The performance assessment of low-cost air pollution sensor in city and the prospect of the autonomous vehicle for air pollution reduction

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\textbf{Abstract.} Urban air pollution is clearly a constantly growing problem and the high level of urban air pollution has been shown to pose a significant risk to city dwellers. It is necessary to have low-cost sensors for data collection, ready data source allowing normal citizen to access to and gain information, and have prospect solutions (e.g. autonomous vehicle) for air pollution reduction in the city. The aim of the study is to illustrate the drivers behind the use of low-cost sensors and to review the performance of sensors. In addition, autonomous vehicle is expected to reduce pollution; therefore, the paper analyzes the benefits and adoption of autonomous vehicles in the future. The challenges and outlook for both low-cost sensor deployment and the adoption of self-driving vehicle will also be discussed. A literature review is used to obtain these aims. The study indicates that the main driver of low-cost sensor is to provide high-density spatiotemporal pollution data, assisting in creating emission inventories of pollutants and detecting pollution hotspots without capital investments. A number of performance aspects considered include the coefficients of determination ($R^2$), variance (CV), repeatability, reproducibility and stability of the sensor. Self-driving vehicle is promising in the change of travel patterns and having impacts on the health of society. Technology and economic challenges, the willingness to use the sensor and the autonomous policy approach are the major challenges. In terms of the outlook, standard guidelines and the calibration methods for low-cost sensors, energy consumption savings and policy supporting for autonomous vehicle should be further investigated.

1. Introduction
The ever-growing population of cities leads to increasing motorization that is one of the major sources of outdoor air pollution. Outdoor air pollution is a major problem attributing to million premature deaths globally. Air pollution is associated with a range of diseases, symptoms and conditions that impair health and quality of life [1]. In addition, air pollution is also responsible for global climate change and...
environmental problems. Developing countries experiencing rapid urbanization are facing acute challenges in abating air pollution. Many efforts have been carried out but overall levels of air pollution remain hazardous in many emerging cities in the Global South.

In most cities, automobile transportation has been found to be a significant factor in the deterioration of the urban environment and it is closely associated with urban air pollution. In general, more than 60 percent is attributed to motor vehicles. Recently, the data on air pollution have an important role in the great effort of government to reduce air pollution. It can be used to agree policy decisions and can be presented to the public to help them make informed travel choices. Conventionally, air pollution concentrations are monitored by government agencies using accurate static monitoring stations equipped with certified reference instruments for measuring regulatory pollutants, such as carbon monoxide (CO), ozone (O3), nitrogen dioxide (NO2), sulphur dioxide (SO2), and particulate matter (PM) [2]. However, instruments at fixed-site air quality monitoring stations require frequent maintenance and calibration. In addition, static stations are less apt in capturing spatial distribution of pollutants.

Recent advancements in technology have enabled the collecting air quality data beyond fixed monitoring stations. By using a network of low-cost sensors for monitoring real-time air pollution concentrations, the data could be used to inform policymakers for developing better policies and measures that would improve public health. A review of recent article of emerging low-cost sensors suggests the majority of studies focus on the benefits and the application of sensors. However, limited attention is paid to performance assessment. Furthermore, many argue that the adoption of autonomous vehicle can reduce the air pollution in the city. Driverless vehicle, also referred to as self-driving vehicle or autonomous vehicle, is vehicle that does not require a person to manually control them [3]. However, many are concerned that autonomous vehicle could cause more air pollution in the city because it increases the travel demand as the time spent in the car will never again seem wasted, and driving will become less tiring and stressful [4].

Table 1. List of commercially available low-cost PM sensors and monitors.

| Sensor/ Monitor | Detectable Range | Measurement Unit | Weight | Price |
|-----------------|------------------|------------------|--------|-------|
| Sharp - GP2Y1010AU0F | 0 to 0.8 mg/m³ approx. | mg/m³ | 16g | $40 |
| Shinyei - PPD42NS | ≥ 1.0 µm | pcs/m³ | 24g | $38 |
| Amphenol SM-PWM-01C | 1 to 2 µm and 3 to 10 µm | pcs/m³ | n/a | $40 |
| Dylos DC1100 PRO | n/a | pcs/m³ | 1.2lb | $260 |
| OPC-N1 | % Concentration at 10⁶ Pcs/l 0.24 | pcs/l | < 70g | $650 |
| SYhitech DSM501 | 0 to 1.4 mg/m³ | mg/m³ | 25g | $7 |
| M-DUST II | 0 to 80 mg/m³ | mg/m³ | 750g | 300 Eur |
| Shinyei AES-1 | 300 to 300000 Pcs/ft³ | Pcs/ft³ | 120g | $1100 |
The objective of the paper is to comprehensively review the usage drivers and performance of low-cost sensors in gathering information high-resolution tempo-spatial pollutant concentration and the adoption of autonomous vehicle as a future solution for urban mobility and air pollution mitigation. The challenges and outlook for the technology deployment and further researches will also be discussed.

