

# Personal Exposure to PM<sub>2.5</sub> in the Various Microenvironments as a Traveler in the Southeast Asian Countries

<sup>1</sup>Semih Ozler, <sup>2</sup>Karoline K. Johnson, <sup>2</sup>Michael H. Bergin and <sup>1</sup>James Jay Schauer

<sup>1</sup>Department of Civil and Environmental Engineering, University of Wisconsin-Madison, 53706, Madison, WI, USA

<sup>2</sup>School of Civil and Environmental Engineering, Duke University, Durham, NC, 27708, USA

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Corresponding Author:

Semih Ozler

Department of Civil and Environmental Engineering,  
University of Wisconsin-Madison, 53706, Madison, WI, USA

Email: ozler@wisc.edu

**Abstract:** Air pollution has become a pressing issue in today's society because of its significant effects on humans, animals, plants, air quality, climate and the wider environment. Most urban areas are associated with one or more air pollutants which are emitted from local or regional pollution sources including vehicle exhausts, fossil fuels using in energy production, emissions from industrial and mining activities, agricultural and construction operations, household usage of chemicals and materials and natural causes. Most personal exposure studies are focused on local environments and short-term periods. Previous controlled experiments and studies were done in a small number of designated areas in cities. Our research study used time-based activity data; 3 main and 17 sub-microenvironments were applied over 37 days-long research while traveling through Southeast Asian countries. In this study, personal exposure of PM<sub>2.5</sub> for a traveler was monitored using an assembled low-cost monitor with Plantower PMS 3003 PM<sub>2.5</sub> sensor which has a light-scattering principle. All time-based activity data was recorded with a smartphone whenever microenvironments changed during the study period. The goal of this study was to understand more about the personal exposure to PM<sub>2.5</sub> related air pollution in the global travel environment as a traveler and to understand how an individual's activity and location impact PM<sub>2.5</sub> exposure. According to the results from the Southeast Asia study, the personal PM<sub>2.5</sub> exposure varied in the categorized microenvironments. Port/Station (outdoor) and Café/Pub/Restaurant (indoor-outdoor) were the most polluted microenvironments with 32.8 and 29.6 µg/m<sup>3</sup> 1-h mean PM<sub>2.5</sub> concentration, respectively. Market/Shopping Mall (indoor), Street (outdoor) and Cable Car/Metro/Tram (vehicle) were also concerning microenvironments with 19.3, 19.3 and 18.9 µg/m<sup>3</sup> 1-h mean PM<sub>2.5</sub> concentrations, respectively. Passenger Car microenvironment had the lowest 1-h mean PM<sub>2.5</sub> concentration of 2.3 µg/m<sup>3</sup> which agrees with some other studies on transportation microenvironments in the literature.

**Keywords:** Air Pollution, Fine Particulate Matter (PM<sub>2.5</sub>), Personal Exposure, Microenvironments, Low-Cost Sensors

## Introduction

Within the last two decades, urban air pollution from large cities has been recognized as one of the world's most concerning environmental issues (Koçak *et al.*, 2011; Yusuf and Resosudarmo, 2009). Most developing countries, following a general trend, have experienced rapid growth including urbanization, urban sprawl, vehicle ownership and industrialization which is reflected in pollutant emissions to the atmosphere. Urbanization not only affects the nearby landscape, air

quality, regional climate and ecosystems of the polluting cities but also affects areas downwind of these regions despite recent improvements in air pollution science, air pollution control technologies and public awareness (Molina *et al.*, 2004). Air pollution remains a massive challenge due to continuing uncontrolled emission discharges, inadequate environmental regulations, poor governmental control mechanisms, individual consumption behaviors and rebound effects of technological improvements for many city dwellers and travelers (Akimoto, 2003).

Moreover, the World Health Organization (WHO) states that 92% of the world's population lives in cities and metropolises where PM<sub>2.5</sub> concentration levels exceed the WHO suggested PM<sub>2.5</sub> concentration limits which are 10 µg/m<sup>3</sup> annual mean and 25 µg/m<sup>3</sup> 24-h mean (2017). Those limits are suggested as guidance to reduce the health impacts of air pollution, but they are not legally binding policies. Many countries don't have any regulations related to PM<sub>2.5</sub>. Some countries regulate PM<sub>2.5</sub> with higher concentration values than WHO's guidelines; this makes it difficult for some cities to comply with the WHO's ambient air quality guidelines (Molina *et al.*, 2004; Sharma *et al.*, 2013). Reported measurements from those cities far exceed WHO's guidelines, resulting in millions of premature deaths (Lim *et al.*, 2012). As seen in the dataset from WHO, there is a large variation in PM<sub>2.5</sub> exposure across different countries and continents. The highest annual average urban PM<sub>2.5</sub> concentration is 127 µg/m<sup>3</sup> in Saudi Arabia and the lowest average urban PM<sub>2.5</sub> concentration is 5 µg/m<sup>3</sup> in New Zealand and Brunei Darussalam. In addition to that, only 19 countries comply with WHO's suggested annual mean PM<sub>2.5</sub> concentration limits. The remaining 160 countries exceed those levels, ranging from 11 to over 100 µg/m<sup>3</sup> (2017). It is not surprising that PM<sub>2.5</sub> related air pollution is a global environmental health problem that affects people worldwide, but low-income and middle-income countries experience this burden more than high-income countries.

Moreover, a new conceptual framework about Earth systems, planetary boundaries, was developed by a group of environmental scientists in 2009 (Rockström *et al.*, 2009). They identified nine planetary boundaries that must not be surpassed in order to maintain global sustainability. It is believed that exceeding one or more planetary boundaries may be deleterious or even catastrophic due to the risk of triggering non-linear, abrupt environmental change from continental to planetary-scale systems (Rockström *et al.*, 2009; Steffen *et al.*, 2015). Atmospheric aerosol loading is one of the most important subjects in the planetary boundaries report because of the influence of aerosols (suspended particles in the atmosphere) on climate systems and their adverse acute and chronic effects on human health (Knibbs and de Dear, 2010; Rockström *et al.*, 2009; Steffen *et al.*, 2015). Although it is hard to determine the exact effects and mechanisms of atmospheric aerosol loading due to the complex composition of particles and gases that are involved in the aerosol production, their atmospheric chemistry and the spatial and temporal dynamics of pollutants.

Long-term exposure of PM<sub>2.5</sub> has been associated with allergies, respiratory diseases, cardiovascular problems and lung cancer; these health outcomes result in increased mortality, morbidity and hospital admissions (Kingham *et al.*, 2013; Wang *et al.*, 2011). The Global Burden of Disease study showed the significant role of air pollution as a global player,

placing it among the top ten risks factors faced by human beings (Lim *et al.*, 2012). According to the summary report of WHO's "Burden of Disease", 4.3 million deaths globally were attributable to household air pollution and 3 million deaths were attributable to ambient air pollution in 2012 (2012). According to the Institute for Health Metrics and Evaluation (IHME)'s dataset, it was estimated that outdoor air pollution resulted in 4.2 million deaths in 2016; this represents an increase from 3.4 million in 1990. Overall, the majority of pollution-related deaths are in South Asia, East Asia and Southeast Asia which alone accounted for nearly 3 million deaths in 2016 (OWiD, 2018). Moreover, as stated in Giannadaki's *et al.* (2016) study, the global premature mortality by PM<sub>2.5</sub> was estimated at 3.15 million/year in 2010. These studies show that PM<sub>2.5</sub> is a global actor and responsible for millions of premature deaths. As stated in Steinfeld's *et al.* (2015) study, controlling air pollution not only directly reduces adverse health effects but also increases general well-being, quality of life, public health and can have positive impacts on the environment in those countries and regions.

