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PM 2.5 Monitoring in Elevated-level Metro System in the Philippines Using Low-Cost Sensors

Nickolai Yummar D. Demagante[a], Julius Rhoan T. Lustro[b]

[a]Environmental Engineering Program, University of the Philippines Diliman, Quezon City Metro Manila 1101, Philippines
[b]Department of Mechanical Engineering, University of the Philippines Diliman, Quezon City Metro Manila 1101, Philippines
jtlustro@up.edu.ph

Indoor air quality has been an increasing health concern globally. Several studies have analyzed elevated concentrations of Particulate Matter (PM) in metro systems, which have shown concerning health results to the commuting public. In the Philippines, there are limited studies on PM concentrations in metro system. With commuters spending a significant amount of their day in metro system, it is paramount to understand the air quality in this space. This study examines the PM 2.5 concentrations inside the train and at station platforms. The interaction between the indoor (metro cabin) and outdoor (station platform) on PM 2.5 concentrations at MRT station line during normal and peak hours are investigated. PM 2.5 concentrations are observed to have elevated concentrations during peak hours, which are relatively higher than the regulated local air quality standards.

1. Introduction

Rapid urbanization and population growth in metropolitan cities worldwide necessitates metro rail systems for daily commuting of people. While metro systems offer an efficient and sustainable mode of transportation, they also present unique challenges regarding air quality, particularly exposure to fine particulate matter (PM 2.5) within the enclosed microenvironments of metro cabins and stations (Kumar et al., 2018). PM 2.5, which is defined as airborne particles with an aerodynamic diameter of 2.5 µg or less, poses significant health risks due to its ability to penetrate deep into the respiratory system, leading to cardiovascular and pulmonary diseases, and in severe cases, premature mortality (Bin and Jinliang, 2017).

Numerous studies have reported elevated PM 2.5 concentrations within metro systems worldwide (Bin and Jinliang, 2017). Research conducted in the Taipei Mass Rapid Transit (MRT) system revealed that PM2.5 levels inside metro trains traveling in underground tunnels were 20–50% higher than those on elevated tracks, primarily due to limited ventilation and particle resuspension caused by mechanical wear and passenger movement (Cheng et al., 2008). Similarly, in the Los Angeles Metro, PM 2.5 levels in underground subway lines were 1.8 times higher than in ground-level light rail systems, with train operations and station environments identified as significant pollution sources (Kam et al. 2011). Studies in the Italian metro system also demonstrated that PM 2.5 levels on underground platforms were 2–14 times higher than outdoor levels, with passenger movement and train turbulence further increasing particulate concentrations inside train carriages (Carteni et al. 2015).

The health implications of PM 2.5 exposure during metro commuting are well-documented. Long-term exposure to elevated PM 2.5 levels has been associated with increased risks of cardiovascular disease, respiratory disorders, and mortality. In Asian transport microenvironments, including metro systems, PM 2.5 exposure has been found to be significantly higher than in European and American cities, with average concentrations reaching 74–76 µg/m³ in metro carriages, nearly double the levels observed in Western countries (Kumar et al., 2018). Furthermore, the presence of PM-2.5-bound toxic compounds, such as polycyclic aromatic hydrocarbons (PAHs), heavy metals, and black carbon, exacerbates the health risks, contributing to oxidative stress and inflammation (Kam et al. 2011).

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Given the widespread use of metro systems and the associated health risks posed by PM 2.5 exposure, it is important to evaluate PM 2.5 levels within metro cabins, identify key influencing factors such as infiltration factor and passenger density, and assess potential health risks for daily commuters. In the Philippines, there is a limited study on air quality in metro system. This study seeks to address this gap by providing insights on the PM 2.5 levels in one of the major metro systems in Metro Manila.

