.00036

Barmpounakis, E., Geroliminis, N., 2020. On the new era of urban traffic monitoring with massive drone data: The pNEUMA large-scale field experiment. Transp. Res. Part C Emerg. Technol. 111, 50–71.

https://doi.org/10.1016/j.trc.2019.11.023

Barmpounakis, E.N., Vlahogianni, E.I., Golias, J.C., 2016. Unmanned Aerial Aircraft Systems for transportation engineering: Current practice and future challenges. Int. J. Transp. Sci. Technol. 5, 111–122. https://doi.org/10.1016/j.ijtst.2017.02.001

Barrenetxea, G., Ingelrest, F., Schaefer, G., Vetterli, M., 2008. Wireless sensor networks for environmental monitoring: The SensorScope experience, in: International Zurich Seminar on Digital Communications. https://doi.org/10.1109/IZS.2008.4497285

Bauerova, P., Šindelarova, A., Rychlik, S., Novak, Z., Keder, J., 2020. Low-Cost Air Quality Sensors : One-Year Field Comparative Measurement of Di ff erent Gas Sensors and Particle Counters with Reference Monitors at Tušimice Observatory. Atmosphere (Basel). 11, 1–15.

Behrisch, M., Bieker, L., Erdmann, J., Krajzewicz, D., 2011. SUMO – Simulation of Urban MObility. Iaria.

Bishop, G.A., Stedman, D.H., 2008. A decade of on-road emissions measurements. Environ. Sci. Technol. https://doi.org/10.1021/es702413b

Bonney, R., Cooper, C.B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K. V., Shirk, J., 2009. Citizen science: A developing tool for expanding science knowledge and scientific literacy. Bioscience. https://doi.org/10.1525/bio.2009.59.11.9

Bosello, M., Delnevo, G., Mirri, S., 2020. On exploiting Gamification for the Crowdsensing of Air Pollution: a Case Study on a Bicycle-based System, in: Proceedings of the 6th EAI International Conference on Smart Objects and Technologies for Social Good. pp. 205–210.

Bukowiecki, N., Dommen, J., Prévôt, A.S.H., Richter, R., Weingartner, E., Baltensperger, U., 2002. A mobile pollutant measurement laboratory - Measuring gas phase and aerosol ambient concentrations with high spatial and temporal resolution. Atmos. Environ. 36, 5569–5579. https://doi.org/10.1016/S1352-2310(02)00694-5

Burgard, D.A., Bishop, G.A., Stadtmuller, R.S., Dalton, T.R., Stedman, D.H., 2006. Spectroscopy applied to on-road mobile source emissions. Appl. Spectrosc. https://doi.org/10.1366/000370206777412185

Cambridge Mobile Urban Sensing (CamMobSens), 2008. . Sens. Rev. https://doi.org/10.1108/sr.2008.08728caf.004

Camprodon, G., González, Ó., Barberán, V., Pérez, M., Smári, V., de Heras, M.Á., Bizzotto, A., 2019. Smart Citizen Kit and Station: An open environmental monitoring system for citizen participation and scientific experimentation. HardwareX 6, e00070. https://doi.org/10.1016/j.ohx.2019.e00070

Castell, N., Dauge, F.R., Schneider, P., Vogt, M., Lerner, U., Fishbain, B., Broday, D., Bartonova, A., 2017. Can commercial low-cost sensor platforms contribute to air quality monitoring and exposure estimates? Environ. Int. 99, 293–302. https://doi.org/10.1016/j.envint.2016.12.007

Castell, N., Kobernus, M., Liu, H.Y., Schneider, P., Lahoz, W., Berre, A.J., Noll, J., 2015. Mobile technologies and services for environmental monitoring: The Citi-Sense-MOB approach. Urban Clim. https://doi.org/10.1016/j.uclim.2014.08.002

Cavaliere, A., Carotenuto, F., Di Gennaro, F., Gioli, B., Gualtieri, G., Martelli, F., Matese, A., Toscano, P., Vagnoli, C., Zaldei, A., 2018. Development of low-cost air quality stations for next generation monitoring networks: Calibration and validation of PM2.5 and PM10 sensors. Sensors (Switzerland) 18. https://doi.org/10.3390/s18092843

Celebi, M., \.Incecik, S., Deniz, A., 2010. Investigation of PM10 Levels in Urban Atmosphere of a Megacity: Istanbul, in: Better Air Quality Conference.

Cheng, Y., He, X., Zhou, Z., Thiele, L., 2020. MapTransfer : Urban Air Quality Map Generation for Downscaled Sensor Deployments, in: 2020 IEEE/ACM Fifth International Conference on Internet-of-Things Design and Implementation (IoTDI). pp. 14–26. https://doi.org/10.1109/IoTDI49375.2020.00010

Cheng, Y., Li, X., Li, Z., Jiang, S., Li, Y., Jia, J., Jiang, X., 2014. AirCloud: a cloud-based air-quality monitoring system for everyone. Proc. 12th ACM Conf. Embed. Netw. Sens. Syst. - SenSys ’14 251–265. https://doi.org/10.1145/2668332.2668346

Cicutto, L., Mccullough, M., Schmoll, E., Cho, S., 2020. Personal Monitoring of Air Quality in an Environmental Justice Community : Wearability , Knowledge , Confidence , and Action Plans, in: HEALTH EFFECTS OF AIR POLLUTION AND AIR TOXICS.

