remote sensing

MDPI

Article

Assessing the Air Quality Impact of Train Operation at Tokyo Metro Shibuya Station from Portable Sensor Data

Deepanshu Agarwal, Xuan Truong Trinh * and Wataru Takeuchi

Institute of Industrial Science, The University of Tokyo, Tokyo 153-8505, Japan; wataru@iis.u-tokyo.ac.jp (W.T.)
* Correspondence: truong@iis.u-tokyo.ac.jp

Abstract: Air pollution remains a critical global health concern, with 91% of the world's population exposed to air quality exceeding World Health Organization (WHO) standards and indoor pollution causing approximately 3.8 million deaths annually due to incomplete fuel combustion. Subways, as major public transportation modes in densely populated cities, can exhibit fine particulate matter (PM) levels that surpass safety limits, even in developed countries. Contributing factors include station location, ambient air quality, train frequency, ventilation efficiency, braking systems, tunnel structure, and electrical components. While elevated PM levels in underground platforms are recognized, the vertical and horizontal variations within stations are not well understood. This study examines the vertical and horizontal distribution of PM2.5 and PM10 levels at Shibuya Station, a structurally complex hub in the Tokyo Subway System. Portable sensors were employed to measure PM concentrations across different platform levels—both above and underground—and at various locations along the platforms. The results indicate that above-ground platforms have significantly lower PM2.5 and PM10 levels compared to underground platforms (17.09 $\mu g/m^3$ vs. 22.73 $\mu g/m^3$ for PM2.5; 39.54 $\mu g/m^3$ vs. 56.98 $\mu g/m^3$ for PM10). Notably, the highest pollution levels were found not at the deepest platform but at the one with the least effective ventilation. On the same platform, PM levels varied by up to 63.72% for PM2.5 and 120.23% for PM10, with elevated concentrations near the platform extremities compared to central areas. These findings suggest that ventilation efficiency plays a more significant role than elevation in vertical PM variation, while horizontal differences are likely influenced by piston effects from moving trains. This study underscores the risk of exposure to unsafe PM2.5 levels in underground platforms, particularly at platform extremities, highlighting the need for improved ventilation strategies to enhance air quality in subway environments.

Keywords: air quality; IoT devices; public health; public transport; low-cost sensors

check for updates

Academic Editor: Carmine Serio

Received: 22 November 2024
Revised: 23 December 2024
Accepted: 31 December 2024
Published: 10 January 2025

Citation: Agarwal, D.; Trinh, X.T.; Takeuchi, W. Assessing the Air Quality Impact of Train Operation at Tokyo Metro Shibuya Station from Portable Sensor Data. *Remote Sens.* **2025**, *17*, 235. https://doi.org/10.3390/rs17020235

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The importance of indoor air quality was recognized during the hygienic revolution in the 1850s, but attention shifted to outdoor environmental issues around 1960 [1]. Even though humans spend most of their time indoors—whether in houses, offices, factories, or during transportation—less emphasis is placed on the quality of indoor air compared to ambient air. The history of indoor air pollution dates to early humans who used campfires for warmth and cooking. Eventually, these campfires were brought into shelters to improve efficiency, leading to poor air quality within these spaces [2]. As much as 91% of the population is exposed to air quality levels that exceed WHO standards, and indoor air pollution alone causes 3.8 million deaths annually. Poor air quality is associated with severe

health issues, including stroke, lung cancer, and heart disease, with impacts comparable to those of smoking [3]. In developing regions, unvented indoor biomass burning significantly contributes to mortality, causing at least 2 million deaths per year [1]. Studies show that indoor air quality is influenced by factors like occupant density, ambient air quality, and emissions from vehicles and industries [4,5].

Among many air pollutants, particulate matter (PM) is particularly hazardous as it can penetrate deep into the lungs and enter the bloodstream, leading to short- and long-term health effects, including asthma, respiratory infections, reduced lung function, chronic bronchitis, and premature death. The WHO's safe limits for particulate matter are 50 $\mu g/m^3$ for PM10 and 25 $\mu g/m^3$ for PM2.5 over 24 h, and 20 $\mu g/m^3$ for PM10 and 10 $\mu g/m^3$ for PM2.5 annually.

