Spatiotemporal Assessment of PM$_{2.5}$ Exposure of a High-risk Occupational Group in a Southeast Asian Megacity

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Abstract

Drivers of open-air public utility jeepneys (PUJs) in the Philippines are regularly exposed to severe levels of fine particulate pollution (PM$_{2.5}$), making them the appropriate sub-population for investigating the health impacts of PM$_{2.5}$ on populations chronically exposed to these kinds of unique sources. Real-time PM$_{2.5}$ exposures of PUJ drivers for a high-traffic route in Metro Manila, Philippines were assessed using Academia Sinica-LUNG (AS_LUNG) portable sensing devices. From all 15-second measurements obtained, the mean concentration of PM$_{2.5}$ is 36.4 μg m$^{-3}$, seven times greater than the mean annual guideline value (5.0 μg m$^{-3}$) set by the World Health Organization (WHO). Elevated levels of PM$_{2.5}$ were observed at key transportation...
microenvironments (TMEs) such as a transport terminal and near a shopping mall. The occurrence of hotspots along the route is mainly attributed to traffic-promoting factors like stoplights and traffic rush hours. Multiple linear regression (MLR) analysis revealed that the area by the shopping mall had the highest contribution ($\beta = 52 \, \mu g \, m^{-3}$) to PUJ driver exposure. To the best of our knowledge, this study is the first in the country to perform a detailed characterization of the exposure of a high-risk occupational group to PM$_{2.5}$. These results reveal information that is normally undetected by fixed site monitoring (FSM), underscoring the importance of mobile measurements as a complement to FSM in assessing the exposure of urban populations to air pollution more extensively. Furthermore, this study demonstrates the heavy influence of traffic-promoting factors on air pollution, and the feasibility of high-resolution mobile sensing for quantifying pollution characteristics in rapidly developing nations with unique air pollution sources. Gaps in our knowledge of their health impacts may be closed through quantifying exposure using reliable sensing devices and methods presented in this work.

**Keywords:** Metro Manila, Personal monitoring, Low-cost sensor, Traffic pollution, Jeepney

1 INTRODUCTION

Poor air quality remains a challenge in many urban areas worldwide, particularly in developing countries with dense urban populations arising from rapid industrialization and urbanization (Mannucci & Franchini, 2017). Deemed as a “silent killer”, air pollution accounts for an estimated 7 million deaths annually, of which 3.7 million deaths are due to outdoor air pollution, and is considered as the world’s largest environmental health risk (WHO, 2013). Compared to the rest of the world, Southeast Asia has the second highest premature mortality due to air pollution in 2010 and is projected to have the highest premature mortality due to air pollution by 2050.
Traffic emissions contribute a major part of air pollution in urban areas (Weijers, 2004; Gertler, 2005; Gualtieri et al., 2020; Wu et al., 2021) and in TMEs (Pant & Harrison, 2013). TMEs are regions of space that have more or less homogenous air quality characteristics, such as various transportation modes (e.g., buses) and facilities associated with boarding or alighting from a mode (e.g., bus stops) (Li et al., 2017). Studies have shown that exposure to particulate pollutants is often highly elevated in on-road TMEs (Goel et al., 2015, Hankey and Marshall, 2015; Cepeda et al., 2016) compared to off-road microenvironments, due to their proximity to traffic emissions. This puts urban populations, particularly those who travel regularly, at higher risk to the adverse health effects of air pollution.

In particular, traffic has been shown to produce high levels of PM\textsubscript{2.5}, a measure of bulk particulate matter that is small enough (2.5 microns or less in diameter) to enter the respiratory system (WHO, 2013). High levels of PM\textsubscript{2.5} in urban areas have been associated with adverse health effects (Xing et al., 2016; Heal et al., 2012), including increased all-cause, lung cancer, and cardiopulmonary mortalities (Pope et al., 2002); increased risk of cardiovascular disease and mortality (Brook et al., 2010); and impaired lung function (Suglia et al., 2008). The transportation sector is a major contributor to PM\textsubscript{2.5} in developing countries, especially in Southeast Asian cities (Lung et al., 2022) where contributions from the transport sector was as high as 46% in Jakarta, Indonesia (Lestari et al., 2020) and up to 88% in Metro Manila, Philippines (DENR-EMB, 2015). Although other pollutants (e.g., black carbon (BC), a component of PM\textsubscript{2.5}) can provide a more direct quantification of traffic-related pollution, PM\textsubscript{2.5} is the closest metric for evaluating traffic-related air pollution in developing regions. Furthermore, current air quality regulations are based
on PM$_{2.5}$ metrics due in part to extensive epidemiological research that has studied the health risks arising from exposure to PM$_{2.5}$.

In developing countries with dense populations like the Philippines, the risk of air pollution exposure is compounded by a considerable increase in ambient levels of PM$_{2.5}$ concentrations due to extensive urbanization, increased transport activities, lack of strict emissions regulations, and an abundance of vehicles with outdated engines or emission control systems. Metro Manila, Philippines, a megacity with a population density of 21,765 persons km$^{-2}$ (Mapa, 2021), has PM$_{2.5}$ concentrations higher than the annual mean guideline value of 5.0 μg m$^{-3}$ set by the WHO (World Bank, 2009; WHO, 2021).

