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Intelligent in-vehicle air quality management: a smart mobility application dealing with air pollution in the traffic

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Abstract
Air pollution in the traffic environment is attracting much stronger attention nowadays from the perspectives of both minimalizing the traveller health risk and maintaining traffic sustainability. The travellers usually lack awareness of their exposure to in-car air pollution and the means to reduce them, such as mobility routing, vehicle usage and maintenance behaviour change actions taken by vehicle drivers. In this paper, we introduce a novel intelligent in-vehicle air quality management solution which consists of the following components: (1) an air quality sensing device in the vehicle measuring the in-car air quality in real-time; (2) a mobile application to offer the travellers air pollution exposure situations and possible actions they could take; (3) a Cloud-based Internet of Things (IoT) platform for collecting, managing, and analysing the sensing data as well as other contextual information ---weather, traffic, road-network structure, etc. Cognitive analytics models are applied to these data and enable the discovery of correlation patterns between in-vehicle air pollution and many other factors, as well as further advise vehicle drivers to adjust behaviours, such as departure time and route selection, vehicle window and air condition system configurations, or vehicle maintenance activities. Test drive result from multiple cities worldwide is also presented to illustrate the effectiveness of this solution for drivers to reduce their air pollution exposure in traffic.

Keywords:
In-vehicle air quality, Traffic pollution, Sustainable traffic

Background

Global industrialization and urbanization have generated growing air pollution issues in the past decades, especially in metropolitan cities of developing countries such as China or India. The awareness of health impact from air pollution has also been increasing and generating much stronger attention from both government and general population. World Health Organization (WHO) reports that in 2012 around 7 million people died, one in eight of the total global deaths, as a result of air pollution exposure, and air pollution is now the world's largest single environmental health risk [1]. Traffic is the major source of air pollution, according to the Health Effect Institute study, and emissions from motor vehicles might contribute as much as 16% of the PM10 and PM2.5 (Particles with an aerodynamic diameter 10 µm and 2.5 µm, respectively) in ambient air [2]. The study also discloses the health effects related with exposure to traffic related air pollution especially exacerbation of asthma, onset of childhood asthma, nonasthma respiratory symptoms, impaired lung function, total and cardiovascular mortality, and cardiovascular morbidity. Travellers spend hours in vehicles on the road every day, however, most travellers lack visibility of their air pollution exposure in the traffic. They do not know the impact factors and the possible actions they could take to reduce their air pollution exposure.

Different industry and academic activities have addressed the traffic related air pollution issues from different perspectives. United States Environmental Protection Agency (EPA) has reduced pollution from new vehicles by establishing more stringent emission standards and cleaner fuel requirements. EPA also sets the health-based National Ambient Air Quality Standards (NAAQS) for pollutants that are emitted from on-road mobile sources and has recently required that air quality monitors shall be placed near high-traffic roadways for determining compliance with the NAAQS for NO2, CO, and PM2.5. Over the past years, EPA has also been conducting research to better understand the phenomenon of near roadway pollution, exposure and adverse health effects, and how to reduce air pollution near these high-traffic areas [3]. Zhang and Berkowicz explore physical modeling and simulation techniques to discover the traffic air pollution impact [4][5]. Devarakonda and Zhu have developed onboard mobile sensing system to measure air quality inside and outside of the vehicle [6][7]. OpenSense---a project run by EPFL and ETH Zurich, Switzerland, aims to study the feasibility of installing sensors on the roofs of buses and trams, and take advantage of the existing public transportation vehicles to form an extensive network of mobile air quality data collection sites [8]. However, there is no comprehensive solution and study about in-vehicle air pollution patterns and the possible ways to reduce exposure for driver by taking systematic approaches and considering the related factors such as weather, traffic, road structure, vehicle condition and car usage behaviors. To address this open problem, we have developed an intelligent in-vehicle air quality management solution and conducted empirical studies.

Intelligent in-vehicle air quality management solution

By leveraging Internet of Things (IoT) platform, as well as cloud and cognitive based analytics technologies, we have built an intelligent in-vehicle air quality management solution as illustrated in Figure 1. This solution employs three major modules: air quality sensor, eco-drive mobile app, and the Cloud based backend data management and analytics platform which collects data from the sensor, mobile app and other data sources such as weather, traffic and map, and then applies analytics to discover air pollution patterns and generates personalized advisor engagement with driver through the mobile app.