Alongside accommodation and workplace, air quality during transportation is an important aspect to consider. Research highlights significant variation in air pollution exposure across different transport modes [6–8]. Among public transport modes, subway systems have the highest PM concentrations, with levels up to 8.4 times greater than those in cars [9]. In London, Adams et al. [10] found that cyclists had the lowest exposure, while subway users experienced exposure levels 3–8 times higher than those using surface transport. These findings underline the need to assess the quality of the air that subway users are exposed to mitigate health risks.

Subway systems contribute significantly to PM levels due to mechanical wear and tear of components such as wheels, rails, and brakes, which release metallic particles into the underground environment. Studies have identified iron (Fe) as a dominant component of subway PM, often accompanied by other trace metals such as manganese (Mn), chromium (Cr), copper (Cu), and various rare earth elements. For example, Jung et al. [11] found that in Seoul, most magnetic floor dust particles less than 25 μm were composed of iron metal, which is relatively harmless, but variations in the presence of elements like Na, Mg, Al, Si, S, Ca, and C between stations were attributed to different ballast types used. In Mexico City, increased levels of metals such as Fe, Mn, and Cr in the subway were linked to mechanical disintegration of steel components, while Cu was associated with arc ablation and mechanical friction [12]. Research comparing European subway systems in Barcelona, Athens, and Oporto demonstrated that higher PM2.5 concentrations in subways compared to ambient air are linked to the specific chemical compositions of wheels, rails, brakes, and current supply metals used in different systems [13]. In Barcelona, distinctive "brake flake" particles with inhomogeneous distributions of trace elements like barium were identified as originating from frictional brake wear, highlighting the impact of brake pad materials on PM composition [8]. Additionally, ambient air particles and biological matter can enter the underground environment through ventilation systems and commuter movement, contributing to the overall PM levels observed in subway stations.

Current findings on PM2.5 levels in subway systems worldwide reveal significant variations across different cities, with many underground systems have. Shanghai [14–16] and Seoul [11,17,18] also report elevated PM2.5 levels in their subways, with averages of 231–366 $\mu g/m^3$ and 118–150 $\mu g/m^3$. In contrast, New York City presents lower PM2.5 concentration, an average PM2.5 level of 30.6 $\mu g/m^3$ [19,20]. These disparities suggest that factors such as the age of the subway system, ventilation efficiency, maintenance practices, and local environmental policies play critical roles in influencing air quality. Kam et al. [21] observed that the PM2.5 levels in underground stations are higher than that of ground-level stations in the Los Angeles (56.7 vs. 29.4 $\mu g/m^3$), but at different stations. However, there are uncertainties in the difference in air quality between above-ground train platforms and underground of the same station, as well as among different positions on a platform. While it has been observed that underground air quality is worse than above ground [22,23],

it is not certain if this relationship between platform's depth and air quality is a simple positive correlation. Therefore, in this research, we aim to verify it by comparing the different platforms in the same station. The complex metro system of Tokyo, exemplified by Shibuya station, presents a unique opportunity to observe the vertical and horizontal variation of PM2.5 within the station.

Recent development in portable sensors may enable measurements to clarify those differences. Air quality measurement tools include satellites, ground stations, and portable sensors, each with distinct advantages and limitations. Recent advancements in geostationary satellite technology, such as HIMAWARI, TEMPO, and GEMS, enable the hourly monitoring of air quality parameters for specific locations, enhancing the temporal resolution of observations [24–26]. Also, the ground observing stations offer highly accurate measurements of individual pollutants but are limited by their fixed locations and the high costs associated with widespread deployment. However, while satellite imagery and ground-based stations excel in ambient air quality monitoring, they do not address indoor air quality. Portable sensors can serve as an alternative for indoor air quality measurement, but their accuracy may be affected by calibration issues and environmental factors, such as humidity, which can lead to overestimation of particulate matter levels. Despite these challenges, portable sensors are versatile and valuable for comprehensive air quality assessments in various environments.