On top of the usual suspects of urban air pollution, countries or even city centers in the Southeast Asian region host some unique sources of air pollution (Lung et al., 2007; Pinichka et al., 2017; Pant et al., 2018; Pani et al., 2019). In Metro Manila, high concentrations of PM$_{2.5}$ are in part due to unique transportation modes such as PUJs (Fig. 1). The PUJ is a kind of share taxi unique to the Philippines, resembling a small bus with large open windows on both sides and a large opening at the rear, providing access for passengers. These vehicles ferry passengers along fixed routes which often have no designated stops, stopping anywhere to the side of the road for passengers to board or alight. As a principal means of public transportation in the Philippines, PUJs have been identified to be a leading source of fine particulate pollution (Madueño et al., 2019) due to their often second-hand and poorly maintained diesel engines (Clean Air Asia, 2017), whose emissions have been found to contribute up to 94% of total urban soot mass (Kecorius et al., 2017). Due to its semi-enclosed structure, the driver and passengers of vehicles such as the PUJ are easily and frequently exposed to particulate pollution. A study by Kaur and Nieuwenhuijsen (2009) found that traveling in enclosed vehicles such as buses and passenger cars contributes considerably to
commuters’ daily exposure levels to air pollutants. Exposure may be higher for PUJ drivers and passengers given the vehicle’s open structure (Fig. 1) and long travel times along highly polluted roads with heavy traffic.

**Fig. 1.** (a) Schematic of the PUJ’s internal layout with the AS-LUNG sensor near the driver’s breathing zone, (b) photograph of the driver’s position in the PUJ with its open windows (photo credit: Maria Obiminda Cambaliza, Manila Observatory) and (c) photograph of a typical PUJ in Quezon City (Photo Credit: Jose Gabriel Abalos, Manila Observatory).

To date, studies of air pollution in the Philippines have focused on characterization of ambient, indoor, and traffic-related PM (Cruz et al., 2019; Alas et al., 2018; Kecorius et al., 2017; Saksena et al., 2007; Oanh et al., 2006), quantifying air pollutant emissions from local activities (Gadde et al., 2009), or modeling of air particulate pollution sources (Cohen et al., 2009; Pabroa et al., 2011; Simpas et al., 2014, Cruz et al., 2019). These studies are in general agreement that the air quality in Metro Manila is poor, especially compared to most European cities. In particular, previous studies by Kim Oanh et al. (2006), Simpas et al. (2014), and Cruz et al. (2019) identified that BC accounts for a majority of PM$_{2.5}$ mass in Metro Manila. Studies by Alas et al. (2018),
Kecorius et al. (2017), and Madueño et al. (2019), quantified traffic aerosols in two Metro Manila cities as part of the Manila Aerosol Characterization Experiment (MACE 2015) campaign. These studies identified that PUJs were a major contributor to BC in Metro Manila and that BC concentrations in the region were higher than in cities of western countries. Alas et al. (2018) reported results from a mobile campaign to sample roadside BC, concluding that BC had a high spatial variability and was most strongly connected to traffic dynamics and street configuration.

A study by Balanay & Lungu (2008) assessed the occupational exposure of PUJ drivers to selected volatile organic compounds (VOCs), relating higher in-vehicle concentrations of target VOCs (benzene, toluene, ethylbenzene, xylene) to the PUJ’s semi-enclosed structure. However, there have been few to no studies that have provided an overarching assessment of personal exposure to fine particulate pollution specifically in the occupational context of PUJ drivers. As their main source of income, PUJ drivers normally ply their routes along roads of different traffic loads and compositions for 10 to 12 hours a day (Coz et al., 2015) over many years. PUJ drivers represent a vulnerable group whose occupation constantly puts them at high risk to the adverse health effects of air pollution. Up to a certain extent, the exposure of PUJ drivers can be extended to the general commuting public who rely on PUJs as a primary mode of transportation due to its accessibility and affordable fare. Such exposure characteristics are worsened for drivers in urban areas because of the PUJ’s open-air structure and the poor air quality in such environments.

Therefore, this study seeks to characterize the personal daily exposure of PUJ drivers in Metro Manila, Philippines by (i) calculating the average hourly personal exposure level of PUJ drivers to PM$_{2.5}$ along a high-traffic route; (ii) characterizing the spatiotemporal distributions of PM$_{2.5}$ along the route during the sampling period; (iii) identifying localized hotspots or key TMEs where elevated concentrations are consistently observed; and (iv) calculating the incremental
contribution of each TME to the personal exposure of PUJ drivers to PM$_{2.5}$. Quantifying personal exposures of PUJ drivers to PM$_{2.5}$ provides essential information to more accurately assess health impacts on populations that are chronically exposed to pollution from unique sources typical of developing nations in the Southeast Asia region.

2 METHODS

2.1 Study Site Description

Quezon City (Fig. 2) is the largest and most populated city in Metro Manila, Philippines, with an area of 165.3 km$^2$, a total of 2.94 million people, and a population density of $\sim$18,000 persons per square kilometer (Philippine Statistics Authority, 2016). The University of the Philippines (UP) Campus-Katipunan Avenue Route (UP-Katipunan route) (Fig. 3) is a PUJ route within Quezon City. The route is $\sim$10-km long, starting at the PUJ terminal at the south end of Katipunan Avenue, heading north into the UP campus, and returning to PUJ terminal through Katipunan Avenue. This route represents different degrees of particulate pollution to which PUJ drivers are exposed, linking a variety of locations including universities, residential areas, transport terminals, several commercial establishments, and a shopping mall. A few main thoroughfares also connect to the route, causing high-density traffic especially during rush hours. Moreover, the route intersects part of the Eastern Truck Route (Katipunan Avenue), an alternate route intended for cargo trucks coming from the port area.

The UP-Katipunan route can be broken down into two major areas, Katipunan Avenue and inside the UP Campus (Uni C), which have very different ambient environments. Katipunan Avenue is a major road with 3-4 lanes on each side that passes by two universities, Ateneo de Manila University (Uni A) and Miriam College (Uni B); numerous commercial establishments;
and a large shopping mall located on the avenue’s northbound side (Mall). From the northbound part of the avenue, the PUJ enters Uni C, which is characterized by mostly forested areas with some campus buildings, and has generally lighter traffic. Traffic here is mainly composed of PUJs and private vehicles.