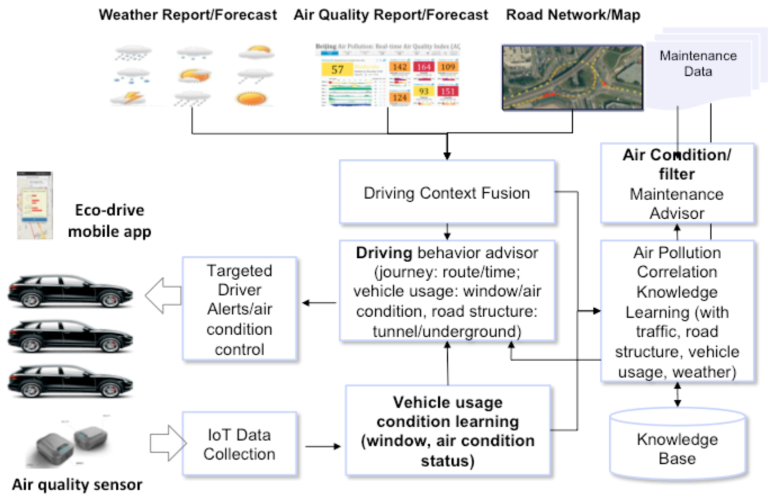

Figure 1– Intelligent in-vehicle air quality management solution framework

Air quality sensor

A device with a couple of air quality sensors is put into the vehicle measuring the air quality in real-time. The air pollution inside the vehicle is generated from multiple sources inside and outside the vehicle in the traffic environment. From inside vehicle sources point of view, the synthetic materials (plastics etc.) make up the vehicle's interior release toxic chemical gases into the air, and "new car smell" is actually an initial stronger release of these chemicals. The vehicle's plastic dashboard, seats, and carpeting release formaldehyde and other toxic chemical gases. This is called "out-gassing" and it affects all vehicles. From outside sources point of view, the traffic environment, especially the vehicle's exhaust emissions include GreenHouse Gases, most notably CO_2, as well as particulate matter, lead, nitrogen oxides, sulfur oxides and volatile organic compounds [9]. In our project, the major goal is to discover the air pollution patterns related with traffic environment, therefore we focus on more about the outside vehicle sources. We design the solution for consumers to improve their awareness of the air pollution associated with their mobility experience. Therefore we select an off-the-shelf device, as shown in Figure 2, with low cost commercial grade air quality sensors, especially for PM2.5 [10], Total Volatile Organic Compound (TVOC) [11], humidity, and temperature. More sensors could be added to the device in the future to support additional metrics such as CO, CO2, etc.

Figure 2– In-vehicle air quality sensor device

The PM2.5 sensors we choose uses laser light scattering based technology. It counts the particulates by tracking laser beam reflection. The TVOC sensor we use utilizes semiconductor-based technology. In the presence of a detectable gas, the sensor's conductivity increases depending on the gas concentration in the air. These sensors have good performance as illustrated in Table 1 and Table 2.

PM 2.5 Sensor	Unit: ug/m³
Range	0-500
Resolution	1
Accuracy	±10% (*in normal use)
Response	1s
Warm up	10s

Table 1. PM2.5 sensor performance

TVOC Sensor	Unit: ppb
Range	0-1000
Resolution	1
Accuracy	±20%
Response	1s
Consistent Accuracy	±15%
Warm up	90s

Table 2. TVOC sensor performance

One of the key issues of such low cost commercial grade sensors is the accuracy comparing with professional sensing systems which are usually adopted by government authorities or research centers. We have benchmarked the sensors we use with a few other professional use devices such as Dylos [12], and find that the variance of the measure stays in 5%~10% level. We have also conducted benchmark with government stationary sensing system's measurement as depicted in Figure 3. In Figure 3, X (in-car AIR device PM2.5 measurement) and Y (nearby government air station PM2.5 measurement) fit almost 1:1 (1:0.9683) linear equation.