Monitoring air pollutants and measuring their ambient concentration is important because regulatory decisions and policies by governmental agencies are made based on those data. As a worldwide application, ambient air pollution concentrations for various air pollutants are measured using instruments such as Fixed Monitoring Stations (FMSs). Although these instruments are reliable and the reliability of the measured data is ensured by applying standard procedures for calibration, data collection and post-processing, these instruments are designed for research purposes (Kumar *et al.*, 2015). In addition, they are generally not user-friendly and require experienced users to operate them due to their complexity. Moreover, they are expensive and a significant amount of investment is required to maintain and regularly calibrate them. Often, small quantities of FMSs are used at designated sampling points (Kumar *et al.*, 2015) which leads limited spatial coverage in many places (Gao *et al.*, 2015). In many cases, these monitoring stations are placed in secured areas with lower human interaction. Additionally, it is preferred to locate FMSs away from roadsides, crowded city centers, industrial zones and major traffic congestion areas where local ambient air quality is affected by various emissions from diverse sources. This distribution method/preference often fails to represent the localized air quality data, local air pollution trends and the actual exposure levels of air pollutants (Kumar *et al.*, 2011; Wang *et al.*, 2011; Gao *et al.*, 2015). The current networks fail to capture spatiotemporal variations of air pollutants (Gao *et al.*, 2015) and as a result, PM<sub>2.5</sub> exposure may be significantly underestimated (Meng *et al.*, 2012). A study in New York showed that the real-time exposure to PM<sub>2.5</sub> can be between 20-200% higher than the readings from local FMSs (Wang *et al.*, 2011). Similar studies that examined personal exposure in different transportation

microenvironments found that individuals may be exposed to much higher ambient PM<sub>2.5</sub> concentrations than local FMSs indicated (de Nazelle *et al.*, 2012; Int Panis *et al.*, 2010; Kaur *et al.*, 2005; 2007).

A new and innovative method of measurement, low-cost monitors, may present a possible solution to the problems with FMSs. Technological improvement and continued development of low-cost sensing technology have made low-cost monitors less expensive, easier to deploy, operate and manage than traditional systems. Low-cost monitors can be deployed in significant numbers for the same price as a single FMS. By doing so, it is easy to create monitoring networks for designated areas or even cities, calculate emission inventories of various pollutants, measure real-time short-term and long-term exposure of users in some designated areas, detect pollution hotspots and high concentration zones and with the help of this more accurate data, focus on air pollution mitigation strategies (Steinle *et al.*, 2013; 2015; Gao *et al.*, 2015). These monitors can be used by individuals or researchers to understand real personal exposure values in different microenvironments. Low-cost monitor networks especially help to provide a more detailed picture of indoor air quality and reliable data about indoor air quality levels, which is quite important since people spend most of their time in indoor environments (Steinle *et al.*, 2015). Some low-cost PM sensors have been evaluated for their performance in designated field and laboratory studies that found these PM sensors were promising for the future applications and useful as monitoring equipment both indoors and outdoors (Austin *et al.*, 2015; Chen *et al.*, 2017; Gao *et al.*, 2015; Holstius *et al.*, 2014; Kelly *et al.*, 2017; Marques *et al.*, 2018; Wang *et al.*, 2015). Moreover, some projects exist that are dedicated to measuring ambient air concentrations of pollutants in the urban areas with low-cost monitors. Some such initiatives are the OpenSenseMap project (2017) which is mainly used by European users, OpenAQ (2017) and Purple Air platform (2017) which have active users both in Europe and in the United States. Air quality data collected from low-cost monitors that are connected to the internet is shared online for the users, public and researchers.

Many particulate matter exposure studies are done using sensors in local environments to address the exposure of selected study groups like pedestrians, city dwellers, commuters, car drivers and cyclists in different transportation environments. Often, findings are different both between and within studies due to different urban settings, cities' vehicle fleet, regional traffic configuration and congestion level, local emission profiles, ambient pollutant concentrations and meteorological conditions (de Nazelle *et al.*, 2012; Int Panis *et al.*, 2010; Kaur *et al.*, 2005; 2007; Kingham *et al.*, 2013; Knibbs and de Dear, 2010; Steinle *et al.*, 2015; Strak *et al.*, 2010; Thai *et al.*, 2008; Wang *et al.*, 2011). In contrast, this study's main framework will focus on a single traveler, including his

daily activity and the total exposure of PM<sub>2.5</sub> in 3 main microenvironments and 17 sub-microenvironments. Travelers are an important group that tend to have high personal exposure levels not only to PM<sub>2.5</sub> but also other pollutants. They can be a concerned group of people because the aims of traveling including exploring new destinations, seeing unfamiliar places, discovering new cultures and traditions, meeting new people and trying new foods and drinks in the relatively short amount of time, lead to prominent levels of body activity. High body activity results in a large increase in breathing frequency and tidal volume which influences their inhaled dose of air pollutants and increased deposition on the target's lung tissues (Int Panis *et al.*, 2010; de Nazelle *et al.*, 2012). It is well-explained in another study that higher concentrations of PM<sub>2.5</sub> don't negate the health benefits of physical activity, but they do decrease the advantages of increased physical activity (Tainio *et al.*, 2015). In this research approach, we believe that understanding more about personal exposure to PM<sub>2.5</sub> related air pollution is not only important for global travelers but also the local populations.

## Materials and Methodology

### *Study Area and Travel Plan*

During the study period, Thailand, Cambodia, Singapore, Taiwan, Hong Kong, Macau, Qatar and the United States (17 cities: Bangkok, Ayutthaya, Phetchaburi, Hua Hin, Pattaya, Sattahip, Aranyaprathet, Poipet, Siem Reap, Phnom Penh, Singapore, Taipei, Hong Kong, Macau, Doha, Chicago and Madison) were visited in 37 days. A summarized Southeast Asia travel plan is shown in Fig. 1. There was no pre-designated travel plan or time distribution in the countries in order to mimic the unpredictable travel choices of a solo traveler. 18 days were spent in Thailand, 6 days in Cambodia, 3 days each in Singapore and Taiwan, 6 days in Hong Kong (nearly half of the day in Macau) and the rest of the activity data was recorded on the way back to Madison, WI, US through Doha, Qatar and Chicago, IL, US. The travel dates and times spent in each country, in addition to maximum, minimum and mean recorded PM<sub>2.5</sub> concentrations during those times are shown in Table 1. Not all recordings are well-represented for all the listed countries due to the limited travel and recording time in cities such as Doha, Qatar. It is believed that others such as Thailand, Cambodia, Singapore, Taiwan and Hong Kong were well represented because a relatively long amount of time was spent in the various microenvironments.

### *Microenvironments Approach*

A microenvironment was described as a small space in which human contact with a pollutant takes place and

which could be treated as a well-characterized, relatively homogenous locations with respect to pollutant concentrations for a specified time in Özkaynak's *et al.* (2008). Moreover, the microenvironments approach is commonly used in personal exposure and air quality studies to understand the effects of different variables on ambient PM<sub>2.5</sub> concentration. Indoor, outdoor and vehicle environments generally have different air pollution

statistics and dynamics even though indoor and vehicle microenvironments are affected directly by outdoor microenvironments. In this study, 3 main-microenvironments and 17 sub-microenvironments were categorized and listed in Fig. 2. This approach was utilized in this study to understand the effects of different microenvironments on personal exposure of PM<sub>2.5</sub> while traveling in different countries.