Clements, A.L., Griswold, W.G., Abhijit, R.S., Johnston, J.E., Herting, M.M., Thorson, J., Collier-Oxandale, A., Hannigan, M., 2017. Low-cost air quality monitoring tools: From research to practice (A workshop summary). Sensors (Switzerland) 17, 1–20. https://doi.org/10.3390/s17112478

Cocker, D.R., Shah, S.D., Johnson, K., Miller, J.W., Norbeck, J.M., 2004a. Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 1. Regulated Gaseous Emissions. Environ. Sci. Technol. 38, 2182–2189. https://doi.org/10.1021/es034888d

Cocker, D.R., Shah, S.D., Johnson, K.C., Zhu, X., Miller, J.W., Norbeck, J.M., 2004b. Development and application of a mobile laboratory for measuring emissions from diesel engines. 2. Sampling for toxics and particulate matter. Environ. Sci. Technol. 38, 6809–6816. https://doi.org/10.1021/es049784x

DeSouza, P., Anjomshoaa, A., Duarte, F., Kahn, R., Kumar, P., Ratti, C., 2020. Air Quality Monitoring Case Study Using Mobile Low-cost Sensors mounted on Trash-Trucks: Methods Development and Lessons Learned. Sustain. Cities Soc. 102239. https://doi.org/10.1016/j.scs.2020.102239

Devarakonda, S., Sevusu, P., Liu, H., Liu, R., Iftode, L., Nath, B., 2013. Real-time air quality monitoring through mobile sensing in metropolitan areas, in: Proceedings of the ACM SIGKDD International Conference on Knowledge Discovery and Data Mining. https://doi.org/10.1145/2505821.2505834

Dhingra, S., Madda, R.B., Gandomi, A.H., Patan, R., Daneshmand, M., 2019. Internet of things mobile-air pollution monitoring system (IoT-Mobair). IEEE Internet Things J. 6, 5577–5584. https://doi.org/10.1109/JIOT.2019.2903821

Dickinson, J.L., Shirk, J., Bonter, D., Bonney, R., Crain, R.L., Martin, J., Phillips, T., Purcell, K., 2012. The current state of citizen science as a tool for ecological research and public engagement. Front. Ecol. Environ. https://doi.org/10.1890/110236

Dutta, P., Aoki, P.M., Kumar, N., Mainwaring, A., Myers, C., Willett, W., Woodruff, A., 2009. Demo abstract: Common sense - Participatory urban sensing using a network of handheld air quality monitors, in: Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems, SenSys 2009. https://doi.org/10.1145/1644038.1644095

Elbir, T., 2003. Comparison of model predictions with the data of an urban air quality monitoring network in Izmir, Turkey. Atmos. Environ. 37, 2149–2157. https://doi.org/10.1016/S1352-2310(03)00087-6

Elen, B., Peters, J., van Poppel, M., Bleux, N., Theunis, J., Reggente, M., Standaert, A., 2013. The Aeroflex: A bicycle for mobile air quality measurements. Sensors (Switzerland). https://doi.org/10.3390/s130100221

EPA, 2020. Village Green Project [WWW Document]. URL https://www.epa.gov/air-research/village-green-project (accessed 4.5.20).

Fattoruso, G., Nocerino, M., Toscano, D., Pariota, L., Sorrentino, G., Manna, V., Vito, S. De, Carten, A., Fabbricino, M., Francia, G. Di, 2020. Site Suitability Analysis for Low Cost Sensor Networks for Urban Spatially Dense Air Pollution Monitoring. 2Atmosphere 11, 1–15.

Gao, Y., Dong, W., Guo, K., Liu, Xue, Chen, Y., Liu, Xiaojin, Bu, J., Chen, C., 2016. Mosaic: A low-cost mobile sensing system for urban air quality monitoring, in: Proceedings - IEEE INFOCOM. IEEE, pp. 1–9. https://doi.org/10.1109/INFOCOM.2016.7524478

Gerçek, H., Demir, O., 2008. Urban Mobility in Istanbul Final report.

Gressent, A., Malherbe, L., Colette, A., Rollin, H., Scimia, R., 2020. Data fusion for air quality mapping using low-cost sensor observations: Feasibility and added-value. Environ. Int. 143, 105965. https://doi.org/10.1016/j.envint.2020.105965

Grossberndt, S., Schneider, P., Liu, H., Fredriksen, M.F., Castell, N., 2020. Public Perception of Urban Air Quality Using Volunteered Geographic. Urban Plan. 5, 45–58. https://doi.org/10.17645/up.v5i4.3165

Gulia, S., Shiva Nagendra, S.M., Khare, M., Khanna, I., 2015. Urban air quality management-A review. Atmos. Pollut. Res. 6, 286–304. https://doi.org/10.5094/APR.2015.033

Haagen-Smit, A.J., Bradley, C.E., Fox, M.M., 1953. Ozone Formation in Photochemical Oxidation of Organic Substances. Ind. Eng. Chem. https://doi.org/10.1021/ie50525a044