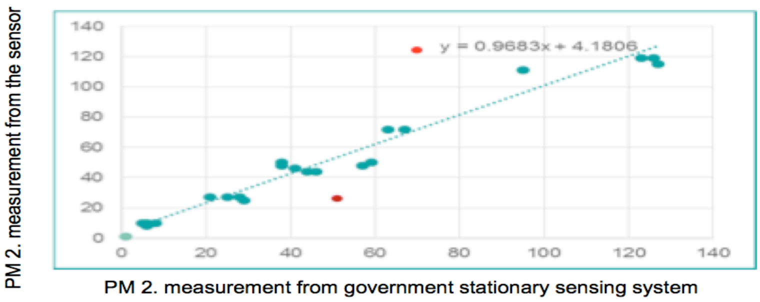

Figure 3– Air Quality sensor and stationary sensing system measurement benchmark

We have also conducted road tests using the sensors we choose, and developed the following findings. The PM2.5 reading has good performance to support the project, specifically:

- Reading's resolution could reach single digital reading such as 1 or 2
- Reading's variance range is within 15% comparing with nearby government air quality monitoring station reading
- Reading's change is very consistently aligned with the change of nearby government air quality monitoring station reading
- Reading's change responds to car usage conditions with very consistent patterns and high sensitivity with seconds of time

There is no ground truth PM2.5 reading even though we benchmark with government air quality monitoring station data, but the above performance characteristics could support the pilot by discovering in-vehicle PM2.5 change patterns, and advising driver to deal with PM2.5 pollutions by taking car usage and vehicle maintenance actions.

The TVOC sensor reading responds to traffic congestion, road structure and car usage condition consistently, specifically:

- Reading's change is very consistently aligned with different levels of traffic pollution produced by different levels of traffic congestion
- Reading's change responds effectively with road structure change (e.g. underground parking) and car usage condition change (e.g. window, air condition status)

There is also no ground truth TVOC reading to benchmark, but the above performance characteristics could support the pilot by discovering traffic pollution patterns, and advising driver to deal with traffic emission air pollution represented with TVOC reading related with traffic congestion and pollution zones through car usage behaviour and maintenance actions.

Eco-Drive mobile application

A mobile application, as shown in Figure 4, is provided to the travellers for tracking their air pollution exposure situations and advising actions they could take through voice based alerts.

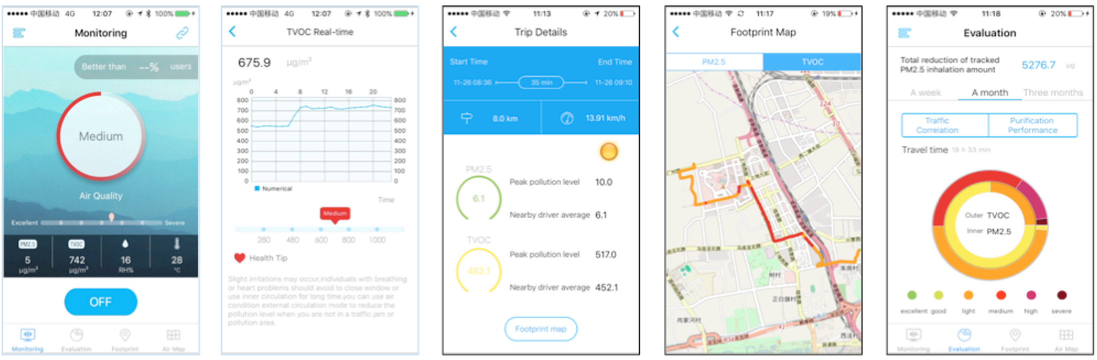

Figure 4– Intelligent in-vehicle air quality management solution mobile application

The key functions of the mobile application include:

- Air quality monitoring: provides real-time measurement of the air quality metrics such as PM2.5, TVOC, temperature and humidity, and highlights the pollution level
- Air quality metric real-time tracking: provides the air quality metrics' time series measurements over time
- Trip detail: provides the summary of a trip with information such as mileage, driving time, average speed, average PM2.5, and average TVOC
- Footprint map: provides visualization of the trip on a map with color-coded trip segments highlighting different air quality statuses during the journey
- Evaluation: provides statics of the user's air pollution exposure based on historical trips data through dashboard highlighting, and the percentage of different pollution levels of different air quality metrics during the user's total driving time
- Air quality rank: provides ranking capabilities for the users to do benchmark in the user community of the same city and encourage gamification activities for helping users to reduce air pollution exposure in their mobility experience
- Real-time alert: provides personalized advisory alerts guiding driver to take actions for reducing air pollution exposure in the trip by opening or closing window, switching air condition across inner and outer circulation with different win speed, etc. The alert is generated for each individual according to their driving behavior observations and profiling. For example, as shown in the Figure 5, when a vehicle follows a bus which has major exhaust emission problem inside a tunnel, the in-vehicle air quality metrics increase immediately. By detecting such air pollution event, a personalized alert will be generated and sent to the driver to advise switching air condition to inner circulation model and closing windows for avoiding more pollutant from getting into the vehicle

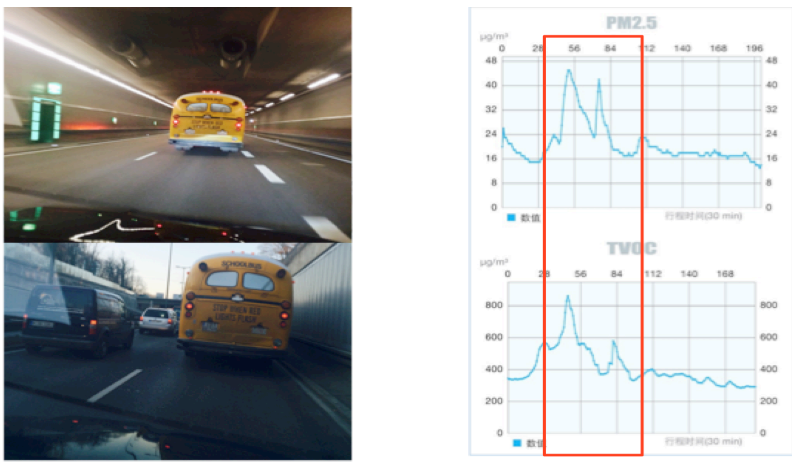

Figure 5– Dynamic air pollution event detection and alert

Cloud based backend data management and analytics platform

The cloud-based IoT platform supports collecting, managing and analysing the sensing data together with other contextual information---such as weather, traffic, road structure, through our data fusion engine. Cognitive analytics models applied to these data enable the learning and reasoning process for understanding the vehicle operation status in terms of window, air condition systems, and discover the correlation patterns between in-vehicle air pollution measurement metrics and related factors extracted from real-time sensing data streams as well as contextual data sources---weather pollution, traffic congestion, road structure like tunnel or underground parking. The travellers will also be advised to change their behaviours, such as departure time and route selection, vehicle window and air condition system configurations, and vehicle maintenance of air filter and exhaust gas processing system, to reduce their exposure to air pollution in the traffic.

As depicted in Figure 6, the key components of the platform in terms of the architecture include:

- Internet of Things (IoT) Gateway: provides the capabilities to collect streaming data from mobile app in high frequency, supports batch data transmission, and enables the alerts' transmission from the platform to the user's mobile application.
- Real-time Monitor and Alert Engine: provides the streaming data processing and analytics to understand and infer the air quality and the car usage conditions, and then generates personalized action alert.

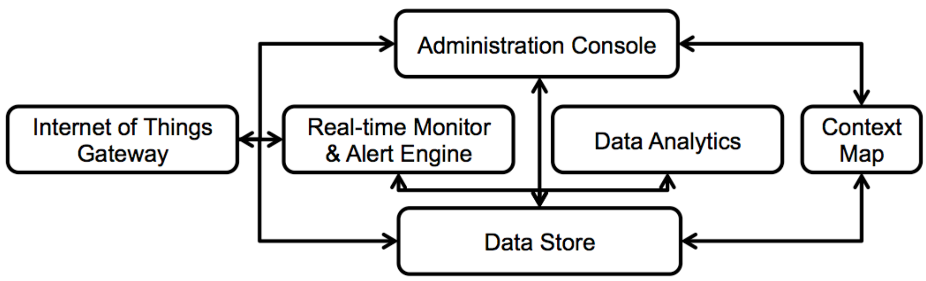

Figure 6– Cloud based backend data management and analytics platform architecture

- Context Map: provides the aggregated data sources on top of map including weather, city air pollution, road structure attributes, traffic, etc.
- Data Store: provides the management of all data from mobile app, context map and real-time engine.
- Data Analytics: provides data analytics infrastructure, statistic and machine learning models to discover the user's air pollution footprints, profile and benchmark, as well

as the correlation patterns with contextual factors, such as traffic or weather, and enable the prediction of the vehicles who need air filter or powertrain maintenance.