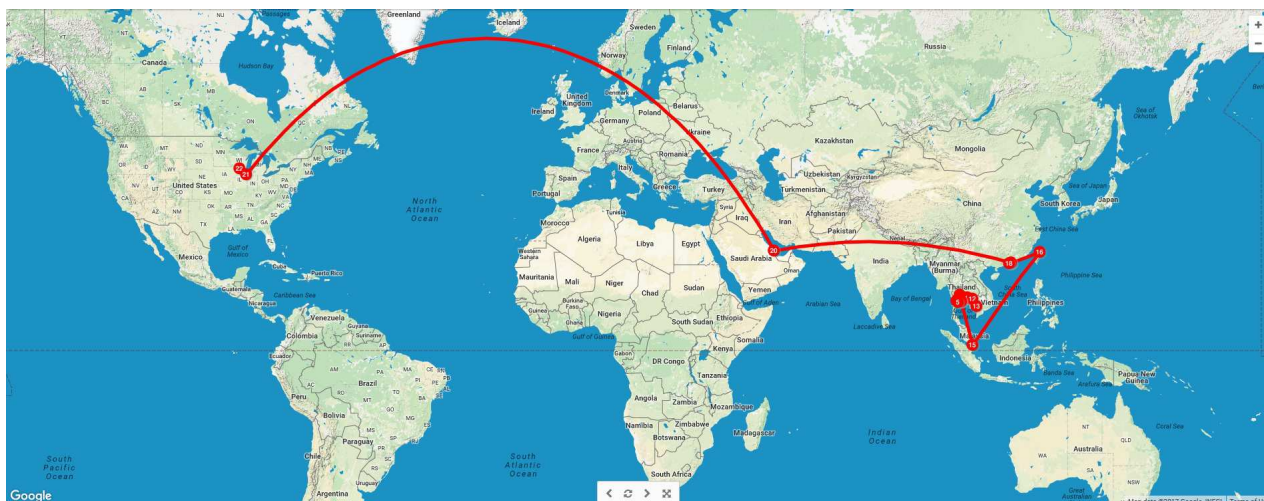


Fig. 1: Summarized Southeast Asia travel plan on the world map

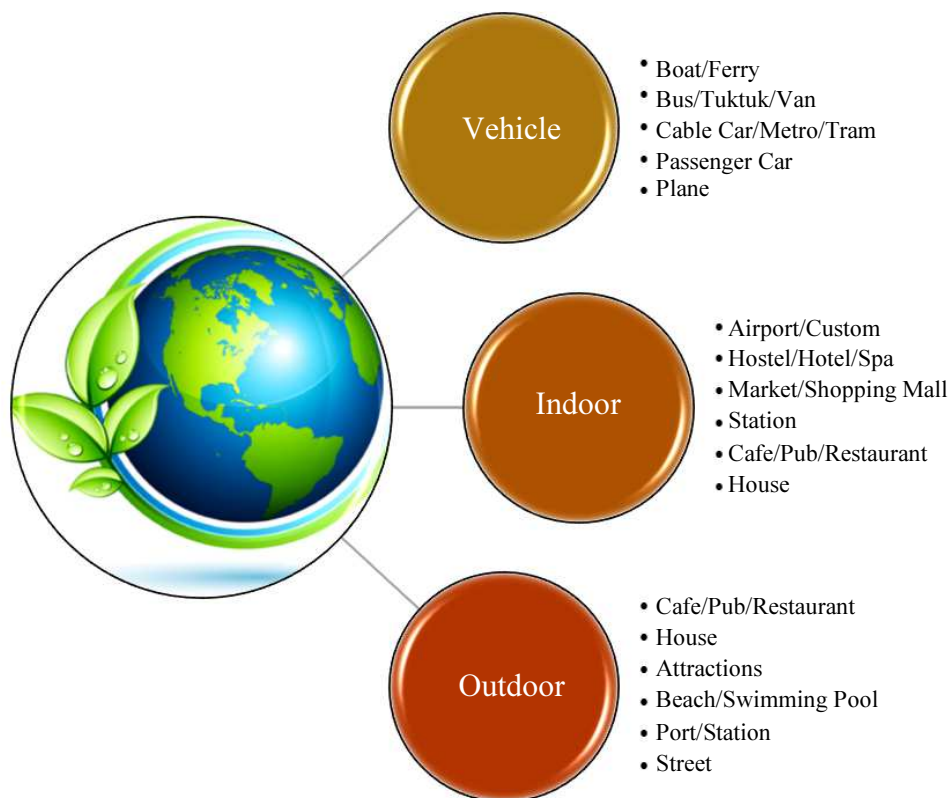


Fig. 2: 3 main-microenvironments and 17 sub-microenvironments approach for this study

**Table 1:** Summary of time spent and measured 1-h mean PM<sub>2.5</sub> concentrations (µg/m<sup>3</sup>) in each country in 2017

Dates	Time Spent	Country	Mean PM <sub>2.5</sub>	Max PM <sub>2.5</sub>	Min PM <sub>2.5</sub>
24.06-05.07	416 hrs.	Thailand	9.6	525	0
11.07-18.07	15 mins.				
05.07-11.07	132 hrs. 24 mins.	Cambodia	14.7	1,142	0
18.07-21.07	68 hrs. 3 mins.	Singapore	16.5	209	0
21.07-24.07	65 hrs. 28 mins.	Taiwan	10.9	161	0
24.07-28.07	134 hrs.	Hong Kong and Macau	16.0	162	0
28.07-28.07	24 mins.				
28.07-30.07					
30.07-30.07	2 hrs. 51 mins.	Qatar	12.4	18	0
30.07-30.07	9 hrs. 4 mins.	USA	6.7	25	0

**Table 2:** Summary of time spent and measured 1-h mean PM<sub>2.5</sub> concentrations in each 17 microenvironments

Microenvironments	Recorded-time (mins.)	Percent Rate (%)	1-h Mean PM <sub>2.5</sub> in µg/m <sup>3</sup>	PM <sub>2.5</sub> Exposure in µg-hour/m <sup>3</sup>
Hostel/Hotel/Spa	15,778	32	9.6	2,524.5
House	13,374	27	6.4	1,426.6
Street	5,526	11	19.3	1,777.5
Attraction	3,239	7	16.9	912.3
Café/Pub/Restaurant	2,938	6	29.6	1,449.4
Passenger Car	1,695	3	2.3	65.0
Bus/Tuktuk/Van	1,468	3	11.3	276.5
Market/Shopping Mall	1,300	3	19.3	418.2
Airport/Custom	1,176	2	13.8	270.5
Cable Car/Metro/Tram	1,093	2	18.9	344.3
Station	864	2	13.6	195.8
Boat/Ferry	475	1	8.4	66.5
Beach/Swimming Pool	379	1	10.6	67.0
Port/Station	361	1	32.8	197.4
Plane	27	0	9.4	4.2
TOTAL	49,693	100		

During the study, the monitor was actively recording PM<sub>2.5</sub> concentrations for about 49,693 min (around 828.22 h/34.51 days). The non-recording time was about 2,991 min (around 49.85 h/2.08 days), due to file copying from a micro-SD card into the computer, changing the drained battery, closing the monitor because of the security checks at the airport, security concerns during international flights and some other unforeseen issues. According to the activity log data, around 59% of the total recording time was spent indoors, 31% outdoors for travel activities and 10% in vehicles for transportation purposes. Table 2 shows a more detailed picture of the total time spent in 17 sub-microenvironments. 32% and 27% of the total recorded time was spent in Hostel/Hotel/Spa category and House category, respectively. It was obvious that the main PM<sub>2.5</sub> exposure occurred in indoor environments; although some of the recorded logs are related to outdoor PM<sub>2.5</sub> concentration in the House category. This is consistent with a previous literature study with a

similar result (Steinle *et al.*, 2015). 11% and 7% of the total recorded time were related to high-level outdoor activities such as walking, hiking and cycling in the Street and Attraction categories respectively. 6% of the total recorded time was also spent in both indoor and outdoor-based activities in Café/Pub/Restaurant category. The total remaining recorded time was spent in other various microenvironment categories which are listed in Table 2.