Haagen-Smit, A.J., Fox, M.M., 1954. Photochemical ozone formation with hydrocarbons and automobile exhaust. Air Repair. https://doi.org/10.1080/00966665.1954.10467649

Hagler, G.S.W., Thoma, E.D., Baldauf, R.W., 2010. High-resolution mobile monitoring of carbon monoxide and ultrafine particle concentrations in a near-road environment. J. Air Waste Manag. Assoc. 60, 328–336. https://doi.org/10.3155/1047-3289.60.3.328

Haiahem, R., Ghazel, C., Saidane, L.A., Boumerdassi, S., 2016. Surveying and Analyzing Urban Environment Approaches of Air Quality Monitoring, in: Renault, E., Boumerdassi, S., Bouzefrane, S. (Eds.), Mobile, Secure, and Programmable Networking 4th. Springer, Paris, France, pp. 1–12. https://doi.org/10.1007/978-3-319-50463-6

Hankey, S., Marshall, J.D., 2015. Land Use Regression Models of On-Road Particulate Air Pollution (Particle Number, Black Carbon, PM2.5, Particle Size) Using Mobile Monitoring. Environ. Sci. Technol. 49, 9194–9202. https://doi.org/10.1021/acs.est.5b01209

Hasenfratz, D., 2015. Enabling Large-Scale Urban Air Quality Monitoring with Mobile Sensor Nodes.

Hasenfratz, D., Saukh, O., Sturzenegger, S., Thiele, L., 2012. IPSN'12 - Proceedings of the 11th International Conference on Information Processing in Sensor Networks. IPSN'12 - Proc. 11th Int. Conf. Inf. Process. Sens. Networks 1–5.

Hodgkinson, B., Lipinski, D., Peng, L., Mohseni, K., 2014. High resolution atmospheric sensing using UAVs, in: Springer Tracts in Advanced Robotics. https://doi.org/10.1007/978-3-642-55146-8_3

Honicky, R.J., Brewer, E.A., Paulos, E., White, R.M., 2008. N-SMARTS: Networked suite of mobile atmospheric real-time sensors, in: Proceedings of the ACM SIGCOMM 2008 Conference on Computer Communications -2nd ACM SIGCOMM Workshop on Networked Systems for Developing Regions, NSDR'08. https://doi.org/10.1145/1397705.1397713

Hu, S.C., Wang, Y.C., Huang, C.Y., Tseng, Y.C., 2011. Measuring air quality in city areas by vehicular wireless sensor networks. J. Syst. Softw. 84, 2005–2012. https://doi.org/10.1016/j.jss.2011.06.043

Hu, S.C., Wang, Y.C., Huang, C.Y., Tseng, Y.C., 2009. A vehicular wireless sensor network for CO2 monitoring, in: Proceedings of IEEE Sensors. https://doi.org/10.1109/ICSENS.2009.5398461

Huang, Y., Mok, W. chuen, Yam, Y. shing, Zhou, J.L., Surawski, N.C., Organ, B., Chan, E.F.C., Mofijur, M., Mahlia, T.M.I., Ong, H.C., 2020. Evaluating in-use vehicle emissions using air quality monitoring stations and on-road remote sensing systems. Sci. Total Environ. 740. https://doi.org/10.1016/j.scitotenv.2020.139868

Im, U., Markakis, K., Poupkou, A., Melas, D., Unal, A., Gerasopoulos, E., Daskalakis, N., Kindap, T., Kanakidou, M., 2011. The impact of temperature changes on summer time ozone and its precursors in the Eastern Mediterranean. Atmos. Chem. Phys. https://doi.org/10.5194/acp-11-3847-2011

Im, Ulas, Poupkou, A., Incecik, S., Markakis, K., Kindap, T., Unal, A., Melas, D., Yenigun, O., Topcu, S., Odman, M.T., Tayanc, M., Guler, M., 2011. The impact of anthropogenic and biogenic emissions on surface ozone concentrations in Istanbul. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2010.12.026

Incecik, S., Im, U., 2012. Air Pollution in Mega Cities: A Case Study of Istanbul, in: Khare, M. (Ed.), Air Pollution - Monitoring, Modelling and Health. InTech, pp. 77–116. https://doi.org/10.5772/32040

Jiao, W., Hagler, G.S.W., Williams, R.W., Sharpe, R.N., Weinstock, L., Rice, J., 2015. Field assessment of the village green project: An autonomous community air quality monitoring system. Environ. Sci. Technol. https://doi.org/10.1021/acs.est.5b01245

Kaivonen, S., Ngai, E.C.H., 2020. Real-time air pollution monitoring with sensors on city bus. Digit. Commun. Networks 6, 23–30. https://doi.org/10.1016/j.dcan.2019.03.003

Kalajdjieski, J., Korunoski, M., Stojkoska, B.R., Trivodaliev, K., 2020. Smart City Air Pollution Monitoring and Prediction: A Case Study of Skopje, in: International Conference on ICT Innovations. pp. 15–27.