2. The Drivers for the Use of Low-Cost Sensors Usage

Urbanization, industrialization and population growth have led to the severe air pollution, in particularly in urban areas. In addition, motorization with the increase in the number of vehicle releases a substantial atmospheric emission, causing significant adverse human health impacts on the global scale [5]. The World Health Organization estimates 4.2 million premature annual deaths globally are linked to ambient air pollution, mainly from heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, and acute respiratory infections in children.

Although the air pollution is recognized among the top ten risks of human development [6], yet many of the world’s cities are still unable to comply with the prescribed concentration limits of air pollutant. It is even more acute for developing countries that are experiencing industrialization - about 4.3 million people deaths are attributed to household air pollution and another 3.7 million are from ambient air pollution.

Air quality varies over a relatively small scale [7]; however, in the urban area, the flow of air masses is more turbulent due to built environment and difficult to predict without sophisticated numerical modeling approaches. In order to develop a real-time high-resolution pollutant concentration maps for urban areas requires a large amount of data that are not available for many cities. This complexity assesses actual human exposure to pollutants challenging [8]. Employing low-cost sensor for air pollution collection is one of the proposed solutions for areas with a shortage of small-scale, high-precision air quality measuring equipment. Despite lower quality data, low-cost sensors can be used in locations simultaneously, which allows for high-resolution exposure assessment mapping of city environments [9].

In order to mitigate the impacts of air pollution on human health, and global environment, cities have put tremendous efforts to air pollution monitoring. For conventional measurements of air pollution, many environmental authorities have set up networks consisting of stationary stations, which are large sized with heavy weight, and require significant investment costs. Another drawback of conventional monitoring instruments is the location of the monitoring stations. The air pollution situation in urban areas is highly related to human activities (e.g., construction activities) and location-dependent (e.g., traffic congestion hotspot). The monitoring stations are generally located away from roadsides and major traffic congestion areas. Therefore, the data collected may not be representative for cities or urban regions [9].

To address this issue, many researchers have developed modeling approaches. However, these methods have problems of inherent aleatoric and epistemic uncertainties due to crude approximations in input
conditions [10]. In order to increase the spatio-temporal resolution of the air pollution information, researchers have deployed low-cost portable ambient sensors widely [11]. Apart from creating emission inventories of pollutants, detecting pollution hotspots, as well as allowing real-time exposure assessment, the low-cost portable sensors enable the mobility and the feasibility in large-scale deployment of the sensor nodes [12]. To facilitate the elaboration of high-resolution air quality maps, sensor nodes can be deployed as dense networks (ubiquitous monitoring) or mounted on vehicles [13][14]. The reduced size of the low-cost platforms also allows new research in personal exposure [15]. ‘Wearable’ sensors are able to consider changes in exposure across different urban environments due to changes in location and activities and provide new capabilities to remotely detect the risk of potential toxic exposure, helping to better understand the nature of the exposure and evaluating the health risk from air pollution [16].

Some programs are already using sensor networks to assess their performance for both fixed-site and mobile monitoring [17]. EPA scientists and engineers advancing air pollution monitoring systems by combining the low-cost portable ambient sensors and the Wireless Sensor Network (WSN) into one system known as the Next Generation Air Pollution Monitoring System (TNGAPMS) [18]. TNGAPMS allows the air pollution information be updated in minutes or even seconds. TNGAPMS also helps researchers to understand the distribution of the air pollutants more efficiently and improve the accuracy of air quality models [18]. Furthermore, there are also community-led sensing network projects, or “citizen science” to involve the public at large in data collection and discussion processes (Air Quality Egg, 2014). Examples include OpenSense and Citi-Sense-MOB [19] that use mobile platforms to monitor air pollution variation in cities, Everyaware that helps citizens collect and share noise and air pollution data. Citi-Sense was able to enlist public participation to use low-cost air quality platforms in eight cities across Europe [19].