#### *The Study Participant/Traveler*

The study participant/traveler was trained to use the monitor before beginning to travel. He had the related Health, Safety and Environment training and gained proper information on how to use the designated research equipment during his travel. He was also provided with a written operational manual. He was informed to choose his daily activity and trip plan randomly, but he was requested to record all microenvironment changes and their times into his smartphone. A set of data which is

related to the 3 main and 17 sub-microenvironments and the time series of the microenvironmental change were gathered by using the notes from his smartphone. Temperature, humidity, 1-min averaged  $PM_{2.5}$  concentrations and time information were gathered from the research equipment itself.

### Research Equipment

During the study period, an assembled low-cost monitor was used. It had a Plantower PMS 3003  $PM_{2.5}$  sensor which was evaluated in controlled laboratory and ambient environmental conditions in the previous studies and presented a reliable performance (Kelly *et al.*, 2017; SCAQMD-AQ-SPEC, 2017a; 2017b; 2017c). The Plantower PMS 3003 uses the light-scattering principle for particle counting. A fan is employed to draw air through a measurement chamber.  $90^\circ$  scattered light is detected by a photo-diode detector and the data is converted to a mass distribution ( $\mu g/m^3$ ). The laser wavelength was estimated to be around  $650 \pm 10$  nm. According to the manufacturer, it detects PM in the range of  $0.3 \mu m$  to  $10 \mu m$ , it has a 10-s response time and its counting efficiencies are 50% @  $0.3 \mu g/m^3$  and 98% @  $> 0.5 \mu g/m^3$  (Kelly *et al.*, 2017). The assembled low-cost monitor and its parts are shown in Fig. 3. The teensy microcontroller, clock, humidity and temperature sensors were the main parts

of the research equipment. Other than these main system parts, some secondary parts included the protection case, voltage regulator, barrel jack power cable, LED indicator, micro-SD card and battery. The research equipment is user-friendly and easy to operate. There is no on/off button or screen that can make things complicated for users. When it is plugged into the energy source, the LED light indicator starts blinking and then continues to blink until it is unplugged from the energy source. It weighs 0.3 kg without the battery and its dimensions are  $15.5 \times 8.5 \times 4.5$  cm which makes the instrument easy to carry.

A 30 L hiking backpack with side pockets was used to carry the instrument with its inlet facing up for proper air uptake into the sensor's chamber. The backpack was generally worn in the outdoor microenvironments and it was kept close to the bearer by placing it on a table, chair, seat, or the bearer's lap when it wasn't being worn in some of the vehicle and indoor microenvironments (Fig. 4). The assembled low-cost monitor can run approximately 55 h with used 10400mAh battery, but this running time is slightly affected by environmental conditions such as temperature. During the study period, two batteries were used. Either every day or two days in a row the used one was replaced with fully charged one. Moreover, an 8 GB micro-SD card was used for proper data storage or management.

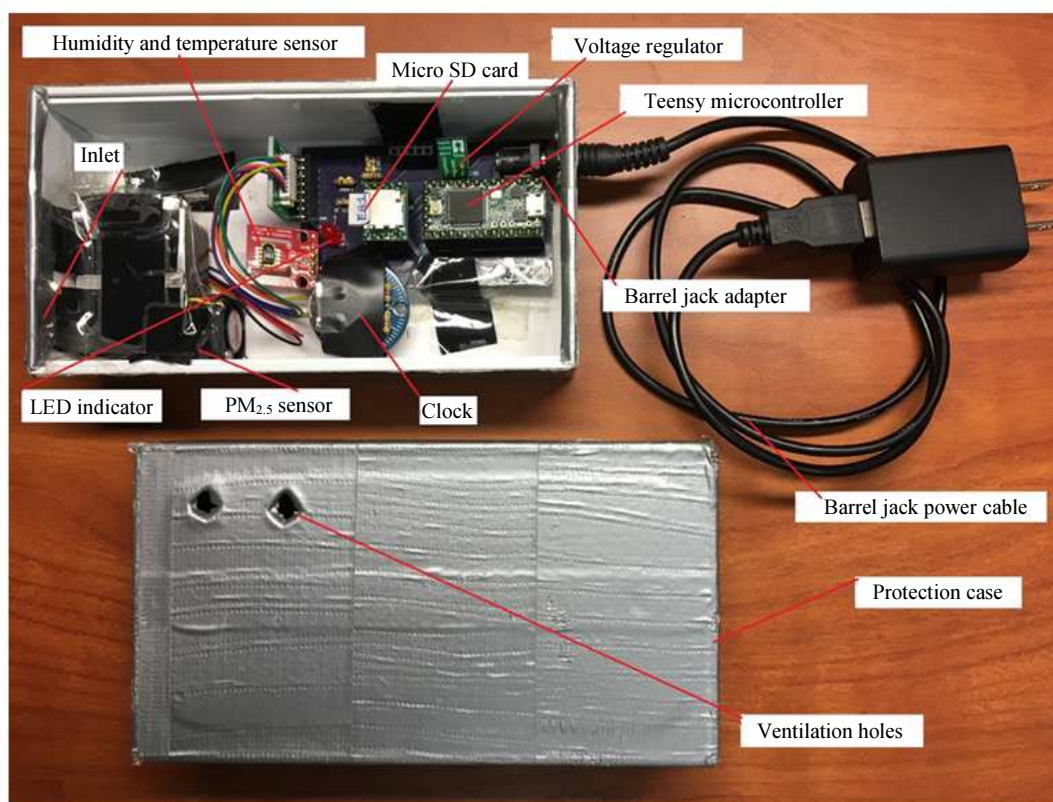


Fig. 3: Description of the assembled low-cost monitor



**Fig. 4:** The backpack set up for the low-cost monitor

### *Data Collection, Management and Processing*

The data was collected for 37 days from June 24, 2017 to July 30, 2017 by using the assembled low-cost monitor. Once the data was moved from the micro-SD card to the computer as a .txt file, the unnecessary data including startup information of the monitor for each start was deleted and then the cleaned data was converted into a .csv file to input microenvironments and countries data manually with using recorded notes data from the smartphone. After inputting, processing and checking the data carefully, the final datasets were prepared. A spreadsheet application Microsoft Excel, a word processor Microsoft Word, a programming language for statistical computing and graphics RStudio and a simple raster graphics editor Microsoft Paint were used to create  $PM_{2.5}$  related figures and tables for this study.

## **Results**

### *Previous Performance Evaluations of Plantower PMS 3003 Low-cost Sensor*

A previous study focused on assessing the performance of a Plantower PMS 1003 sensor against one of the Federal Reference Method (FRM), two of the Federal Equivalent Methods (FEM) (TEOM and Sharp) and a research-grade monitor (GRIMM) under ambient  $PM_{2.5}$  concentrations in Salt Lake City, Utah during winter. They compared 1-h averaged data from the measurements and they found high  $PM_{2.5}$  correlations with FEMs ( $R^2 = 0.82-0.92$ ) and the research-grade instrument (0.83-0.93) (Kelly *et al.*, 2017). Another study focused on using a Plantower PMS 3003 sensor and an Unmanned Aerial Vehicle (UAV) to gather environmental data including temperature, humidity and

$PM$  in Nan province of Thailand. Before starting their field research, they tested the Plantower PMS 3003 sensor against a FEM (TEOM). Their 1-h averaged data showed low  $PM_{2.5}$  correlations with TEOM ( $R^2 = 0.66$ ) (Chunitiphisan *et al.*, 2018).