Fig. 2. Location of the Philippines in Southeast Asia (left) and Metro Manila, which includes Quezon City (right). (Figure source: www.d-maps.com)
Fig. 3. Map of the UP-Katipunan route in Quezon City, Philippines, with highlighted TMEs: Uni A: Ateneo de Manila University, Uni B: Miriam College, Mall: shopping mall, Uni C: University of the Philippines, Transport: transport terminal, FFR: fast-food restaurant, PUJ: PUJ terminal.

2.2 Personal Monitoring Design

As concentrations of air pollutants from traffic are elevated along roadways, personal exposure in TMEs may not be adequately characterized by fixed-site monitoring (FSM) methods, which derive only annual ambient average pollutant concentrations (Apte et al., 2011; Moreno et al., 2009; Steinle et al., 2013). As opposed to FSM, personal monitoring can provide detailed insight into an individual’s short-term exposure as they traverse a specified area (Steinle et al., 2015, Lung et al., 2007) using portable and wearable monitors (e.g. Sherwood and Greenhalgh, 1960, Lung et al., 2021). It is substantially different from how traditional methods generate population-level exposure estimates using expensive, complex, and stationary equipment operated in FSM networks (Steinle et al., 2013). In this study, the personal exposure levels of PUJ drivers
for a busy thoroughfare in Metro Manila are assessed using portable personal monitoring equipment, accounting for their mobility across various areas with equally variable air quality characteristics.

Intensive field measurements were carried out across 33 days from 12 November to 15 December 2018, including both weekdays and weekends. Using AS-LUNG portable PM$_{2.5}$ devices inside PUJs traversing the UP-Katipunan route, PM$_{2.5}$ measurements were recorded for 10 – 12 hours a day at a 15-second resolution. A PUJ driver of the route completes an average of eight roundtrips per day, with travel times that are highly dependent on traffic conditions. Considering various factors such as driver mobility and instrument stability, sensors were installed on the dashboard directly in front of the PUJ driver, near their breathing zone. Seven drivers were assigned one device each to monitor their PM$_{2.5}$ personal exposure levels for a week and were replaced by another set of PUJ drivers for each week of the entire monitoring period. Profiles of the participating drivers’ age and body mass index (BMI) are shown in Figure S1 (supplementary material). Real-time PM$_{2.5}$ personal exposure levels of 31 drivers over 12 hours of each monitoring day, using 7 portable devices, yielded data for a total of 862 complete circuits.

### 2.3 Device Description

The AS-LUNG is a portable sensing device (Lung et al., 2020) using a Plantower laser particle counter (model PMS3003, Plantower, Beijing, China) which detects passing particles by their reflectivity (South Coast Air Quality Management District, 2019), counting suspended particles in size cut-offs of 1.0, 2.5, and 10 μm. Particle counts are processed by the sensor using a confidential proprietary algorithm to calculate PM$_1$, PM$_{2.5}$ and PM$_{10}$ mass concentrations in μg m$^{-3}$ (Kelly et al., 2017; Zheng et al., 2018). The AS-LUNG device determines aerosol mass concentrations with a 15-s resolution, enabling measurement of short-term exposure levels and
concentration profiles during daily trips. The device is GPS-enabled and also measures relative humidity and ambient temperature.

2.4 Field Evaluation of AS-LUNG Portable Sensors

The AS-LUNG devices were calibrated against a Beta Attenuation Monitor (BAM), a fixed-site reference instrument during a 16-day colocation experiment at the Manila Observatory from 27 March to 12 April 2019 to ensure the accuracy of measured PM$_{2.5}$ values. Figure S2 (supplementary material) shows the experimental setup for the colocation measurement at the Manila Observatory. A sample scatter plot of PM$_{2.5}$ concentrations from the AS-LUNG and the BAM is shown in Figure S3 (supplementary material). In general, measurements from the AS-LUNG were highly linear with respect to the reference data, and AS-LUNG devices overestimated the PM$_{2.5}$ concentrations obtained by the BAM by about 40%. Further details on the colocation experiment can be found in the supplementary material. Regression coefficients derived through the colocation experiments shown in Table S1 (supplementary material) were used to calibrate the PM$_{2.5}$ concentrations measured by the AS-LUNG sensors.

2.5 Geo-spatial Averaging Technique

Spatial averaging was performed by grouping calibrated 15-second data points along the route into segmented circular areas to reveal the spatial variability of PM$_{2.5}$ concentrations throughout the route (Birmili et al., 2013; Van den Bossche et al., 2015; Alas et al., 2018). Data points that fall into each circle were averaged, revealing the spatial variability of PM$_{2.5}$ and PM$_{2.5}$ hotspots along the entire route. Although tests on various configurations of diameter and spacing yielded qualitatively similar results, 60 m diameter circles at 30 m spacing were selected to best display spatial variability. Spatial maps were generated using the cartopy and matplotlib packages in Python. Map tiles, provided by Stamen Design using data from OpenStreetMap, were added using contextily in Python.
2.6 Estimation of Inhaled PM$_{2.5}$ Dose

The total PM$_{2.5}$ dose inhaled by a person for a single circuit ($D_{total}$) can be estimated by Eq. (1), where $r$ is a constant breathing rate, and $C$ is the concentration at each time step $dt$.

$$D_{total} = r \int C dt$$  \hspace{1cm} (Eq. 1)

Fifteen-second (15-s) PM$_{2.5}$ concentrations from the dataset were integrated numerically using a trapezoidal integration scheme. This simple model assumes a breathing rate of 5.11 × 10$^{-3}$ m$^3$ min$^{-1}$, following the U.S. EPA’s Exposure Factors Handbook (U.S. EPA, 2011). The value corresponding to sedentary activity levels was selected due to the fact that the PUJ’s passengers and driver are normally only seated in the vehicle.