Karagulian, Federico, Barbiere, M., Kotsev, A., Spinelle, L., Gerboles, M., Lagler, F., Redon, N., Crunaire, S., Borowiak, A., 2019. Review of the performance of low-cost sensors for air quality monitoring. Atmosphere (Basel). 10. https://doi.org/10.3390/atmos10090506

Karagulian, F., Gerboles, M., Barbiere, M., Kotsev, A., Lagler, F., Borowiak, A., 2019. Review of sensors for air quality monitoring, JRC Technical Reports. https://doi.org/10.2760/568261

Koçak, M., Theodosi, C., Zarmpas, P., Im, U., Bougiatioti, A., Yenigun, O., Mihalopoulos, N., 2011. Particulate matter (PM10) in Istanbul: Origin, source areas and potential impact on surrounding regions. Atmos. Environ. https://doi.org/10.1016/j.atmosenv.2010.10.007

Kolumban-Antal, G., Lasak, V., Bogdan, R., Groza, B., 2020. A secure and portable multi-sensor module for distributed air pollution monitoring. Sensors (Switzerland) 20. https://doi.org/10.3390/s20020403

Kolumban-Antal, G., Lasak, V., Bogdan, R., Groza, B., 2019. Air pollution monitoring with secure low-cost Vehicular Sensor Networks. ITM Web Conf. 29, 03007. https://doi.org/10.1051/itmconf/20192903007

Koval, A., Irigoyen, E., 2016. Mobile Wireless System for Outdoor Air Quality Monitoring, in: SOCO 2016, CISIS 2016, ICEUTE 2016: International Joint Conference SOCO'16-CISIS'16-ICEUTE'16. pp. 345–354. https://doi.org/10.1007/978-3-319-47364-2

Kristiani, E., Lee, C.F., Yang, C.T., Huang, C.Y., Tsan, Y.T., Chan, W.C., 2020. Air quality monitoring and analysis with dynamic training using deep learning. J. Supercomput. https://doi.org/10.1007/s11227-020-03492-8

Kumar, P., Jain, S., Gurjar, B.R., Sharma, P., Khare, M., Morawska, L., Britter, R., 2013. New directions: can a "blue sky" return to Indian megacities? Atmos. Environ. 71, 198–201.

Kumar, P., Morawska, L., Martani, C., Biskos, G., Neophytou, M., Di Sabatino, S., Bell, M., Norford, L., Britter, R., 2015. The rise of low-cost sensing for managing air pollution in cities. Environ. Int. https://doi.org/10.1016/j.envint.2014.11.019

Le, D. Van, Tham, C.K., 2018. Machine learning (Ml)-based air quality monitoring using vehicular sensor networks. Proc. Int. Conf. Parallel Distrib. Syst. - ICPADS 2017-Decem, 65–72. https://doi.org/10.1109/ICPADS.2017.00020

Lee, H., 2020. Improving Accuracy of Urban Particulate Matter Sensor Network via Data-Driven Sensor Calibration. Seoul National University.

Lee, J.K., Christen, A., Ketler, R., Nesic, Z., 2017. A mobile sensor network to map carbon dioxide emissions in urban environments. Atmos. Meas. Tech. 10, 645–665. https://doi.org/10.5194/amt-10-645-2017

Li, C., Hsu, N.C., Tsay, S.C., 2011. A study on the potential applications of satellite data in air quality monitoring and forecasting. Atmos. Environ. 45, 3663–3675. https://doi.org/10.1016/j.atmosenv.2011.04.032

Lim, C.C., Kim, H., Vilcassim, M.J.R., Thurston, G.D., Gordon, T., Chen, L.C., Lee, K., Heimbinder, M., Kim, S.Y., 2019. Mapping urban air quality using mobile sampling with low-cost sensors and machine learning in Seoul, South Korea. Environ. Int. 131, 105022. https://doi.org/10.1016/j.envint.2019.105022

Liu, J.H., Chen, Y.F., Lin, T.S., Lai, D.W., Wen, T.H., Sun, C.H., Juang, J.Y., Jiang, J.A., 2011. Developed urban air quality monitoring system based on wireless sensor networks, in: Proceedings of the International Conference on Sensing Technology, ICST. IEEE, pp. 549–554. https://doi.org/10.1109/ICSensT.2011.6137040

Lo Re, G., Peri, D., Vassallo, S.D., 2014. Urban air quality monitoring using Vehicular Sensor Networks. Adv. Intell. Syst. Comput. https://doi.org/10.1007/978-3-319-03992-3_22

Loglisci, C., Zappatore, M., Longo, A., Bochicchio, M.A., Malerba, D., 2020. Leveraging Machine Learning in IoT to Predict the Trustworthiness of Mobile Crowd Sensing Data. Springer International Publishing. https://doi.org/10.1007/978-3-030-59491-6_22

Long, N.Q., Cuong, C.X., Canh, L.V.A.N., 2020. 3D Spatial Interpolation Methods for Open-Pit Mining Air Quality with Data Acquired by Small UAV Based Monitoring System. Inżynieria Miner. 263–274.