Another study from the South Coast Air Quality Management District (SCAQMD) - Air Quality Sensor Performance Evaluation Center (AQ-SPEC) focused on field-testing commercially available low-cost monitors such as the Laser Egg Sensor (Plantower PMS 3003), the PurpleAir (Plantower PMS 1003) and the PurpleAir PA-II (Plantower PMS 5003) (2017a, b, c). They collocated these monitors next to a FEM (BAM) and a research-grade monitor (GRIMM) under ambient environmental conditions in Southern California and compared 1-h averaged data from the measurements. They reported low  $PM_{2.5}$  correlations for the Plantower PMS 3003 with a BAM ( $R^2 = 0.57$ ), high  $PM_{2.5}$  correlations for the Plantower PMS 1003 with a GRIMM ( $R^2 = 0.91$ ) and medium  $PM_{2.5}$  correlations for the Plantower PMS 1003 with a BAM ( $R^2 = 0.77$ ) and high  $PM_{2.5}$  correlations for the Plantower PMS 5003 with a GRIMM ( $R^2 = 0.93$ ) and a BAM ( $R^2 = 0.86$ ) (2017a, b, c).

A recent study campaign was designed to evaluate the performance of Plantower PMS 3003 sensors under ambient  $PM_{2.5}$  concentrations. During the first stage of their study, they deployed the Plantower PMS 3003 sensors to low  $PM$  concentration suburban regions of Durham, North Carolina. At the first site, those sensors were compared to an E-BAM and at the second site, they were compared to FEMs (Sharp and TAPI T640). They reported low  $PM_{2.5}$  correlations with the E-BAM ( $R^2 = 0.41$ ) at the first site, both low  $PM_{2.5}$  correlations with the SHARP ( $R^2 = 0.28$ ) and medium  $PM_{2.5}$  correlations with the TAPI T640 ( $R^2 = 0.70$ ) at the second site. Then they

deployed those sensors to high concentration urban locations of Kanpur, India to compare their results with the E-BAM. They reported low PM<sub>2.5</sub> correlations for Plantower PMS 3003 sensors with the E-BAM ( $R^2 = 0.61$ ) during monsoon season and medium PM<sub>2.5</sub> correlations ( $R^2 = 0.78$ ) during the post-monsoon season (Zheng *et al.*, 2018).

### Results from Southeast Asia Study

Figure 5 gives brief information about the total measurements from the monitor for PM<sub>2.5</sub> exposures on selected days. All the concentration values that were used for graphing were 1-min averaged PM<sub>2.5</sub> concentration. 3 days (June 25, 2017 - in Thailand, July 2, 2017 - in Thailand and July 8, 2017 - in Cambodia) were selected to show prominent levels of PM<sub>2.5</sub> exposure while engaging in travel activities. The highest recorded concentration was 1,142 µg/m<sup>3</sup> in an Outdoor – Café/Pub/Restaurant microenvironment while being exposed to tobacco smoke of the cigarette users around the pub. The second highest was 525 µg/m<sup>3</sup> in an Indoor – Café/Pub/Restaurant microenvironment with exposure to hookah and tobacco smoke from the cigarette and hookah users in the café. This recorded value was lower than the first one even though they had a similar pollution source. The differences may have been related to distance from the pollution source, dilution effects of the air and wind, the position and placement of the monitor and the average ambient concentration of PM<sub>2.5</sub> in those microenvironments. The third highest PM<sub>2.5</sub> concentration value was 492 µg/m<sup>3</sup> in an Outdoor – Attraction microenvironment while being exposed to smoke from burning candles and incenses around the temple. As stated in Int Panis's and Gao's paper, the health effects of short bursts of high exposure to PM<sub>2.5</sub> in contrast to chronic exposure are not well understood (Int Panis *et al.*, 2010; Gao *et al.*, 2015).

Table 3 summarizes annual mean ambient PM<sub>2.5</sub> concentrations of traveled countries from various data sources such as The Organization for Economic Cooperation and Development (OECD, 2017), the World Health Organization (WHO, 2018), The World Bank (2017), State of Global Air (2017) and the Southeast Asia study result. As can be seen from the table, all recordings from the study are lower than the countries' yearly statistics from the given sources. Although PM<sub>2.5</sub> concentration values from the Southeast Asia study are very similar to the United States and Singapore and relatively similar to Cambodia, they are not well matched with WHO's country statistics shown in Table 3. Moreover, the same pattern is observed when the Southeast Asia study's outdoor 1-hour mean PM<sub>2.5</sub> concentrations are compared to WHO's country statistics except in the United States, Singapore and Qatar where concentrations are lower for the United States, higher in Singapore and there is no outdoor data for Qatar.

Figure 6 shows WHO's suggested 24-h mean PM<sub>2.5</sub> concentration limit as a green line which at 25 µg/m<sup>3</sup>, WHO's annual mean ambient PM<sub>2.5</sub> concentration data for each country as a red triangle and 1-h mean PM<sub>2.5</sub> concentrations from the Southeast Asia study in the traveled countries as a blue square which was shown in Table 3. The probable reasons for low PM<sub>2.5</sub> concentration values compared to WHO's annual mean statistics are having only indoor measurements at the airport in Doha, Qatar, relatively good ambient air quality due to monsoon season which affects the air quality positively, other meteorological factors such as temperature, humidity, precipitation, wind speed and wind direction which yielded lower PM<sub>2.5</sub> concentration values in Thailand, Taiwan, Hong Kong and Macau at that time of the year and at last but not least, it may be related to having low performance of the monitor during those measurement periods as compared to FMSs.

**Table 3:** Annual mean ambient PM<sub>2.5</sub> concentrations from various data sources and 1-hour mean PM<sub>2.5</sub> concentrations from Southeast Asia study for the traveled countries

Country	PM <sub>2.5</sub> Data Source (µg/m <sup>3</sup> )					
	OECD <sup>α</sup>	WHO <sup>β</sup>	The World Bank <sup>γ</sup>	State of Global Air <sup>δ</sup>	SE Asia Study <sup>ε</sup>	SE Asia Study Out. <sup>ζ</sup>
Thailand	28.9	24.6	26.4	26	9.6	13.1
Cambodia	18.7	23.0	29.0	29	14.7	20.0
Singapore	30.8	17.0	18.7	19	16.5	21.4
Taiwan	*48.8	*54.3	*58.4	30	10.9	15.4
Hong Kong and Macau	*48.8	*54.3	*58.4	58	16.0	22.2
Qatar	89.2	103.4	107.3	107	12.4	-
USA	10.9	8.2	8.4	8	6.7	4.5

α → OECD's 1-year mean PM<sub>2.5</sub> concentration data belongs to the year of 2015 (OECD, 2017);

β → WHO's 1-year mean PM<sub>2.5</sub> concentration data belongs to the year of 2014 (WHO, 2018);

γ → The World Bank's 1-year mean PM<sub>2.5</sub> concentration data belongs to the year of 2015 (the World Bank, 2017);