- Administration Console: as shown in Figure 7, provides the user interface for the administrator or operator to track all the vehicles and their air quality conditions with different color-coded moving icons on the map, users' air quality footprint and exposure profile dashboards, and maintenance advisor suggesting the users whose vehicle needs to do diagnosis or maintenance to improve air quality condition comparing with other users in the same city.

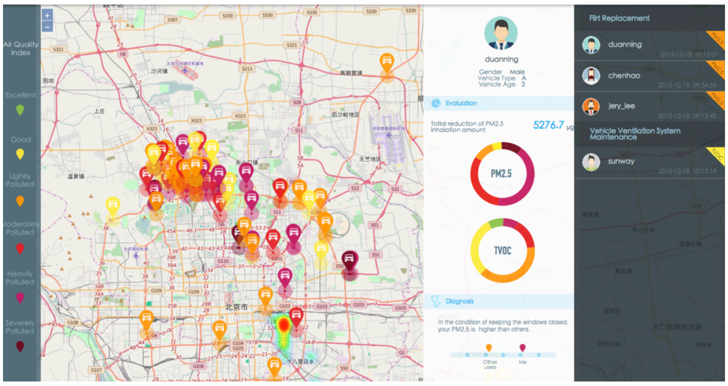

Figure 7– Cloud based backend data management and analytics platform console

Empirical studies

We have conducted a rich amount of empirical studies with multiple vehicles and drivers in several metropolitan cities worldwide---Beijing, Shanghai, New York, Las Vegas, and Munich, driving under different weather, traffic, and road type situations. Different configuration of vehicle and car usage context, are tested, namely: (i) various of vehicle usage behaviour, like opening window, closing window and turning on air condition (ii) various of car usage context, composed of weather, external air quality, traffic and road type. Figure 8(a) is an example of a single trip with different behaviour and running context. As illustrated from the figure, there is a significant gap between the in vehicle air quality and the outside air quality, the data of which is read from public available government air station of the same area. By utilizing our system, the air quality in the car dramatically improves if appropriate behaviour recommended are adapted. Through the data analytics, we summarize our key findings as below.

In-vehicle air quality varies a lot with different mobility contexts

In the same road segment of the same city, the in-vehicle air quality of different cars in different weather, traffic and maintenance conditions varies a lot. As shown in Figure 8, the vehicles coded with D9, A5, 22A, 4Q have very different TVOC reading metrics across multiple trips with different traffic, weather contexts. As a result, it is important for the travellers to know the patterns of the air pollution on the road, and then find an appropriate way to effectively reduce their air pollution exposure.

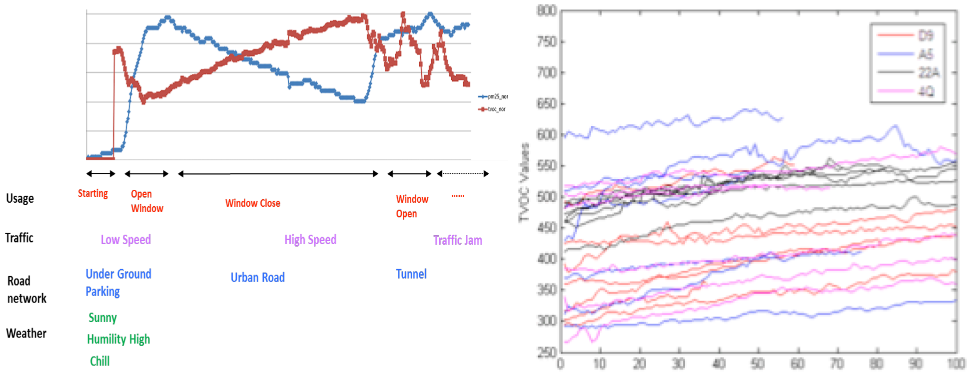

Figure 8- (a) One trip example of in car air quality change with vehicle, traffic and weather conditions; (b)TVOC measurement in the same road associates with vehicle, traffic and weather conditions