2.7 Determination of Incremental Contribution of TMEs to Personal Exposure

Seven areas where passengers usually board and alight were selected as TMEs to predict the influence of these areas on the exposure of PUJ drivers. These areas include the PUJ terminal, three universities (A, B, C), a shopping mall, a transport terminal, and a fast-food restaurant. A multiple linear regression (MLR) model was adopted to statistically determine the impact of these selected TMEs (Lung et al., 2020) on exposure. Specifically, the relationship between the PM$_{2.5}$ concentration at any point in the route and the incremental contribution of each TME to the personal exposure ($\mu$g m$^{-3}$) is described by the following equation:

$$A_x = \beta_0 \gamma + \sum_{i=1}^{P} \beta_i x_i + \epsilon$$  \hspace{1cm} (Eq. 2)

where $A_x$ is the measured concentration at some area of the route; $\beta_0 \gamma$ is the intercept, representing the baseline value where $\gamma$ is the lowest concentration of each circuit; $\beta_i$ are regression coefficients; $x_i$ are Boolean variables for TMEs; and $\epsilon$ is an error term. Each $x_i$ is assigned a value of 1 when the device is within the associated TME, and 0 if outside the TME. $\beta_i$ values are calculated to represent...
the contribution of the corresponding TME to the personal exposure levels of PUJ drivers (in μg m\(^{-3}\)). Hence, the estimated PM\(_{2.5}\) exposure level at any point in the route \(A_x\) consists of the baseline term representing a regional background value \((\beta_0 \gamma)\), and the incremental contribution of each TME \((\beta_i x_i)\). For the regression model, the geospatial averaging scheme described earlier was used, but using circles with centers spaced 60m apart to avoid autocorrelation issues from overlapping circles.

3 RESULTS AND DISCUSSION

3.1 Descriptive Statistics of Real-time PM\(_{2.5}\) Measurements

Fig. 4. Histogram of all data points collected, showing the total number of data points (N), mean, median, standard deviation (SD), and interquartile range (IQR). A histogram of all 15-s calibrated measurements is presented in Fig. 4, along with descriptive statistics. The mean value for all measurements taken during the 33-day campaign was calculated to be 36.4 μg m\(^{-3}\), and concentrations well above 90 μg m\(^{-3}\) have been measured, accounting for 4.76% of all 15-s measurements. Considering that PUJ drivers experience such
levels of exposure on a regular basis over many years, the average exposure of 36.4 μg m⁻³ greatly exceeds annual guidelines set by the WHO (5.0 μg m⁻³) and US EPA (12.0 μg m⁻³) by a factor of ~7.3 times and ~2.5 times, respectively (WHO, 2021; US EPA, 2020). The fact that PUJ drivers take up this occupation over many years puts them at an especially high risk of harmful health effects that may manifest from prolonged exposure to high amounts of PM₂.₅. In addition, taking the average value of 36.4 μg m⁻³ as a yearly average means that riding the PUJ puts regular drivers and passengers at risk to concentrations that are characteristic of those reported in other Southeast Asian countries such as Thailand, Vietnam, Taiwan, and Singapore (Kim Oanh et al., 2013; Hien et al., 2019; Lung et al., 2014; Tran et al., 2020), which are about twice those found in countries such as the UK (Harrison et al., 2012), Poland (Juda-Rezler et al., 2020) or many urban centers in the USA (Pinto et al., 2004).

3.2 Spatiotemporal Variability of PM₂.₅ Mass Concentrations

Spatial averaging was performed on all 15-s PM₂.₅ measurements taken from 862 total paths (circuits) along the UP – Katipunan route to examine the spatial variability of PM₂.₅. Spatial averaging revealed hotspots in specific areas along the route, arbitrarily determined by having concentrations much higher than the route mean. Throughout the spatiotemporal analysis, four TMEs along Katipunan Avenue were identified to contain PM₂.₅ hotspots: the northbound sections of the route in front of (1) Uni A and (2) Uni B, (3) the segment in front of a shopping mall (Mall), and (4) a transport terminal (Transport).
Fig. 5. Spatial distribution and histogram of PM$_{2.5}$ concentrations along the PUJ route (n = 862 circuits). Histograms are normalized by bin width (10 µg m$^{-3}$). Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under ODbL.

Fig. 5 shows the spatial distribution of PM$_{2.5}$ concentrations for all 862 circuits, with each dot representing the spatially averaged PM$_{2.5}$ measurements. PM$_{2.5}$ concentrations show a high spatial variability throughout the route. Hotspots comprise about 20% of all spatial circles of the route for all runs. The lowest concentrations for the route were measured at some parts of the
northbound section in front of Uni A, and at the entrance to Uni C. The highest concentrations for the route (above 90 µg m\(^{-3}\)) were measured along the northbound section in front of the shopping mall, and 2.2% of the spatial circles exceeded 90 µg m\(^{-3}\). Most geospatial circles have concentrations in the range of 40 to 60 µg m\(^{-3}\). Overall, PM\(_{2.5}\) concentrations along Katipunan Avenue (mean: 53.3 µg m\(^{-3}\)) are relatively higher than the concentrations inside Uni C (mean: 36.2 µg m\(^{-3}\)).