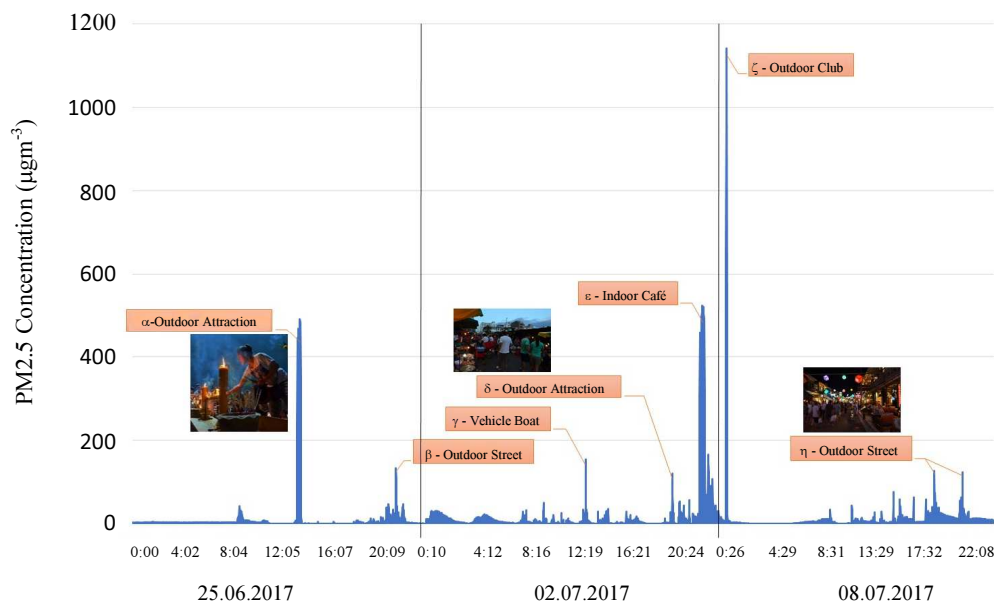
δ → State of Global Air's 1-year mean PM<sub>2.5</sub> concentration data belongs to the year of 2015 (State of Global Air, 2017);

ε → 1-hour mean PM<sub>2.5</sub> measurements from Southeast Asia study;

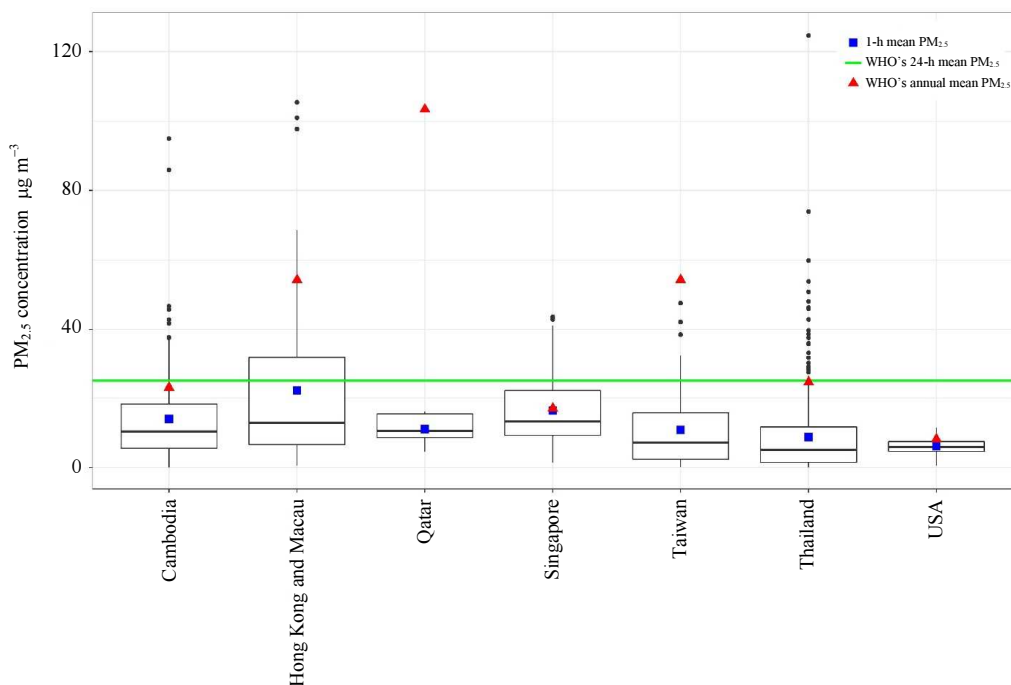
ζ → Outdoor microenvironments 1-hour mean PM<sub>2.5</sub> measurements from Southeast Asia study;

\*China's average PM<sub>2.5</sub> concentration value was used because of limited data related to Taiwan, Hong Kong and Macau.

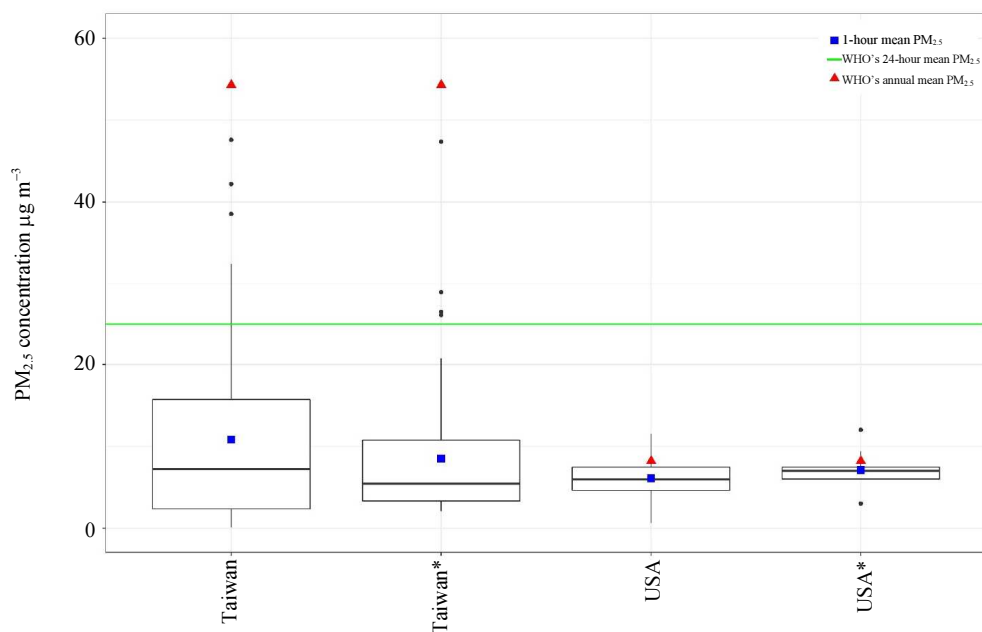




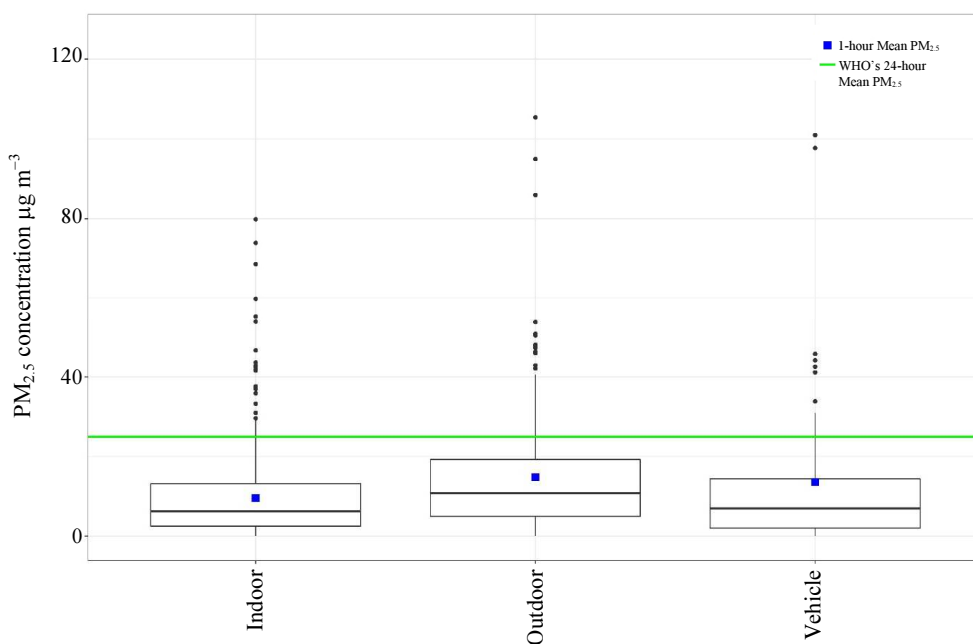
**Fig. 5:** 1-min averaged  $PM_{2.5}$  concentrations in the various microenvironments for selected days (25.06.2017/02.07.2017/08.07.2017) and the possible reasons and explanations for the recorded high concentrations;  $\alpha \rightarrow$  Outdoor – Attraction, min242 max492  $\mu g/m^3$  (19), Probable Reason: Burning Candles and Incense;  $\beta \rightarrow$  Outdoor – Street, min35 max133  $\mu g/m^3$  (15), Probable Reason: Cooking;  $\gamma \rightarrow$  Vehicle – Boat, min35 max154  $\mu g/m^3$  (5), Probable Reason: Vehicle Exhaust;  $\delta \rightarrow$  Outdoor – Attraction, min42 max121  $\mu g/m^3$  (4), Probable Reason: Vehicle Exhaust, Road Dust;  $\varepsilon \rightarrow$  Indoor – Café, min302 max525  $\mu g/m^3$  (25), Probable Reason: Hookah Smoke, Tobacco Smoke; Outdoor – Café, min35 max166  $\mu g/m^3$  (45), Probable Reason: Hookah Smoke, Tobacco Smoke;  $\zeta \rightarrow$  Outdoor – Pub, min49 max1142  $\mu g/m^3$  (8), Probable Reason: Tobacco Smoke;  $\eta \rightarrow$  Outdoor – Street, min35 max127  $\mu g/m^3$  (23), Probable Reason: Vehicle Exhaust, Road Dust