In-vehicle air quality changes effectively through car usage behaviour actions

Car usage behaviours such as window open/close and air condition inner/outer circulation on/off impact the in-vehicle air quality a lot. As illustrated in Figure 9, PM2.5 reading increases when the window opens with outside air getting into the vehicle, and decreases when the window closes. Especially if the air condition is on, the PM2.5 decreases even faster.

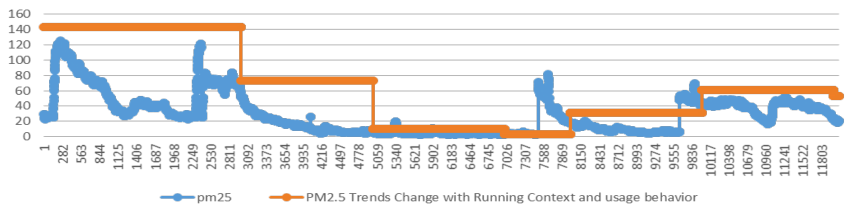

Figure 9- In-vehicle PM2.5 measurement changes with car usage behaviour actions

In-vehicle air quality changes effectively through car usage behaviour actions

Traffic pollution emission from other vehicles on the road brings instant impact to the in-vehicle air quality of a car in the traffic environment. As shown in the Figure 10, the speed of the vehicle is an indicator of the traffic congestion level, the lower speed means higher traffic congestion level. There is a clear correlation between TVOC measurement and the traffic congestion which produces more exhaust emissions in the particular congestion zone.

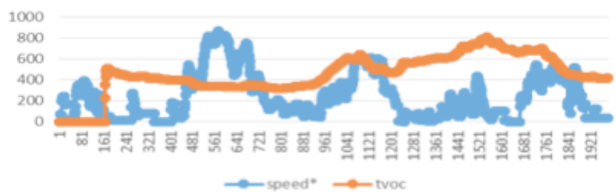

Figure 10- In-vehicle TVOC measurement changes with traffic conditions

In-vehicle air quality relates with vehicle maintenance conditions

Vehicle may have different maintenance problems which would lead to abnormal air quality inside the vehicle.

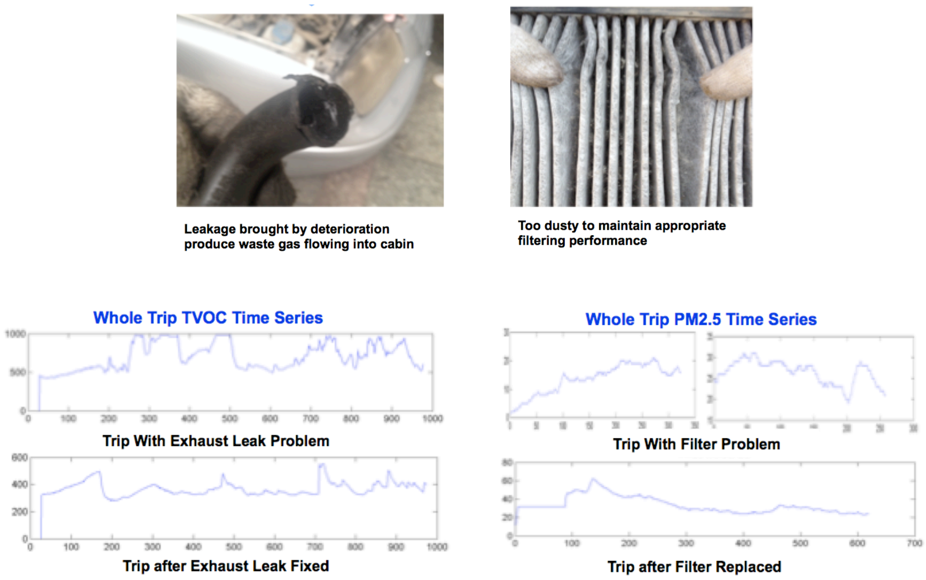

Figure 11- In-vehicle air quality relates with vehicle maintenance conditions

As illustrated in Figure 11, we used the solution to detect the maintenance problems of a test vehicle that has exhaust pipe leakage problem and air filter deterioration problem. These problems make the in-vehicle air quality much worse comparing with other vehicles in the same city operated in the same context. After the maintenance in the workshop, the air quality of the vehicle dramatically improves.