The incidence of PM\(_{2.5}\) hotspots along Katipunan Avenue is also attributed to the increased number of emission sources due to heavy traffic loads along a wide 3 to 4-lane road. The five identified PM\(_{2.5}\) hotspots are areas where there is frequent traffic buildup along the route. Furthermore, the northbound section in front of the shopping mall has considerably higher concentrations than the southbound section (Fig. 5), which is likely due to traffic: many vehicles (both public and private) stop at the three designated drop-off areas along the northbound side of the road. Entrance and exit gates to the mall’s parking area are also found nearby. All these factors contribute to traffic build-up in the mall’s vicinity. Two spatial circles south of the shopping mall also appear as hotspots in the analysis. These areas are (1) a gasoline station where vehicles frequent, and (2) an entrance to a subdivision which tends to slow down traffic along the avenue. Concentrations are lighter on the southbound side of the road where these features are absent, which further underlines the role of traffic-promoting factors (commercial establishments, stoplights, public utility vehicle stops, etc.) in the production of PM\(_{2.5}\) hotspots. Contrary to expectations, the PUJ terminal does not appear to contain any PM\(_{2.5}\) hotspots. Further analysis of how features within this area affect PM\(_{2.5}\) concentrations using street-level pollutant dispersion modeling may reveal the exact reason why concentrations are low in this area.
Notably, the identified TMEs with hotspots along Katipunan Avenue (Uni A, Uni B, shopping mall, transport terminal) are areas near stoplights where many vehicles tend to gather. Due to a lack of proper PUJ stops along the route, these areas also serve as usual stops where passengers frequently board and alight. At these stops, pollutants may accumulate inside the cabin as a result of its semi-enclosed structure. When the PUJ is idling at stops, sometimes together with surrounding vehicles, there is a lack of incoming outside air to disperse the pollutants in the cabin. Ott et al., (2008) reported that air exchange rates inside moving vehicles increased by about 10 times from opening a single window by 3 inches. On the other hand, the air exchange rate is lower for slow-moving vehicles, and pollutants may accumulate in the cabin at stops or areas with slow-moving traffic despite the PUJ’s open structure. Cabin pollutant dispersion is also hindered by surrounding emission sources that reduce the availability of cleaner air near the PUJ. Studies on personal exposures for open-air vehicles similar to the PUJ such as the tuktuk and auto-rickshaws have also shown a similar result: drivers and passengers of these vehicles are exposed to higher concentrations of PM$_{2.5}$ due to their exposure to on-road emissions (Jinstart et al., 2012; Goel et al., 2015, Maji et al., 2021).

Patterns in the spatial maps suggest that PM$_{2.5}$ hotspots occur in areas with dense, slow-moving traffic where there is an increased number of sources around the sensing device and a reduced cabin air exchange rate that restricts the dilution of pollutants. In one round trip, PUJ drivers spend more time on Katipunan Avenue than inside Uni C due to heavier traffic on Katipunan Avenue, where most of the route’s hotspots were discovered. This means that although the overall average of the PM$_{2.5}$ measurements (36.4 $\mu$g m$^{-3}$) indicates that the quality of air along the entire route is merely ‘unhealthy for sensitive groups’ based on the US EPA Air Quality Index (AQI), moments of acute exposure (up to more than 90 $\mu$g m$^{-3}$) are not adequately reported using this number alone. In fact, epidemiological studies have shown that even brief exposures to high
concentrations of PM$_{2.5}$ may already have adverse health effects (Gold et al., 2000; Vallejo et al., 2006; Gutiérrez-Avila, 2018; Ebisu et al., 2019). Thus, these results provide good confirmation for the suitability of taking fine, spatially-resolved mobile measurements for assessing exposures to fine particulate pollution in such scenarios, allowing for better accounting of on-road PM$_{2.5}$.

3.3 Weekday-Weekend Analysis

Fig. 6. Spatial distribution and histogram of PM$_{2.5}$ measurements on (a) weekdays ($n = 711$ routes) and (b) weekends ($n = 151$ routes) during the monitoring period. Histograms are normalized by bin width (10 µg m$^{-3}$). Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under ODbL.
Weekday-weekend analysis (Fig. 6) showed that although spatial trends of mean PM$\text{}_{2.5}$ concentrations during weekdays (Monday to Friday) and weekends (Saturday & Sunday) are similar, higher concentrations are more frequent during weekdays than on weekends. The mean 15-s PM$\text{}_{2.5}$ levels are 39.0 $\mu$g m$^{-3}$ for weekdays and 35.4 $\mu$g m$^{-3}$ for weekends. Spatial circles with PM$\text{}_{2.5}$ concentrations above 90 $\mu$g m$^{-3}$ are 2.5% and 1.3% for weekdays and weekends, respectively (15-s data: 3.82% of weekdays, 5.48% of weekends). PM$\text{}_{2.5}$ levels in front of Uni A, Uni B, and inside Uni C are lower on weekends than on weekdays. On the other hand, the shopping mall and the gasoline station north of Uni B appear as consistent hotspots throughout the week. While school zones such as Universities A-C have decreased activity during weekends, the shopping mall and gasoline station might not have a significant difference in activity level between weekdays and weekends. Unlike universities, these locations are open all throughout the week and see consistently high traffic in their vicinity. Weekday-weekend patterns for the route, especially for areas around campuses, as well as consistently elevated levels near a shopping mall and gasoline station, emphasize the influence of anthropogenic activities on PM$\text{}_{2.5}$ concentrations.
Fig. 7. Spatial distribution of mean PM$_{2.5}$ measurements taken along the UP – Katipunan route during (a) AM rush hours, (b) Non-rush hours, and (c) PM rush hours for all weekday runs (n=711 routes). Histograms are normalized by bin width (10 µg m$^{-3}$). Map tiles by Stamen Design, under CC BY 3.0. Data by OpenStreetMap, under OdbL.

3.4 Rush Hour Analysis

Spatial trends of mean PM$_{2.5}$ concentrations during the morning (AM) and afternoon (PM) rush hours for all weekday runs are shown in Fig. 7. Rush hours include 7:00 to 9:00 for the morning and 16:00 to 18:00 for the afternoon (local time), while non-rush hours are times in between. Mean PM$_{2.5}$ levels were 46.7, 32.5, and 39.0 µg m$^{-3}$ for morning rush hours, non-rush hours, and afternoon rush hours for weekdays, respectively. Spatial circles with concentrations above 90 µg m$^{-3}$ make up 2.9% of morning rush hours, 2.2% of non-rush hours, and 2.8% of afternoon rush hours (15-s data: 7.5% of morning rush hours, 3.4% of non-rush hours, 5.7% of
Many segments of both northbound and southbound sections of the route are characterized by high PM$_{2.5}$ levels (55 – 84 μg m$^{-3}$) during morning rush hours. Percentile analysis for the entire 15-s dataset revealed that 70% of the highest concentrations (top 5%) were measured during rush hours, while 76% of the lowest concentrations (bottom 5%) were measured during non-rush hours.