**Fig. 6:** 1-h mean  $PM_{2.5}$  concentrations in different countries and their comparison to WHO's suggested 24-h mean  $PM_{2.5}$  concentration limit and annual mean ambient  $PM_{2.5}$  concentrations of studied countries



**Fig. 7:** 1-h mean PM<sub>2.5</sub> concentrations from Southeast Asia study and OpenAQ for Taiwan and the USA and their comparison to WHO's suggested 24-h mean PM<sub>2.5</sub> concentration limit and annual mean ambient PM<sub>2.5</sub> concentrations for Taiwan and USA from WHO; Taiwan\* → The data is taken from OpenAQ from Songshan station in Taipei, Taiwan between 21.09.2017 13:00-24.09.2017 08:00. (Original days; 21.07.2017-24.07.2017); USA\* → The data is taken from OpenAQ from Desplns station in Chicago, IL between 30.07.2017 14:00-30.07.2017 16:00 and Madison East station in Madison, WI between 30.07.2017 17:00-31.07.2017 00:00



**Fig. 8:** 1-hour mean PM<sub>2.5</sub> concentrations in 3 microenvironments and their comparison with WHO's suggested 24-hour mean PM<sub>2.5</sub> concentration limits

Web-based low-cost monitors data from OpenAQ are used and compared to our Southeast Asia findings for

Taiwan and the United States by choosing the closest stations and similar travel dates and times in Fig. 7. These

were the only available countries that OpenAQ has low-cost monitor users and PM<sub>2.5</sub> recordings. According to data from those low-cost sensors and the assembled monitor which was used in our study, the results matched well for the United States and Taiwan datasets.

In addition, Fig. 8 informs us that the Southeast Asia study's 1-h mean PM<sub>2.5</sub> concentrations for 3 microenvironments are less than WHO's 24-h mean PM<sub>2.5</sub> exposure limits. Indoor, outdoor and vehicle microenvironments' PM<sub>2.5</sub> concentrations are 9.8, 16.1 and 13.5 µg/m<sup>3</sup>, respectively.

Figure 9 illustrates the Southeast Asia study's 1-h mean PM<sub>2.5</sub> concentrations for 17 microenvironments. The microenvironments approach is important for understanding the effects of environments on personal PM<sub>2.5</sub> exposure. Despite spending a relatively small amount of time in microenvironments that have high pollutant concentrations, they may be a significant predictor of 24-h mean personal exposure (Strak *et al.*, 2010; de Nazelle *et al.*, 2012). One study in Flanders, Belgium showed that spending 6% of volunteers' time in the different travel modes resulted in 21% of the total personal exposures and 30% of the total inhaled dose in a single day (Dons *et al.*, 2012). The average PM<sub>2.5</sub> concentrations for the 17 microenvironments varied between 2.3 and 32.8 µg/m<sup>3</sup>. According to the findings

of this study, the most problematic/polluted microenvironments are Port/Station (outdoor) and Café/Pub/Restaurant (indoor-outdoor) with 32.8 and 29.6 µg/m<sup>3</sup>, respectively. The main reasons for measuring high concentrations of PM<sub>2.5</sub> in these microenvironments were proximity to tailpipe emissions from transportation sourced combustion engines such as cars, buses, boats, ferries and light-duty vehicles and emissions from food cooking/baking activities. Market/Shopping Mall (indoor), Street (outdoor) and Cable Car/Metro/Tram (vehicle) were the second most concerning microenvironments after measuring 19.3, 19.3 and 18.9 µg/m<sup>3</sup>, respectively. Interestingly, the Passenger Car (vehicle) microenvironment had the lowest PM<sub>2.5</sub> concentration with 2.3 µg/m<sup>3</sup>. This both agrees and disagrees with some studies on transportation microenvironments in the literature (Knibbs and de Dear, 2010; Wang *et al.*, 2011; Kaur *et al.*, 2005; de Nazelle *et al.*, 2012). During the transportation, all the windows were closed and all of the air passed through the Air Conditioning (AC) and it is highly likely that the used passenger car had an effective AC system for particle removal which resulted in low PM<sub>2.5</sub> concentrations and exposure compared to other microenvironments.

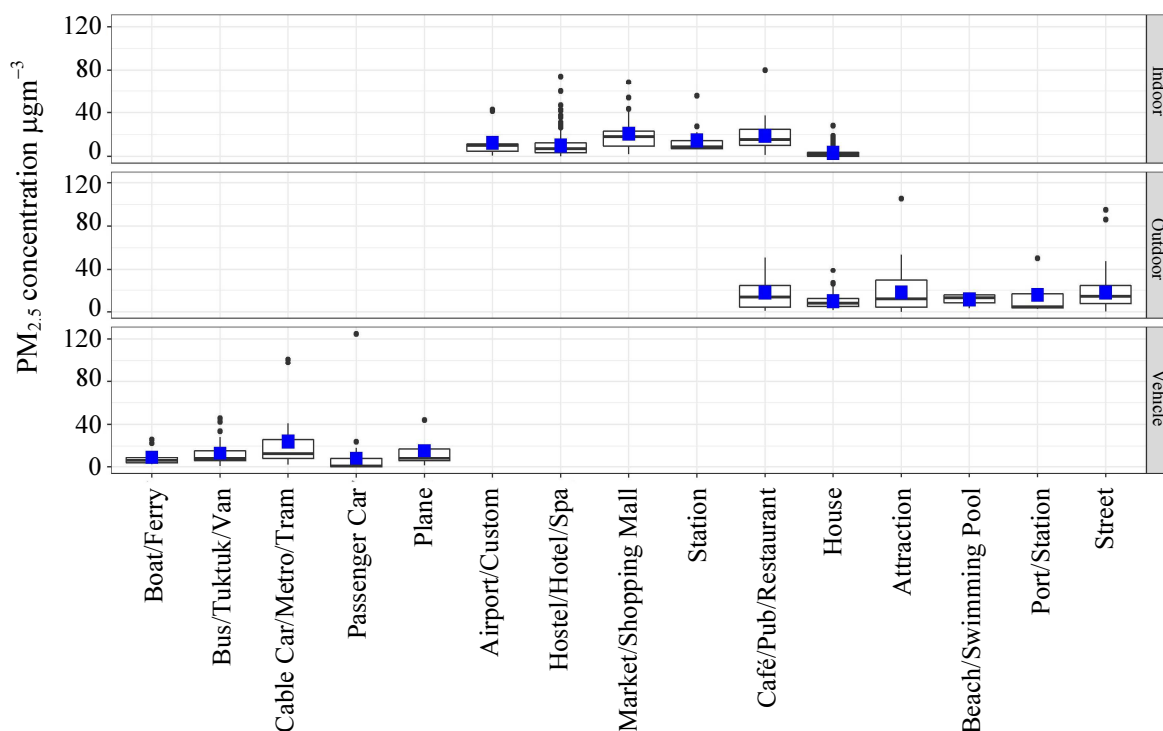


Fig. 9: 1-h mean PM<sub>2.5</sub> concentrations in 17 microenvironments in this study