Ma, Y., Richards, M., Ghanem, M., Guo, Y., Hassard, J., 2008. Air pollution monitoring and mining based on sensor Grid in London. Sensors. https://doi.org/10.3390/s8063601

Maag, B., Zhou, Z., Thiele, L., 2018. A Survey on Sensor Calibration in Air Pollution Monitoring Deployments. IEEE Internet Things J. https://doi.org/10.1109/JIOT.2018.2853660

Mahajan, S., Kumar, P., Pinto, J.A., Riccetti, A., Schaaf, K., Camprodon, G., Smári, V., Passani, A., Forino, G., 2020. A citizen science approach for enhancing public understanding of air pollution. Sustain. Cities Soc. 52, 101800. https://doi.org/10.1016/j.scs.2019.101800

Mansour, S., Nasser, N., Karim, L., Ali, A., 2014. Wireless sensor network-based air quality monitoring system, in: 2014 International Conference on Computing, Networking and Communications, ICNC 2014. IEEE, pp. 545–550. https://doi.org/10.1109/ICCNC.2014.6785394

Mao, W., Wang, W., Jiao, L., Zhao, S., Liu, A., 2020. Modeling air quality prediction using a deep learning approach : Method optimization and evaluation. Sustain. Cities Soc. 102567. https://doi.org/10.1016/j.scs.2020.102567

Marinov, D., Sigrist, M.W., 2003. Monitoring of road-traffic emissions with a mobile photoacoustic system. Photochem. Photobiol. Sci. 2, 774–778. https://doi.org/10.1039/b301774e

Marinov, M.B., 2020. In-situ Calibration of Networked Air-Quality Sensor Nodes, in: 2020 XXIX International Scientific Conference Electronics (ET). pp. 18–21.

Mazutti, J., Brandli, L.L., Salvia, A.L., Gomes, F., Damke, L.I., Tibola da Rocha, V., Santos Rabello, R. b., 2020. Smart and learning campus as living lab to foster education for sustainable development : an experience with air quality monitoring. Int. J. Sustain. High. Educ. https://doi.org/10.1108/IJSHE-01-2020-0016

Middelweerd, A., Mollee, J.S., van der Wal, C.N., Brug, J., te Velde, S.J., 2014. Apps to promote physical activity among adults: A review and content analysis. Int. J. Behav. Nutr. Phys. Act. https://doi.org/10.1186/s12966-014-0097-9

Molina, L.T., Molina, M.J., Slott, R.S., Kolb, C.E., Gbor, P.K., Meng, F., Singh, R.B., Galvez, O., Sloan, J.J., Anderson, W.P., Tang, X., Hu, M., Xie, S., Shao, M., Zhu, T., Zhang, Y.H., Gurjar, B.R., Artaxo, P.E., Oyola, P., Gramsch, E., Hidalgo, D., Gertler, A.W., 2004. Air quality in selected megacities. J. Air Waste Manag. Assoc. https://doi.org/10.1080/10473289.2004.10471015

Montesinos, M., Barmpounakis, E.N., Gonzalez, E., Geroliminis, N., 2021. Vehicle emissions estimation using naturalistic data from a swarm of drones, in: TRB 100th Annual Meeting January 24-28, Washington, D.C. US. Washington, D.C.

Montola, M., 2005. Exploring the edge of the magic circle: Defining pervasive games. Proc. DAC 1966, 16–19. https://doi.org/10.1.1.125.8421

Morawska, L., Thai, P.K., Liu, X., Asumadu-Sakyi, A., Ayoko, G., Bartonova, A., Bedini, A., Chai, F., Christensen, B., Dunbabin, M., Gao, J., Hagler, G.S.W., Jayaratne, R., Kumar, P., Lau, A.K.H., Louie, P.K.K., Mazaheri, M., Ning, Z., Motta, N., Mullins, B., Rahman, M.M., Ristovski, Z., Shafiei, M., Tjondronegoro, D., Westerdahl, D., Williams, R., 2018. Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: How far have they gone? Environ. Int. 116, 286–299. https://doi.org/10.1016/j.envint.2018.04.018

Morselli, F., Zabini, F., Conti, A., 2018. Environmental Monitoring via Vehicular Crowdsensing. IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC 2018-Septe, 1382–1387. https://doi.org/10.1109/PIMRC.2018.8580783

Murty, R.N., Mainland, G., Rose, I., Chowdhury, A.R., Gosain, A., Bers, J., Welsh, M., 2008. CitySense: An urban-scale wireless sensor network and testbed, in: 2008 IEEE International Conference on Technologies for Homeland Security, HST'08. https://doi.org/10.1109/THS.2008.4534518

Nikzad, N., Verma, N., Ziftci, C., Bales, E., Quick, N., Zappi, P., Patrick, K., Dasgupta, S., Krueger, I., Rosing, T.S., Griswold, W.G., 2012. Citisense: Improving geospatial environmental assessment of air quality using a wireless personal exposure monitoring system. Proc. - Wirel. Heal. 2012, WH 2012. https://doi.org/10.1145/2448096.2448107

Nyarku, M., Mazaheri, M., Jayaratne, R., Dunbabin, M., Rahman, M.M., Uhde, E., Morawska, L., 2018. Mobile phones as monitors of personal exposure to air pollution: Is this the future? PLoS One 13, 1–18. https://doi.org/10.1371/journal.pone.0193150

Pares, M.E., Garcia, D., Vazquez-Gallego, F., 2020. Mapping air quality with a mobile crowdsourced air quality monitoring system (C-AQM). Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. XLIII, 685–691.