Rush hour observations point to a strong influence of local anthropogenic activity levels on PM$_{2.5}$ measurements. PM$_{2.5}$ levels during afternoon rush hours are relatively lower than those in the morning, but elevated levels still appear at some sections of the route. Higher PM$_{2.5}$ concentrations during morning rush hours may possibly be due to how traffic volume is compressed within a smaller time window during morning rush hours. The start of classes and office hours usually coincide within a narrow period, usually 7:00 to 9:00 for schools and 8:00 to 10:00 for commercial establishments, given that students and employees need to arrive on time for class or for work. In contrast, there is greater flexibility in choosing when to go home in the afternoon, even until later in the evening. Elevated PM$_{2.5}$ levels are consistently observed in front of the shopping mall (74.5 μg m$^{-3}$) and transport terminal (57.4 μg m$^{-3}$) during both morning and afternoon rush hours. Concentrations are at their lowest in the middle of the day outside of rush hours, with the exception of the segment in front of the shopping mall. Spatial circles in this area still appear as hotspots in this time period, with concentrations generally exceeding 80 μg m$^{-3}$. Although most areas in Uni C consistently exhibit low PM$_{2.5}$ levels, throughout the day some areas have high concentrations (55-69 μg m$^{-3}$), specifically in the exit/entrance areas leading out to Katipunan Avenue in the morning. A similar study of PM$_{2.5}$ in Guangzhou, China also pointed to changes in street conditions, land use, and human activity to explain the diurnal pattern of PM$_{2.5}$, which, in their case, was found to be higher in the evening (Zhou and Lin, 2019).
Based on AM-PM rush hour and weekday-weekend spatial trends, PUJ drivers are regularly exposed to high concentrations of PM$_{2.5}$ when passing by or stopping in front of the shopping mall.

### 3.5 Diurnal Trends of PM$_{2.5}$ Mass Concentrations

![Fig. 8. Diurnal boxplots for each hour of day for all measurements with legend on the right. Percentages on the legend indicate the fraction of data below the corresponding PM$_{2.5}$ value.](image)

A time series plot of hourly averages of all PM$_{2.5}$ measurements is shown in Fig. 8 to present the diurnal patterns in PM$_{2.5}$ concentrations of the route. The hourly diurnal pattern reflects the pattern found in the AM/PM rush hour analysis. Highest concentrations were observed in the morning from 6:00 to 9:00 with a peak at 7:00, decreasing up to a midday minimum at around 13:00. A slowly increasing trend is observed towards the end of the day, from 15:00 until about 19:00. Concentrations are at their lowest after the afternoon rush hours, from 19:00 to 21:00. The distinct peak of PM$_{2.5}$ concentrations in the morning (Figs. 7 and 8) suggests that targeting factors which increase concentrations in the morning would be particularly effective at reducing exposures of commuters, both on-road and along the roadside. More specifically, improving mass transit infrastructure would be the best measure to address this problem. Establishing an efficient mass transport scheme would greatly reduce the amount of privately owned passenger cars on the road,
which was found to make up 57% of the traffic along Katipunan Avenue in 2018 (Metro Manila Development Authority, 2019).

![Diurnal boxplots for each TME.](image)

**Fig. 9.** Diurnal boxplots for each TME.

The diurnal variation and range of values of PM$_{2.5}$ measurements for each TME are presented in Fig. 9. In general, there is a common diurnal pattern for most TMEs where PM$_{2.5}$ is highest during morning rush hours (6:00 – 8:00), gradually decreasing throughout the day and increasing slightly in the afternoon rush hours (17:00 – 19:00). This further shows that the greatest exposures of PUJ drivers to PM$_{2.5}$ generally occur during both morning and afternoon rush hours.
PM$_{2.5}$ concentrations in Uni C (Fig. 9e) have a diurnal pattern similar to the Uni A, Uni B, and transport terminal TMEs but with comparably lower values. Other TMEs like the shopping mall (Fig. 9c) and fast-food restaurant (Fig. 9f) lack a similar morning-noon-afternoon trend. Concentrations are highest at the shopping mall and maintain such high levels regardless of the time of day.

This diurnal variation in PM$_{2.5}$ concentrations may be partly explained by meteorology, specifically through the role of diurnal air temperature, and changes in atmospheric stability on the distribution of air pollutants in the surface layer. Higher PM$_{2.5}$ concentrations measured in the morning may be attributed to a shallower boundary layer height due to lower air temperatures. Lower air temperatures near the surface usually occur in the morning, gradually increasing over the course of the day until reaching a peak in the afternoon, giving rise to a greater atmospheric mixing volume. Changes in the mixing depth influence the observed concentrations by affecting how pollutants are diluted. Hence, the observed diurnal variation of PM$_{2.5}$ may be induced by a joint effect from both planetary boundary layer dynamics and traffic rush hours, significantly increasing PUJ driver exposure, especially in the morning. However, consistently elevated concentrations near the shopping mall appear to be insensitive to changes in mixing volume throughout the day. This observation may suggest that emissions from mobile sources are the dominant factor in the variability of PM$_{2.5}$ concentrations in urban areas.
3.6 Potential Inhaled PM$_{2.5}$ Dose

![Image](image_url)

**Figure 10.** Estimated inhaled dose (µg) over trip time (min). Least squares R-squared and regression coefficients are shown. 95% confidence interval for the coefficient is expressed by the transparent red area.