As can be seen from the results, PM<sub>2.5</sub> concentration measurements ( $\mu\text{g}/\text{m}^3$ ) are given in 1-h mean format but WHO's guideline value is in the 24-h mean. It seems an inappropriate way to compare 1-h personal exposure values to WHO's 24-h ambient guideline value directly, due to the limited data of personal exposure for each microenvironments that were listed in this study and short-term measurement in some of the microenvironments during the study period, it is the only applicable way to compare measured concentrations. By comparing the measurement results in the listed microenvironments to WHO's guideline value, each microenvironment can be categorized as polluted, concerned or not-concerning. This gives a broad idea and helps for understanding the effects and dynamics of these microenvironments on presented PM<sub>2.5</sub> concentration levels. Moreover, it is generally true that long-term and short-term measurements may be correlated with each other in some cases and studies, so we believe that applying this approach to this study is acceptable.

Moreover, multiplying 1-h mean PM<sub>2.5</sub> concentrations by the time spent in each microenvironment gives PM<sub>2.5</sub> exposure in  $\mu\text{g}\text{-hour}/\text{m}^3$  (in Table 2). It helps us to understand which microenvironment is dominant during our study. Unsurprisingly, the Hostel/Hotel/Spa microenvironment had the highest exposure due to having the highest time spent, 32%, even though it has a relatively low-level 1-h mean PM<sub>2.5</sub> concentration. The Street microenvironment was the second highest PM<sub>2.5</sub> exposure, having a relatively high 1-h mean PM<sub>2.5</sub> concentration, although less time was spent there, 11%. Interestingly, the Café/Pub/Restaurant and House microenvironments had the third highest PM<sub>2.5</sub> exposure, 1,449.4  $\mu\text{g}\text{-hour}/\text{m}^3$  and 1,426.6  $\mu\text{g}\text{-hour}/\text{m}^3$ , respectively. The Café/Pub/Restaurant microenvironment was one of the most polluted environments and just 6% of the recording time was spent there. The House microenvironment had a relatively low 1-h mean PM<sub>2.5</sub> concentration, but one of the highest recording times, 27%. It is obvious that personal exposure has a strong correlation with ambient PM<sub>2.5</sub> concentrations and time spent in the different microenvironments, both determine the daily exposure of PM<sub>2.5</sub> for an individual person.

## Discussion

As noted in previous studies, the low-cost sensors need more improvement and further studies to understand their technological limitations and to overcome their drawbacks. They are not as accurate or as consistent as FMSs and can be affected by meteorological conditions such as temperature, humidity, precipitation, wind speed and wind direction, seasonal variations, the chemical composition of PM<sub>2.5</sub> and other factors (Gao *et al.*, 2015; Wang *et al.*, 2015). They have relatively short operational time because of

their fragility under diverse and extreme environmental conditions (Kumar *et al.*, 2015). This issue leads to another environmental concern, the additional burden of electronic-waste management because of the low-cost monitors' short-term operational time. Furthermore, maintenance, data management, analysis, post-processing and visualization costs can exceed the cost of the actual monitor itself (Kumar *et al.*, 2015). Low-cost sensing introduces opportunistic sensing under the banner of citizen science which can cause another challenge in addition to present ones. PM<sub>2.5</sub> and other pollutants' concentration values have been collecting and posting online. Some concerns include managing the enormous amount of data collected by the monitor networks, transparency of the recorded concentrations and organizations and access possibilities to them as users, citizens, scientists and government officials. In addition, without giving proper information and training to users, concentration measurements may cause unnecessary public concern or complacency about real air pollution levels. Lastly, they are also vulnerable to manipulation which may create unrealistic datasets that cause public pressure on environmental agencies with or without purpose.

Limitations of our study include working with just one traveler, using one monitor to sample the PM<sub>2.5</sub> concentration, not having a perfect design of the low-cost monitor, potential airflow perturbations when the monitor was used in the side pocket of the backpack, a lack of any co-location study with traditional monitoring stations to compare the PM<sub>2.5</sub> readings with a robust reference instruments and also the effect of environmental variables (weather patterns, chemical compositions of PM).

## Conclusion

Low-cost sensing provides advanced spatial and temporal variability exposure datasets which help to improve the characterization of air pollutants, air pollution levels, exposure patterns and increase the quality of exposure models via representative personal exposure studies. These datasets allow environmental health scientists, epidemiologists and allergists to have current knowledge of air pollution levels and trends in order to advise their patients accordingly (White *et al.*, 2012). They can advise their patients to minimize their outdoor activities during days with high pollution levels to avoid harmful effects and recommend them to review their indoor activities and pollution sources to manage their indoor exposure levels. Our measurements showed that some microenvironments are concerning due to higher PM<sub>2.5</sub> concentrations. Sensitive people should spend less time in these microenvironments in order to limit their PM<sub>2.5</sub> exposure. Moreover, by sharing air pollution and quality results with the public via mobile phone applications or the internet, sensitive people,

especially those already at risk, can plan their outdoor activities, check their residential areas' and workplaces' air quality and may choose new residential locations or workplaces which are away from localized air pollution sources. Individuals may also make decisions about which countries/cities to travel based on pollution data (Bernstein *et al.*, 2004). An environmentally sensitive tourism approach, defined by choosing less polluted, more environmentally friendly and sustainable developed countries/cities will create economic pressure on countries/cities with higher PM<sub>2.5</sub> pollution levels not to lose their share of the tourism industry. Furthermore, patients, doctors, patient advocates, engineers and environmentalists who support clean air movements can push governments and environmental agencies to implement stricter and more science-based air pollution standards and regulations.

Several aspects of this study can be addressed in future work such as: encouraging researchers to set up personal exposure studies, raising awareness to the effects of microenvironments and people's activities on potential exposure, extending measurements to a longer time frame, using more low-cost monitors and working with more travelers to have more spatial coverage, increasing the study area to other countries and continents, considering dose calculation for individual travelers and examining particle composition and toxicity of PM<sub>2.5</sub>.

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## Author's Contributions

**Semih Ozler:** Designed the research, planned and organized the study, managed the database, analyzed the data, developed illustrations, did the data analysis, wrote the paper and revised the manuscript.

**Karoline K. Johnson, Michael H. Bergin and James Jay Schauer:** Read and reviewed the paper.

Authors give final approval of the version to be submitted this journal.

## Ethics

The authors declare no conflicts of interest and confirm that the manuscript has been submitted solely to this journal and is not published, in the press, or submitted elsewhere.

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#### Abbreviations

AC	Air Conditioning
AQ-SPEC	Air Quality Sensor Performance Evaluation Center
FEM	Federal Equivalent Method
FMS	Fixed Monitoring Station
FRM	Federal Reference Method
IHME	Institute for Health Metrics and Evaluation
OECD	The Organization for Economic Co-operation and Development
OWiD	Our World in Data
SCAQMD	South Coast Air Quality Management District
UAV	Unmanned Aerial Vehicle
WHO	The World Health Organization