2. Methodology

The study focuses on 15-day sampling campaign of indoor and outdoor PM 2.5 monitoring for metro systems during peak and non-peak hours. The Metro Rail Transit 3 or known as MRT-3 line in the Philippines, which began operations in 1999, is a ground-elevated metro line system covers 13 stations that spans approximately 16.9 km connecting Taft Avenue in Pasay City to North Avenue station in Quezon City. The indoor PM 2.5 sampling campaign covered 13 stations between Taft Avenue station (end point of southbound trips) to North Avenue station (end point of northbound trips) while outdoor PM 2.5 monitoring covered four selected station platforms, namely: Taft Avenue, Guadalupe, Araneta-Cubao, and North Avenue stations. This represents both the end stations and two intermediate stations. Trains pass every 3-4 minutes during peak hours and 5-8 minutes during normal hours.

Considering the short sampling duration and the real-time measurements performed in the different locations the O-1SPT (AirGradiis Open Air) and I-9PSL (AirGradient ONE, 9th Generation) sensors were used in monitoring air quality inside the metro cabin and station platforms, respectively. These are low-cost sensors that measure PM 2.5, PM 10, NO_x, VOC, temperature, CO_2, and relative humidity. Both sensors employ Plantower PMS5003T and Plantower PMS5003 laser scattering principle, with temporal resolution of 60 seconds. Accuracy of the sensors are at ±10% at 100~500 μg/m³, and ±10μg/m³ at 0~100 μg/m³. These sensors have been utilized for measuring PM 2.5 in the studies of Fameli et al. (2024) and Nguyen et al. (2021).

The sampling campaign took place for 15 days between December 3 to 23, excluding holidays and Sundays. The sampling focused on measuring real-time PM 2.5, relative humidity, CO_2, and temperature simultaneously at station platforms (outdoor) and inside the train (indoor). The sampling campaign was conducted during MRT-3 operational hours considering peak and normal hours of working days of December 2024, specifically: peak hours during 7:30 am - 9:00 am (morning peak) and 5:00 pm - 6:30 pm (afternoon peak), as well as normal hours during 11:00 am - 12:30 pm. In indoor PM 2.5 monitoring, the sensor was placed inside the middle carriage of the cabin approximately 1.65 m above the floor at about 1.50 m from the station platform. One person holding the sensor is deployed inside the cabin for one round trip going northbound and vice versa for roughly 1.5 hours. Prior to indoor air sampling, sensors were deployed at the four selected station platforms. In the outdoor environment the sensors were attached to a pole roughly 1.65 m above the station platform floor and 1.50 m from the middle carriage of the cabin. Once everything is deployed, the indoor air sampling activity will start with the data collection. The sampling begins when the northbound train is leaving Taft Avenue station. The indoor and outdoor data sampling will start concurrently at each selected station platform, e.g., recording indoor and outdoor PM 2.5 readings when the train stops at a station. This continues until the southbound train returns to Taft Avenue station. The same sampling method is applied for all time slots.

To ensure homogenous and comparable readings, the monitoring was conducted on clear weather days with ambient temperature maintaining at 10-28^{o}C, with low wind conditions (wind speed <10 km/h or 5 m/s) and less than 70% relative humidity rate. These conditions were carefully considered as excessively high relative humidity level can lead to anomalously high PM values measured with photometric samplers (Chakrabarti et al., 2004).

Source of particulate matter PM 2.5 can be identified using simple linear regression. Indoor PM 2.5 levels may derive from emissions of indoor PM 2.5 sources and emissions from outdoor PM 2.5 sources. Therefore, indoor PM 2.5 sources may be estimated using equation (1) as follows (Rojano et al., 2023).

$$C_{PM2.5_{Ind}} = C_{PM2.5_{Ein}} + F_{in} * C_{PM2.5_{Out}} \quad (1)$$

where $C_{PM2.5_{Ind}}$ is the total indoor PM 2.5 levels, $C_{PM2.5_{Ein}}$ is the levels generated indoors, and F_{in} is the PM 2.5 infiltration factor. $C_{PM2.5_{Out}}$ is the total outdoor PM 2.5 levels.