Fig. 10 shows the least squares linear regression that was performed for datapoints of all circuits, producing an $r^2$ value of 0.41 and a coefficient of 0.15 µg min$^{-1}$. From estimations following Eq. (1), the mean inhaled dose is 7.8 ± 3.9 µg for a single circuit of the PUJ route. The maximum inhaled dose is 34.7 µg, which was recorded over a period of 112 minutes on the route. A trip time of 112 minutes corresponds to heavy traffic conditions along the ~10-km route. The average dose for one circuit of the route (7.7 µg) is small compared to results by Morales Betancourt et al. (2017), who performed a similar mobile campaign for multiple transport modes in a major urban environment in Bogotá, Colombia. They reported total doses ranging from 12.8 µg (car) to 125.9 µg (pedestrian). The discrepancy in these results may likely be due to the fact that PM$_{2.5}$ concentrations in their study (200-1500 µg m$^{-3}$) greatly exceed the values reported in this work, combined with the fact that a sedentary breathing rate is assumed for passengers of the PUJ. Compared to values reported by de Nazelle et al. (2012) in Barcelona, the mean inhaled dose is
smaller than all transport modes for PM$_{2.5}$. When compared to their reported doses for BC, the mean inhaled dose of 7.8 µg falls between bus (5.3 µg) and bike (8.7 µg) modes.

Figure 11. Estimated dose rates (µg hr$^{-1}$) for the PUJ route. The median rate of 11.2 µg hr$^{-1}$ (0.19 µg min$^{-1}$) is shown by the red line. A histogram of the data points along the same vertical scale is shown on the right. Histogram heights are normalized by bin width (1 µg hr$^{-1}$).

Dose rates for each trip in the route (Fig. 11) were obtained by dividing the total dose by the corresponding trip time. The mean dose rate for the route is 0.2 µg min$^{-1}$ (12.2 µg hr$^{-1}$), and the median dose rate of 0.19 µg min$^{-1}$ (11.2 µg hr$^{-1}$) matches the slope (regression coefficient) in Fig. 10. Dose rates for the circuits in the PUJ route are fairly variable, with a standard deviation of 4.7 µg hr$^{-1}$ (0.078 µg min$^{-1}$). This means that a typical commuter of the route can expect to inhale somewhere around 6.7 to 16.1 µg of PM$_{2.5}$ for every hour spent inside the PUJ. Computed dose rates reached a maximum of 33.0 µg hr$^{-1}$, with the top 25% of the circuits registering above 14.4 µg hr$^{-1}$. Unlike passengers that generally ride the PUJ for only a small fraction of the route at a time, PUJ drivers that spend over 10 hours inside the vehicle intake much more PM$_{2.5}$, up to over
100 µg of PM$_{2.5}$ in a single working day, following these estimates. This further highlights the potential health risk that PUJ drivers face in the course of their occupation.

Analysis of dose rates allows for comparisons irrespective of the short trip times (40-60 mins per circuit) in the PUJ route. When compared to values reported by Morales Betancourt et al. (2017), the highest dose rate obtained in this study (33.0 µg hr$^{-1}$/0.55 µg min$^{-1}$) is closest in comparison to values that were measured inside a car (0.4 µg min$^{-1}$). PM$_{2.5}$ values inside the car had a median concentration of 62.3 µg m$^{-3}$. Kumar et al. (2018) also measured PM concentrations in Guildford, UK for various transport modes (bus, car, cycle, walk modes), with the walk mode yielding the highest mean dose rate (5.5 ± 0.3 µg h$^{-1}$) for PM$_{2.5}$. This figure is closest to the median dose rate (11.4 µg hr$^{-1}$) obtained in this study.

3.7 Estimated Contribution of TMEs to PM$_{2.5}$ Personal Exposure

Multiple linear regression (MLR) analysis was performed to statistically analyze the contribution of TMEs to the PM$_{2.5}$ personal exposure levels of PUJ drivers. TMEs that passengers frequent were selected for the MLR analysis: the PUJ terminal, a shopping mall, Unis A, B, C, a transport terminal, and a fast-food restaurant. Four of the TMEs along Katipunan Avenue (Uni A, Uni B, shopping mall, transport terminal) were found to contain PM$_{2.5}$ hotspots.

Table 1 shows the incremental contributions of the TMEs for weekdays and weekends, where $\beta_i$ are the estimated contribution of a given TME to the observed concentrations. The regression produced an $R^2$ value of 0.53, which suggests that 53% of the variability in PM$_{2.5}$ concentrations of the route is explained using just these 7 TMEs and a baseline value. During both weekdays and weekends, this $R^2$ value is at its highest during AM rush hours, suggesting that heavy traffic combined with a shallow boundary layer contributes significantly to PUJ driver exposure compared to other factors.
Of all the TMEs, the segment of the route in front of a shopping mall has the highest estimated PM$_{2.5}$ contribution to the personal exposure of PUJ drivers on average (51.9 µg m$^{-3}$) and for each time period (weekday/weekend, AM/PM rush hours). This corresponds with the hotspot in front of the mall in the spatial maps, where extremely high PM$_{2.5}$ concentrations are observed regardless of the time and day.

PM$_{2.5}$ concentrations in some TMEs vary greatly during the course of the week and at certain times of the day, indicated by the standard deviation of their regression coefficients. The contribution of the transport terminal (Transport) and fast-food restaurant (FFR) TMEs showed the highest temporal variability (σ=9.9 and 8.9, respectively), which reflect the occurrence of hotspots in these areas only during certain times of the day. Higher concentrations near the fast-food restaurant were measured mainly during non-rush hours in the middle of the day (10:00 – 15:00), due to the increased activity in this area at around lunchtime. On the other hand, the Uni C TME exhibits consistently low ($\beta = 12.7$, $\sigma = 2.6$) contributions to PUJ driver exposure regardless of the time of day.