In comparison with other instruments for measuring air pollutants, the low-cost sensors are easy to deploy, operate and manage. Retrieving data from the sensors is simple and their automatic operation allows for extensive deployment in the urban settings. The advantage of the sensors provides information on the pollution sources and helps support more conclusive studies on the effects of air pollution on a wide range of aspects of human life [20].

Most low-cost sensor network adopted a centralized model - data collected from sensors are managed, processed and analyzed centrally. The data storage networks are Internet connected, as is the dissemination channel. Data is shared with all stakeholders, ranging from policy makers, and researchers to the general public via mobile phone applications. This helps to raise public awareness of air pollution and allows populations, especially those already at risk, to make informed decisions relating to their health by avoiding areas of high pollution level [19].

3. Performance Evaluation
Many researchers use the coefficient of determination (R^2) obtained from linear function as a criterion to calibrate the sensor response with the reference measurements. Higher R^2 value implies better sensor performance. However, linear function suffers some drawbacks in capturing pollutant concentration when size distribution (i.e., mean size and geometrical standard deviation) and composition of particles are varied. Therefore, other response functions need to be selected in these cases for a particular sensor by calibrating it under the full range of concentrations [21].

In addition, the difference between real world and the laboratory findings may affect sensor performance (small R^2 values) [22]. Although individual site calibration results in time-consuming and increases labor costs, each sensor must be calibrated on-site in order to increase the accuracy and the precision of the measurements. Laboratory-calibrated sensors should not be used for real-world measurements.

Repeatability of measurements of a particular sensor unit and reproducibility of units of the same sensor model [19] [22] can be used to evaluate the precision of the sensors. Repeatability and
reproducibility are the closeness between successive measurements of the same measure and carried out under identical and non-identical conditions of measurement, respectively [23]. Estimating the repeatability of PM sensors is very difficult in non-laboratory conditions due to the difficulty of maintaining constant particle concentrations [22]. A number of studies evaluated the variability of output signals from copies of the same sensor model (intramodel variability). According to [24], repeatability characteristics for different low-cost PM sensors are between 2 and 28% and the repeatability deteriorated at low PM concentrations (CV lies in the range of 23–26% at ~50 \( \mu g/m^3 \) PM concentration).

To ensure reproducibility, sensors need to be calibrated individually so as to improve their reproducibility characteristics [25] [26]. Prior studies reported CV values ranging from 0.9 to 16%. Sensors with lower CV values signify with higher reproducibility. CV values below 10% are considered acceptable for low-cost sensor testing studies [27]. In addition, when sensors are exposed to larger sized particles, the level of reproducibility could deteriorate due to the accumulation of particles at the sensing zone.

Stability is another sensor characteristic that needs to be investigated. For the purposes of research or knowledge-based decision making of the government, sensors are normally used for a relatively long duration (up to few months). Due to the sensor aging problems and accumulation of dust, the stability of the sensors also deteriorates. [28] reported that \( R^2 \) increases for a sensor when the cofounding variable “days of use” was used in the predictive regression model. Further researches need to be conducted to deal with the issue and ensure that the sensor works sufficiently over a long duration.

4. The benefit of autonomous vehicle as a solution for air pollution mitigation

There are many ways to reduce traffic-related air pollution in the city. One of the emerging solutions is the usage of autonomous vehicle. Autonomous vehicle is believed to be the next-generation technology for the sustainable future societies [29]. There are several ways that autonomous vehicles can reduce pollution in the city.

4.1 More efficient driving pattern

By enabling more efficient driving pattern that avoids excessive acceleration and braking, an autonomous vehicle could help to reduce emission in the urban city. In fact, gasoline is burned when braking and re-accelerating. Autonomous mode could change the driver driving style resulting in less burned gas and less consumed battery power, which leads to less air pollution. In addition, autonomous cars could travel closer to each other, which improved aerodynamics [30]. Accelerating is known to be a particularly energy intensive process. Smooth driving will minimalize the necessity of accelerating. One of the advantages of the autonomous vehicle is that it would not violate the traffic regulations, particularly speed limits. The fuel consumption of vehicular traffic on a given road section depends strongly on the velocity profiles of the vehicles. Driving with the imposed limits would make vehicle obtain the best fuel efficiency and pollution at minimum level [29].