Paulos, E., Honicky, R.J., Hooker, B., 2008. Citizen science: Enabling participatory urbanism, in: Handbook of Research on Urban Informatics: The Practice and Promise of the Real-Time City. https://doi.org/10.4018/978-1-60566-152-0.ch028

Pavani, M., Rao, P.T., 2017. Urban air pollution monitoring using wireless sensor networks: A comprehensive review. Int. J. Commun. Networks Inf. Secur. 9, 439–449.

Pavani, M., Rao, P.T., 2016. Real time pollution monitoring using Wireless Sensor Networks, in: 7th IEEE Annual Information Technology, Electronics and Mobile Communication Conference, IEEE IEMCON 2016. https://doi.org/10.1109/IEMCON.2016.7746315

Peng, J.F., Hu, M., Wang, Z.B., Huang, X.F., Kumar, P., Wu, Z.J., Guo, S., Yue, D.L., Shang, D.J., Zheng, Z., He, L.Y., 2014. Submicron aerosols at thirteen diversified sites in China: Size distribution, new particle formation and corresponding contribution to cloud condensation nuclei production. Atmos. Chem. Phys. https://doi.org/10.5194/acp-14-10249-2014

Penza, M., Suriano, D., Pfister, V., Prato, M., Cassano, G., 2017. Urban Air Quality Monitoring with Networked Low-Cost Sensor-Systems, in: EUROSENSORS 2017. p. 573. https://doi.org/10.3390/proceedings1040573

Rai, A.C., Kumar, P., Pilla, F., Skouloudis, A.N., Di Sabatino, S., Ratti, C., Yasar, A., Rickerby, D., 2017. End-user perspective of low-cost sensors for outdoor air pollution monitoring. Sci. Total Environ. 607–608, 691–705. https://doi.org/10.1016/j.scitotenv.2017.06.266

Rickenbacker, H., Brown, F., Bilec, M., 2019. Creating environmental consciousness in underserved communities: Implementation and outcomes of community-based environmental justice and air pollution research. Sustain. Cities Soc. 47, 101473. https://doi.org/10.1016/j.scs.2019.101473

Rickenbacker, H.J., Vaden, J.M., Bilec, M.M., 2020. Engaging Citizens in Air Pollution Research: Investigating the Built Environment and Indoor Air Quality and Its Impact on Quality of Life. J. Archit. Eng. 26, 4020041. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000439

Samad, A., Vogt, U., 2021. Mobile air quality measurements using bicycle to obtain spatial distribution and high temporal resolution in and around the city center of Stuttgart. Atmos. Environ. 244, 117915. https://doi.org/10.1016/j.atmosenv.2020.117915

Samad, A., Vogt, U., Yeung, H.-Y., Panta, A., 2018. Three Dimensional Observations of the Air Quality in Stuttgart under the Project "Urban Climate Under Change [UC]2," in: 10th International Conference on Urban Climate (ICUC10.

Sanchez, L., Galache, J.A., Gutierrez, V., Hernandez, J.M., Bernat, J., Gluhak, A., Garcia, T., 2011. Smartsantander: The meeting point between future internet research and experimentation and the smart cities, in: 2011 Future Network & Mobile Summit. pp. 1–8.

Sanchez, L., Gutierrez, V., Galache, J.A., Sotres, P., Santana, J.R., Casanueva, J., Munoz, L., 2013. SmartSantander: Experimentation and service provision in the smart city, in: International Symposium on Wireless Personal Multimedia Communications, WPMC.

Sanchez, L., Muñoz, L., Galache, J.A., Sotres, P., Santana, J.R., Gutierrez, V., Ramdhany, R., Gluhak, A., Krco, S., Theodoridis, E., others, 2014. SmartSantander: IoT experimentation over a smart city testbed. Comput. Networks 61, 217–238.

Santana, P., Almeida, A., Mariano, P., Correia, C., Almeida, S.M., 2020. An Affordable Vehicle-Mounted Sensing Solution for Mobile Air Quality Monitoring, in: 2020 5th International Conference on Smart and Sustainable Technologies (SpliTech).

Schneider, P., Castell, N., Vogt, M., Dauge, F.R., Lahoz, W.A., Bartonova, A., 2017. Mapping urban air quality in near real-time using observations from low-cost sensors and model information. Environ. Int. 106, 234–247. https://doi.org/10.1016/j.envint.2017.05.005

Schoeppe, S., Alley, S., Rebar, A.L., Hayman, M., Bray, N.A., Van Lippevelde, W., Gnam, J.P., Bachert, P., Direito, A., Vandelanotte, C., 2017. Apps to improve diet, physical activity and sedentary behaviour in children and adolescents: A review of quality, features and behaviour change techniques. Int. J. Behav. Nutr. Phys. Act. https://doi.org/10.1186/s12966-017-0538-3

Shi, Y., Lau, K.K.L., Ng, E., 2016. Developing Street-Level PM2.5 and PM10 Land Use Regression Models in High-Density Hong Kong with Urban Morphological Factors. Environ. Sci. Technol. 50, 8178–8187. https://doi.org/10.1021/acs.est.6b01807

Sivaraman, V., Carrapetta, J., Hu, K., Luxan, B.G., 2013. HazeWatch: A participatory sensor system for monitoring air pollution in Sydney. Proc. - Conf. Local Comput. Networks, LCN 56–64. https://doi.org/10.1109/LCNW.2013.6758498

Song, J., Han, K., 2019. Exploring Urban Air Quality with MAPS: Mobile Air Pollution Sensing 1–28.