3. Results and Discussion

Figure 1 shows the PM 2.5 levels inside the metro cabin indoor as the train moves across the 13 stations during peak hours in the morning and afternoon and during normal hours. Taft Avenue station consistently shows the highest PM 2.5 levels across all time periods, with the morning peak hours showing the most elevated PM 2.5 levels. The consistent pattern of elevated values of PM 2.5 during morning peak hours suggests that peak traffic hours and atmospheric conditions in the morning exacerbate PM 2.5 levels.

Taft Avenue station is in a congested area where there is moderate to heavy traffic conditions. When southbound trains end at Taft Avenue station, the doors remain open from the time the passengers get off until the time the northbound passengers are picked up. This event lasts for about 6 to 8 minutes. With the station platform at street level, there is significant influence of vehicular emissions and other pollution sources in the area in the PM 2.5 levels. This observation is similar with that of Kam et al. (2011) where the indoor air quality for trains above the ground is directly influenced by outdoor traffic emissions.

PM 2.5 levels show a declining trend as the train moves northbound from Taft Avenue station to North Avenue station, with North Avenue and Quezon Avenue stations registering the lowest PM 2.5 levels. This decline could be attributed to less pollution in these areas (Carteni et al. 2015). In addition, northbound trains move towards less congested area. Wang et al. (2024) demonstrated that congested areas with higher building density often experience increased PM 2.5 levels due to restricted airflow and pollutant dispersion.

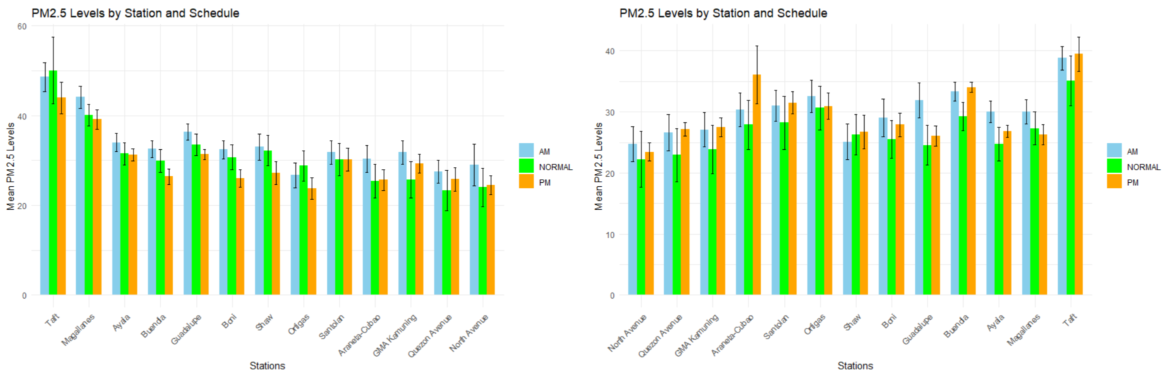

Figure 1: PM 2.5 levels inside MRT-3 cabin during peak (morning and afternoon) and normal hours for northbound (left) and southbound (right) trains

The southbound trains exhibit a more dynamic trend that is related to the passenger movement. The stations with the lowest and highest PM 2.5 levels remain consistent. The increase in PM 2.5 levels towards the southern end of the line (Taft and Magallanes stations) reinforces the influence of traffic congestion and local pollution sources in these areas. One notable observation is the temporal variation, where morning peak periods generally exhibit higher PM 2.5 levels compared to normal and afternoon peak hours. Passenger movement also contributes to particle resuspension, allowing outside PM 2.5 particles to also infiltrate inside the metro cabin. This was also suggested by Zarandi et al. (2013) that stations near high congested-traffic streets, arrival and departure of passengers are the possible factors that might influence the high spike in PM 2.5 levels. This trend is consistent across all stations and is likely driven by the morning rush hour and less atmospheric dispersion due to cooler temperatures. This observation is also demonstrated by Gupta and Elumalai (2019), where PM levels can be 1.8 to 6.7 times higher near roadways during peak traffic compared to outdoor levels.