Finding the correlation between in-vehicle PM2.5 and related factors is important and can produce valuable insights. [13] Figure 12 shows our results of the correlation matrix between impact factors and the in car PM2.5 under different action status---opening window and air condition on. There are many interesting observations. For example, from the figure of the second column and first row of Figure 12, we can see that high pollution usually happens in the condition when the outside humidity is very high, especially when the temperature is also high, based on which we can alert the drivers to pay special attention for driving under such conditions. As another example, the green square points ratio, which represents the trip segments that have in-vehicle PM2.5 less than 25, when the air condition is on (right figure) is much higher than the condition where the window is open (left figure). This indicates that turning on the air condition can reduce the PM2.5 exposure, and thus is advised when outside air quality is poor, while opening the window in such environment is highly not recommended, which is consistent with our previous analysis.

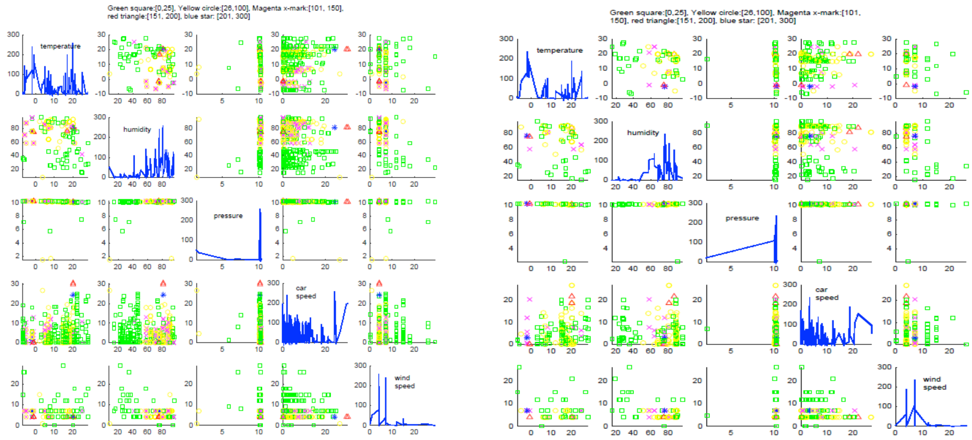

Figure 12-Correlation between impact factors and the in-vehicle PM2.5.

Conclusions

Through the empirical studies, it is clear that such an in-vehicle air quality monitoring and management solution could effectively disclose air pollutions patterns in the traffic environment and suggest travellers to better plan their trips as well as operate their vehicles to reduce air pollution exposure. In summary, the followings are several key findings we would like to highlight:

- Traffic congestions directly impact in-vehicle air pollution on the road, as demonstrated by TVOC measurement's increase in such environment. This is a invariant pattern independent with the vehicle's location across the cities worldwide. Travellers should avoid traffic congestion to get the benefit of reducing air pollution exposure on the road.
- Vehicle usage and maintenance behaviours, such as window, air filter, air condition system configurations, directly impact in-vehicle air quality. Travellers should get trained and be advised to take appropriate vehicle control and maintenance actions in different situations.
- Road structure type the vehicle goes through, such as tunnel, underground parking, and the lead vehicle type in the traffic such as truck, bus with significant exhaust emission problems, have direct and immediate impact to the in-vehicle air quality. Travellers should avoid staying in such circumstances for long time and make sure that the windows get closed and air condition switches to inner circulation mode.

Moving forward, we plan to do further research and empirical studies considering more air quality measurements such as CO, CO2, and NO2. Also we are developing fine grained air quality prediction models associated with road, traffic and weather conditions, and explore physical air flow and chemical simulation models, to discover more traffic pollution insights and support sustainable traffic management and green mobility experiences for travellers by taking appropriate measures.

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