Stolz, T., Huertas, M.E., Mendoza, A., 2020. Assessment of air quality monitoring networks using an ensemble clustering method in the three major metropolitan areas of Mexico. Atmos. Pollut. Res. https://doi.org/10.1016/j.apr.2020.05.005

Tao, X., Hafid, A.S., 2020. DeepSensing: A Novel Mobile Crowdsensing Framework with Double Deep Q-Network and Prioritized Experience Replay. IEEE Internet Things J. 4662, 1–1. https://doi.org/10.1109/jiot.2020.3022611

Theodosi, C., Im, U., Bougiatioti, A., Zarmpas, P., Yenigun, O., Mihalopoulos, N., 2010. Aerosol chemical composition over Istanbul. Sci. Total Environ. https://doi.org/10.1016/j.scitotenv.2010.02.039

Thompson, J.E., 2016. Crowd-sourced air quality studies: A review of the literature & portable sensors. Trends Environ. Anal. Chem. https://doi.org/10.1016/j.teac.2016.06.001

Tudose, D.S., Patrascu, T.A., Voinescu, A., Tataroiu, R., Tapus, N., 2011. Mobile sensors in air pollution measurement, in: Proceedings of the 8th Workshop on Positioning Navigation and Communication 2011, WPNC 2011. pp. 166–170. https://doi.org/10.1109/WPNC.2011.5961035

Vagnoli, C., Martelli, F., Filippis, T.D., Lonardo, S.D., Gioli, B., Gualtieri, G., Matese, A., Rocchi, L., Toscano, P., Zaldei, A., De Filippis, T., Di Lonardo, S., Gioli, B., Gualtieri, G., Matese, A., Rocchi, L., Toscano, P., Zaldei, A., 2014. The SensorWebBike for air quality monitoring in a smart city, in: IET Seminar Digest. pp. 4–7. https://doi.org/10.1049/ic.2014.0043

Vardoulakis, S., Fisher, B.E.A., Pericleous, K., Gonzalez-Flesca, N., 2003. Modelling air quality in street canyons: A review. Atmos. Environ. https://doi.org/10.1016/S1352-2310(02)00857-9

Velasco, A., Ferrero, R., Gandino, F., Montrucchio, B., Rebaudengo, M., 2016. A mobile and low-cost system for environmental monitoring: A case study. Sensors (Switzerland) 16. https://doi.org/10.3390/s16050710

Vito, S. De, Giudice, A. Del, Esposito, E., Fattoruso, G., Terzini, E., Francia, D., Elia, G.D., Ferlito, S., Auria, P.D., Intini, F., 2020. High Resolution Air Quality Monitoring with IoT Intelligent Multisensor devices during COVID-19 Pandemic Phase 2 in Italy.

Vlahogianni, E.I., Barmpounakis, E.N., 2017. Gamification and sustainable mobility: Challenges and opportunities in a changing transportation landscape, in: Hussein, D. (Ed.), Low Carbon Mobility for

Future Cities. Institution of Engineering and Technology.

Völgyesi, P., Nádas, A., Koutsoukos, X., Lédeczi, Á., 2008. Air quality monitoring with SensorMap, in: Proceedings - 2008 International Conference on Information Processing in Sensor Networks, IPSN 2008. pp. 529–530. https://doi.org/10.1109/IPSN.2008.50

Wang, A., Xu, J., Tu, R., Saleh, M., Hatzopoulou, M., 2020. Potential of machine learning for prediction of traffic related air pollution. Transp. Res. Part D Transp. Environ. 88, 102599. https://doi.org/10.1016/j.trd.2020.102599

Wang, Y.C., Chen, G.W., 2017. Efficient Data Gathering and Estimation for Metropolitan Air Quality Monitoring by Using Vehicular Sensor Networks. IEEE Trans. Veh. Technol. 66, 7234–7248. https://doi.org/10.1109/TVT.2017.2655084

Wang, Y.C., Chen, K.C., 2019. Efficient Path Planning for a Mobile Sink to Reliably Gather Data from Sensors with Diverse Sensing Rates and Limited Buffers. IEEE Trans. Mob. Comput. 18, 1527–1540. https://doi.org/10.1109/TMC.2018.2863293

Weilenmann, M.F., Vasic, A.M., Stettler, P., Novak, P., 2005. Influence of mobile air-conditioning on vehicle emissions and fuel consumption: A model approach for modern gasoline cars used in Europe. Environ. Sci. Technol. 39, 9601–9610. https://doi.org/10.1021/es050190j

WHO, 2020. World Health Organization - Air pollution [WWW Document].