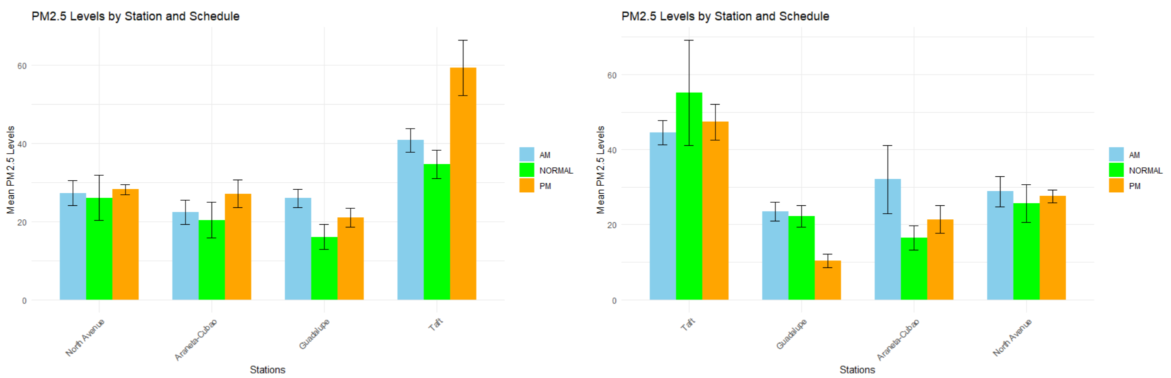

Figure 2: PM 2.5 levels on selected station platforms during peak (morning and afternoon) and normal hours for Northbound (left) and Southbound (right) trains

Figure 2 shows the PM 2.5 levels at the selected MRT-3 station platforms during different schedules. In both graphs, Taft Avenue consistently shows the highest PM 2.5 levels compared to other stations, particularly during the afternoon peak hours for southbound trips. This could be attributed to the station's proximity to heavy traffic and traffic congestion as also demonstrated by Kam et al. (2011), which particulate pollutants originate from local sources, such as vehicular emissions and road dust. On the other hand, stations like North Avenue and Quezon Avenue exhibit relatively lower PM 2.5 levels, potentially due to situated at higher elevated areas having farther emission sources. The error bars suggest variability in the measurements, particularly at Taft Avenue station, indicating significant fluctuations in PM 2.5 levels, which might be influenced by local meteorological conditions or transient traffic patterns. The overall trend indicates that peak hours generally experience higher PM 2.5 levels compared to normal hours. However, the PM 2.5 levels during normal hours in Taft Avenue shown an unusual trend. This is due to the 6-8-minute waiting time of the train cabin prior to its departure.
The findings in this study are consistent to findings that show PM 2.5 levels on station platforms are significantly influenced by factors such as station location and proximity to traffic streets. Study in Hongkong by Chan et al. (2002) observed that PM 2.5 levels on station platforms operating above ground are more influenced by outdoor PM 2.5 levels. While Li et al. (2017) and Fameli et al. (2024) suggested that during peak commuting hours, PM 2.5 levels become elevated when passenger density is higher during these times.