Concentrations for weekend afternoon rush hours are comparable to or even higher than on the weekdays. This is likely due to increased activity in general on weekend evenings, as many commercial establishments are located along Katipunan Avenue. Anecdotally, the heaviest traffic in Metro Manila throughout the week is observed late during weekends, beginning at around 16:00.

Table 1. Summary of $\beta$-values computed for the chosen TMEs in µg m$^{-3}$, with mean and standard deviation (σ) included. The mean is the average of the 6 columns under weekday and weekend. Coefficients presented in this table are all statistically significant, with p-values less than 0.01.
Hotspots identified at several TMEs in the UP – Katipunan route (Uni A, Uni B, shopping mall, transport terminal, and fast-food restaurant), as well as the periods when extreme exposures are experienced by PUJ drivers (AM/PM rush hours), reflect the persistent challenges in improving the transportation system and traffic conditions in Metro Manila. These results demonstrate the strong influence of traffic on PM$_{2.5}$ concentrations, which calls for consistent monitoring of vehicle compliance to emission standards and shifting towards cleaner technologies for vehicles with diesel engines in the metropolis.

Occupational groups at risk of exposure to elevated levels of PM$_{2.5}$, like PUJ drivers, are generally advised to wear masks with a PM$_{2.5}$ filter in order to minimize its harmful effects on their health. However, even the best masks cannot filter out 100% of PM$_{2.5}$. Furthermore, masks which filter out a significant percentage of PM$_{2.5}$ are usually expensive and disposable, requiring these to be purchased regularly. Considering that these occupational groups earn mostly minimum-wage or below-minimum-wage, they cannot practically afford to regularly wear PM$_{2.5}$ masks. In actuality, the only effective means for widespread reduction of personal exposure levels is through improving the ambient air quality. This can be achieved through efforts in implementing effective policies on
traffic-related air pollution, considering air pollution dynamics in urban planning, and investing in automated, real-time mobile instruments alongside FSM stations for a more comprehensive assessment of air quality.

4 CONCLUSIONS

Following previous research that identified a high degree of traffic-related PM$_{2.5}$ in urban areas of Metro Manila, Philippines, a series of field measurements was carried out for 33 days in a high-traffic key site in Quezon City, Metro Manila to characterize the spatial and temporal distribution of fine particulate pollution from inside public utility jeepsneys (PUJs) using real-time PM$_{2.5}$ monitors. To our knowledge, such a unique high-density data set obtained in this study is the first in the country to provide a high-resolution characterization of fine particulate pollution exposure for a high-risk occupational group over a long period (~1 month), with a large number of participants (n=31 drivers).

The overall mean PM$_{2.5}$ concentration of the route (36.4 μg m$^{-3}$) is over seven times greater than the mean annual PM$_{2.5}$ guideline value (5.0 μg m$^{-3}$) set by the WHO. Although this mean value is merely considered “unhealthy for sensitive groups” following US EPA AQI breakpoints, reporting a single average value fails to take into account the high spatial variability of PM$_{2.5}$. We note that the mean PM$_{2.5}$ concentration of the route is similar to concentrations reported in other Southeast Asian countries, which are generally higher than concentrations found in developed Western countries.

Spatial averaging identified elevated levels of PM$_{2.5}$ at various locations, especially in most key TMEs. The occurrence of hotspots, especially near the shopping mall, is attributed mainly to factors that increase traffic density and thus PM$_{2.5}$ emissions in the area. Furthermore, the exposure of PUJ drivers is further aggravated at stops where polluted air accumulates within the cabin. In
these hotspots, PUJ drivers see the highest exposures to PM$_{2.5}$ (up to over 90 µg m$^{-3}$). Diurnal patterns of PM$_{2.5}$ in hotspots such as those near universities show that anthropogenic activity plays a role in their formation, as their intensities are also linked with the level of activity in these areas. For most of the route, the highest concentrations were observed in the morning. Morning rush hours have higher concentrations compared to afternoon rush hours and non-rush hours due to changes in traffic and boundary layer depth throughout the day. The more detailed influence of street configuration and meteorology on the measured concentrations may be further explored with street-level dispersion modeling of PM$_{2.5}$ pollutants at locations of interest identified in this study.

Inhaled dose estimations were rather low for the PUJ route compared to other studies. Passengers of the PUJs in this route can expect to inhale 7.8 µg in a single circuit. Dose rates for the route are fairly variable, with a median rate of 11.2 µg hr$^{-1}$. Compared to results from similar analyses in other countries, these values are moderately low. This is likely due to lower PM$_{2.5}$ concentrations and the assumed sedentary breathing rate for this study. Although the passengers do not usually stay in the PUJ for the entire circuit, drivers that operate these vehicles for over 10 hours daily would be the most susceptible to the dangers of the degree of fine particulate pollution measured in this campaign.

Multiple linear regression (MLR) results showed that the shopping mall had the highest contribution (52.0 µg m$^{-3}$) among the TMEs. A high temporal variability in incremental contribution for TMEs like the fast-food restaurant indicates that these areas only see occasional spikes in concentrations, which have also been identified in the rush hour and weekday/weekend spatial maps.

All in all, the results presented above mainly demonstrate the state of air quality in urban areas that is often not accounted for by traditional FSM. Values reported over large areas and long
periods fail to take into account the highly variable nature of fine particulate pollution, overlooking moments and locales of extreme exposures as a result. On the other hand, mobile measurements are effective at revealing this variability, which is important because acute exposures already pose a risk to many commuters and drivers in urban environments, who are regularly subjected to these throughout their daily lives. Fortunately, the abundance of these studies shows that generating population-level figures of air pollution is not the only tool in our arsenal for determining how to mitigate it. Regular implementation of the methods used in this study over long periods as an aid to FSM holds promise in better understanding the conditions that give rise to polluted air, which can greatly inform strategies for tackling the problem.

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