4.2 Traffic congestion and fuel consumption

Traffic congestion puts pressure on the urban transport system and leads to the increased environment impacts. In fact, traffic congestion typically leads to the increase in fuel consumption and emission. The level of fuel consumption estimated for the rush hour is 30 to 50% higher than those in in the conditions of an ideal traffic flow [31]. By suggesting an uninterrupted path with the aid of autonomous technology, the vehicle can maintain the green speed that ensures the lowest fuel consumption. A number of studies have investigated the potential for autonomous vehicles to reduce congestion. Studies conducted in the USA stated that delays on motorways would decrease by 60% and fuel consumption by 25% if the autonomous vehicle occupies 90% of the traffic share [32]. Depending on the vehicle-to-vehicle communication and how traffic-smoothing algorithms are implemented, [33] indicated that the adoption
of self-driving vehicles could increase fuel economy and congested traffic speeds by 23–39% and 8–13%, respectively, for all vehicles in the freeway travel stream.

4.3 The increase of car-sharing demand
Several researchers have examined the comprehensive impacts of the deployment of self-driving vehicle fleets in the context of car-sharing and ride-sharing. Many expect that the services will lead to an essential lower demand for private cars. A study by [34] suggests that shared self-driving fleet could remove two thirds of the vehicles currently operating in Singapore while still delivering all of the trips currently made by private vehicles [35]. An agent-based model that is set up in such a way that the fleet of shared and self-driving vehicles deliver the same daily trips in Lisbon have proved that there may be even 65% fewer passenger cars in the streets in peak traffic hours than at present [35]. This will lead to a radical reduction of the congestion level and will significantly reduce the emission. [36] developed a model of a fleet of Shared Autonomous Vehicles. The modeling results suggest that environmental impacts of the implementation of such a fleet are positive, with 5.6% less greenhouse gas emissions, 34% less carbon monoxide emitted, and a 49% reduction in volatile organic compound emissions, among others, compared to the traditional US light duty fleet [35] [36].

5. The Challenges
There are still many technological and economic challenges for the use of low-cost mobile sensors. Because most gaseous and particulate matter sensors require independent evaluation under a range of ambient environmental conditions, the greatest barrier against the uptake of low-cost sensor is the reliability of measured air pollution data.

Other issues are the relatively short working time of sensors as well as their durability. This warrants further evaluation of low-cost sensors in various environmental conditions. In terms of economic challenges, in many cases the costs of maintenance and data management/analysis are much more expensive than the manufacturing cost of sensors. The ability of citizen science approach in raising awareness of people about the impact of air pollution on the health should not be understated. Community-based air pollution projects and a focus on educational effects might lead to a paradigm shift in air pollution monitoring practice.

In order to deal with air pollution in the urban area, several ways have been implemented, ranging from gasoline consumption reduction to electric vehicle usage [37] [38]. Autonomous vehicle is concerned as one of the promising solutions. The environmental impacts of autonomous vehicles have been realized to be important issues, but many are concerned that autonomous vehicles could encourage more driving, more fossil fuels consumption, and more emissions. In addition, it is very difficult to accurately estimate the potential of autonomous vehicles in the reduction of urban emissions due to a series of variable factors that condition the functioning of the future transport system [39]. Furthermore, self-driving vehicles are still years away and it is difficult to reliably predict the future following disruptive paradigm shifts [32].

6. The Outlook
Firstly, low-cost sensors contribute significantly to the body of information that is important for exposure assessment and subsequent hazard mitigation. Thus, for the use in a citizen based observatory network, we need to develop appropriate infrastructure and quality assurance and control systems. Secondly, due to recent development in sensor devices and other related technologies, the initial (manufacturing) cost of low-cost sensor is not a major problem, however the costs involved in their installation, maintenance and data analysis need to be considered. Thirdly, increasing the sensitivity of the particle sensors necessary to be addressed. Because of the limitation to measure low concentrations, the existing sensors cannot measure ultrafine particles that pose greater risk to human health. In addition, further investigation on the sensor’s
stability are necessary in order to ensure that the sensor works sufficiently over a long duration. Finally, yet importantly, autonomous cars have the potential to dramatically change the transportation network and contribute to the air pollution reduction. However, before autonomous vehicle hits the road, it will be necessary to change the existing international legal regulations [39]. Policy makers should begin supporting research into how self-driving vehicle could affect transportation and air pollution mitigation, and how to best alter our transportation system as well as travel behavior to maximize their benefits while minimizing any negative consequences of the transition to a largely autonomous fleet of motor vehicles [36].

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