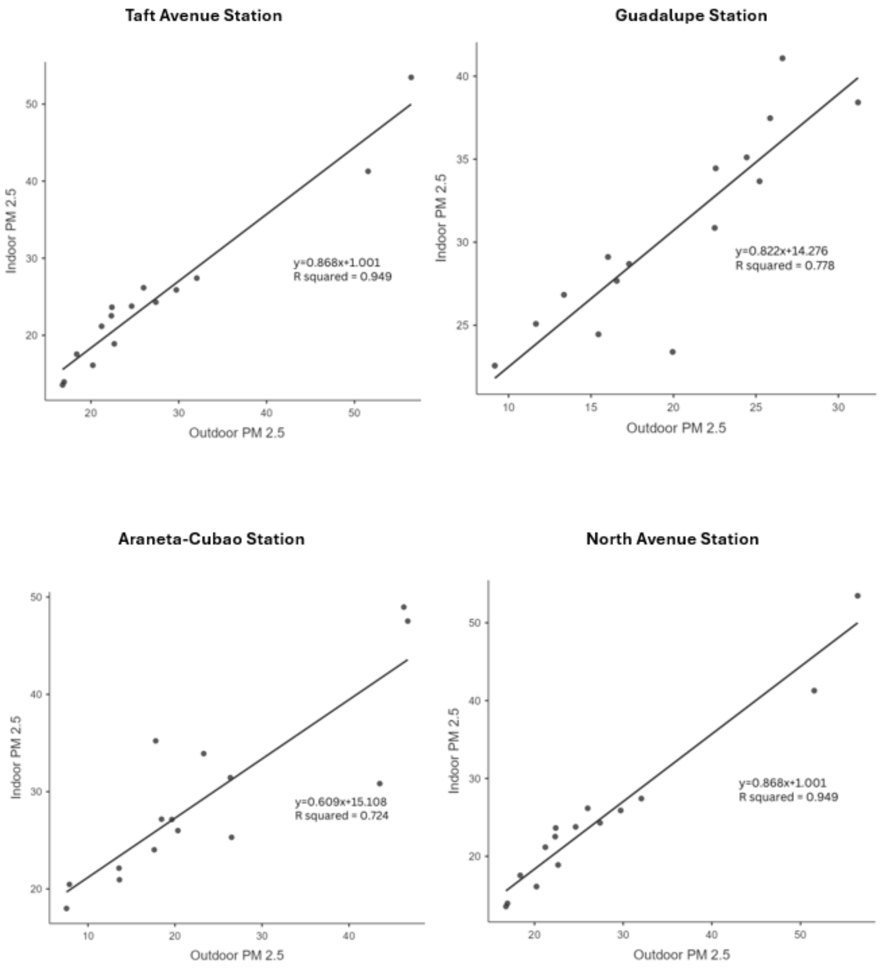

Figure 3: Regression model Indoor-Outdoor PM 2.5 levels in Taft, Guadalupe, Araneta Cubao, and North Avenue Stations

Figure 3 shows the relationship between outdoor PM 2.5 and indoor PM 2.5 levels at the four selected MRT-3 stations. Each plot includes a linear regression line and the corresponding equation and R-squared value, indicating the strength of the correlation between outdoor and indoor PM 2.5 levels.
Among the stations, North Avenue has the highest correlation (R^2 = 0.74), suggesting a strong dependency of indoor PM 2.5 levels on outdoor concentrations. This might be due to less effective indoor air filtration, allowing

outdoor particles to infiltrate easily. Araneta Cubao station also exhibits a significant correlation ($R^2 = 0.61$), with a steeper slope (0.667), indicating a strong influence of outdoor PM 2.5 on indoor air quality, though less pronounced than in North Avenue. Guadalupe station has a moderate correlation ($R^2 = 0.40$), while Taft Avenue station shows the weakest correlation ($R^2 = 0.22$), indicating that other factors may play a larger role in PM 2.5 levels at this station.

The y-intercept values differ across stations, with Taft Avenue and Guadalupe having higher baseline indoor PM 2.5 levels compared to North Avenue. This suggests a consistent indoor PM 2.5 presence even when outdoor concentrations are low, potentially from indoor sources like passenger movement or station equipment. In general, North Avenue stands out with the strongest correlation ($R^2 = 0.74$) meaning outdoor PM 2.5 levels heavily influence indoor concentrations. This suggests limited air filtering or high infiltration of outdoor air. Araneta Cubao follows with a moderately strong correlation ($R^2 = 0.61$), indicating similar trends but slightly better indoor air isolation compared to North Avenue.