WHO, 2018. WHO Global Ambient Air Quality Database (update 2018) [WWW Document]. URL http://www9.who.int/airpollution/data/cities/en/ (accessed 3.13.20).

Williams, R., Kilaru, V.J., Snyder, E.G., Kaufman, A., Dye, T., Rutter, A., Russell, A., Hafner, H., 2014. Air Sensor Guidebook. Epa/600/R-14/159 1–5. https://doi.org/10.1017/CBO9781107415324.004

Wong, K.J., Chua, C.C., Li, Q., 2009. Environmental monitoring using wireless vehicular sensor networks, in: Proceedings - 5th International Conference on Wireless Communications, Networking and Mobile Computing, WiCOM 2009. IEEE, pp. 1–4. https://doi.org/10.1109/WICOM.2009.5303846

Wu, D.I., Xiao, T.A.O., Liao, X., Luo, J.I.E., 2020. When Sharing Economy Meets IoT : Towards Fine-grained Urban Air Quality Monitoring through Mobile Crowdsensing on Bike-share System 4.

Wu, Y.C., Shiledar, A., Li, Y.C., Wong, J., Feng, S., Chen, X., Chen, C., Jin, K., Janamian, S., Yang, Z., Ballard, Z.S., Göröcs, Z., Feizi, A., Ozcan, A., 2017. Air quality monitoring using mobile microscopy and machine learning. Light Sci. Appl. 6. https://doi.org/10.1038/lsa.2017.46

Xiaojun, L., Hongyuan, W., Ao, L., Di, X., Zhengxuan, H., 2020. Research of multi-rotor UAV atmospheric environment monitoring system based on 4G network, in: 2020 2nd International Conference on Civil Architecture and Energy Science (CAES 2020). https://doi.org/https://doi.org/10.1051/e3sconf/202016502029

Xie, S., Meeker, J., Perez, L., Eriksen, W., Bocage, C., Ndicu, G., Localio, A., Park, H., Jen, A., Goldstein, M., Christie, C., 2020. Feasibility of Using Low-Cost Sensors to Monitor Personal Exposure to PM2 . 5 Among People with Asthma, in: Novel Causes of Environmental Asthma.

Xie, X., Semanjski, I., Gautama, S., Tsiligianni, E., Deligiannis, N., Rajan, R.T., Pasveer, F., Philips, W., 2017. A review of urban air pollution monitoring and exposure assessment methods. ISPRS Int. J. Geo-Information. https://doi.org/10.3390/ijgi6120389

Yang, Z., Wang, J., 2017. A new air quality monitoring and early warning system: Air quality assessment and air pollutant concentration prediction. Environ. Res. 158, 105–117. https://doi.org/10.1016/j.envres.2017.06.002

Yi, W.Y., Leung, K.S., Leung, Y., 2018. A modular plug-and-play sensor system for urban air pollution monitoring: Design, implementation and evaluation. Sensors (Switzerland) 18. https://doi.org/10.3390/s18010007

Yi, W.Y., Lo, K.M., Mak, T., Leung, K.S., Leung, Y., Meng, M.L., 2015. A survey of wireless sensor network based air pollution monitoring systems. Sensors (Switzerland) 15, 31392–31427. https://doi.org/10.3390/s151229859

Yuan, Q., Zhou, H., Liu, Z., Li, J., Yang, F., Shen, X., 2019. CESense: Cost-Effective Urban Environment Sensing in Vehicular Sensor Networks. IEEE Trans. Intell. Transp. Syst. 20, 3235–3246. https://doi.org/10.1109/TITS.2018.2873112

Zhang, D., Woo, S., 2020. Real Time Localized Air Quality Monitoring and Prediction Through Mobile and Fixed IoT Sensing Network. IEEE Access 8, 89584–89594. https://doi.org/10.1109/ACCESS.2020.2993547

Zheng, K., Zhao, S., Yang, Z., Xiong, X., Xiang, W., 2016. Design and Implementation of LPWA-Based Air Quality Monitoring System. IEEE Access 4, 3238–3245. https://doi.org/10.1109/ACCESS.2016.2582153

Zheng, T., Li, B., Li, X.-B., Wang, Z., Li, S.-Y., Peng, Z.-R., 2020. Vertical and horizontal distributions of traffic-related pollutants beside an urban arterial road based on unmanned aerial vehicle observations. Build. Environ. https://doi.org/10.1016/j.buildenv.2020.107401

Zhu, Y., Fung, D.C., Kennedy, N., Hinds, W.C., Eiguren-Fernandez, A., 2008. Measurements of ultrafine particles and other vehicular pollutants inside a mobile exposure system on Los Angeles freeways. J. Air Waste Manag. Assoc. 58, 424–434. https://doi.org/10.3155/1047-3289.58.3.424

Zimmerman, N., Presto, A.A., Kumar, S.P.N., Gu, J., Hauryliuk, A., Robinson, E.S., Robinson, A.L., Subramanian, R., 2018. A machine learning calibration model using random forests to improve sensor performance for lower-cost air quality monitoring. Atmos. Meas. Tech. https://doi.org/10.5194/amt-11-291-2018