Guadalupe shows a weaker correlation ($R^2 = 0.40$), implying indoor air quality is less dependent on outdoor levels, possibly due to location near the Pasig River functioning as basin of particles. Taft Avenue, with the weakest correlation (R2 = 0.22), indicates that indoor PM 2.5 is influenced by other sources, such as indoor activities, equipment, or poor ventilation.

Table 1: Infiltration Factor for PM2.5 at selected station and platforms

Stations	Pearson's r	Intercept	Infiltration Factor	p value
Taft Avenue	0.7785	21.6860	0.4470	<0.0001
Guadalupe	0.8820	14.2760	0.8220	<0.0001
Araneta-Cubao	0.8509	15.1080	0.6090	<0.0001
North Avenue	0.9742	1.0010	0.8680	<0.0001

Table 1 presents the infiltration factors for PM 2.5 at selected MRT stations, highlighting variations in PM 2.5 infiltration. North Avenue has the highest correlation (Pearson's r = 0.9742), suggesting that its indoor PM 2.5 levels are strongly influenced by outdoor air quality, while Taft Avenue has the lowest infiltration factor (0.4470), indicating PM2.5 levels are strongly influenced by local emissions. North Avenue station exhibits the highest infiltration factor (0.8680), meaning outdoor PM 2.5 significantly impacts indoor air quality from outdoor sources. The statistically significant p-values (<0.0001) confirm that these relationships are not due to chance.

Meteorological factors were investigated and results suggest that temperature does not influence indoor and outdoor PM 2.5 levels. However, relative humidity levels were linked to increased outdoor PM 2.5 levels. This is likely because higher humidity levels can lead to particle suspension in the air, contributing to elevated PM 2.5 levels while higher relative humidity in indoor cabin could marginally influence PM 2.5 levels. This might result from increased particle suspension which can enhance particle aggregation (Zarandi et al., 2013).

High CO_2 levels during peak hours indicate dense passenger occupancy, which contributes to the resuspension of particles indoors, amplifying PM 2.5 levels. However, CO_2 levels alone are not the primary determinant of PM 2.5 levels, as outdoor PM 2.5 infiltration remains the dominant factor.

4. Concluding Remarks

The 15-day sampling campaign demonstrates a strong interaction between outdoor PM 2.5 levels and indoor PM 2.5 levels in MRT-3 trains, where indoor air quality closely follows outdoor air quality trends. This highlights significant outdoor air infiltration into the train cabins. Stations such as Taft Avenue and Guadalupe consistently experience higher outdoor PM 2.5 levels, contributing to elevated indoor concentrations. This suggests that these stations are more exposed to nearby traffic or urban emissions. During normal hours, indoor PM 2.5 levels tend to be lower and more stable compared to peak hours, indicating that passenger density and outdoor air conditions significantly influence indoor air quality during rush periods.

The study shows significant levels of PM 2.5 observed in key indoor stations and station platforms and it is recommended to install high-efficiency particulate air (HEPA) filters in MRT-3 trains to reduce outdoor PM 2.5 infiltration. Enhance cabin sealing and regularly maintenance of ventilation systems is essential to minimize the exchange of outdoor and indoor air. Measures on improving air quality at key stations like Taft Avenue and Guadalupe requires addressing surrounding emission sources through stricter traffic regulations or emission controls. Regular air quality monitoring inside MRT-3 trains and stations is recommended to assess the effectiveness of implemented measures and to ensure that passengers are exposed to healthier air quality standards. As for future works, it is also paramount to investigate other indoor air pollutants and other station platforms to further broaden the behaviour of PM 2.5 at significant peak hour times.

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