This research aims to (1) compare the PM levels at various above-ground and underground platforms to verify if the platform depth's is the most important factor in its PM levels; and (2) compare PM levels variation at various positions on the same platform using portable sensors. It is hypothesized that while underground platforms would have poorer air quality due to the lack of ventilation, air conditioning facilities may affect the PM levels. Furthermore, positions near the extremes of the platforms are thought to have higher PM levels due to the piston effect. Despite being in a closed environment, the air quality may vary even within short distances; positions close to the front part of the train are exposed to more PM concentrations due to train piston effect [13,27]. The train piston effect describes the phenomenon whereby when the train is arriving at a platform in a tunnel, it pushes the air in front of it to the sides and on top of it. Hence, when a train passes by, the walls of the tunnel constrain the air (unlike for above-ground lines), and this pushes the air in front for the train; when train stops, the air is accumulated there. When the train starts to leave the station, there is negative pressure generated in the rear part of the train, so fresh air from the rear ventilation shaft is sucked into the tunnel [27].

As the subway is an important means of transport for the majority of people in densely populated cities, understanding its environment and potential health risks will benefit the wellbeing of the population. The outcome of this study will provide important insights into improving the air quality of metro stations and ensuring a healthy environment for metro users.

2. Materials and Methods

2.1. Measurement Device

For this research, the sensor "Pocket PM2.5", developed and manufactured by Yaguchi Electric Corporation, Miyagi Province, Japan [28], shown in Figure 1, was used for data collection. This portable air quality monitor is a compact device designed to measure particulate matter (PM2.5 and PM10) using laser scattering technology. With a measurement range of 0 to 999 $\mu g/m^3$ and a response time of 10 s, it provides accurate real-time data, maintaining a relative error within $\pm 15\%$ or ± 10 $\mu g/m^3$ under standard conditions (25 °C and 50% humidity). The device draws power directly from a smartphone via a Micro USB connection, eliminating the need for external batteries, and outputs data

in CSV format for spreadsheets and KML for Google Earth and Google Maps integration. Although the product has been discontinued, it was compatible with various Android smartphones and tablets from brands like SHARP, Samsung, Huawei, Sony, ASUS, and Google Nexus. Software applications for Android and Windows, along with user manuals and technical documents, were provided to assist users.



(**a**) (**b**)

Figure 1. (**a**) Portable sensor used in this research. (**b**) Measuring PM2.5 and PM10 using portable sensor at the underground metro platform.

2.2. Description of the Measurement Site and Measurement Setup

The readings were taken at Shibuya Station in Tokyo, Japan, the second busiest train station in the city, with approximately 2.8 million daily users. The station was chosen thanks to its complex structure, having four underground lines and four above-ground lines. This vertical and horizontal variation may help elucidate the variation in PM levels within the station. Data were collected from six lines: Lines 1 and 2 are above ground, while Lines 3, 4, 5, and 6 are underground, Line 3 and 4 are on Basement Level 3, and Lines 5 and 6 on Basement Level 5.

The data for particulate matter were collected using portable sensors in subway stations and platforms. The device was held at chest level while standing two meters from the railway to avoid obstructing ongoing traffic. Readings were taken at various positions on the platforms of these six lines, and the timing of train arrivals and departures was also recorded. The position of the lines can be seen in Figure 2. For trains with five to six cars, readings were taken at three positions on the platform, and for trains with eight to ten cars, readings were taken at four positions. The device was held and monitored by a person standing on the platform. To avoid disrupting passengers during peak times, on weekdays, we avoided the busy 5 PM–7 PM period, while on weekends, we conducted measurements during the less crowded afternoon-to-late-evening hours. This ensured accurate data collection without interfering with passenger flow in and out of trains.

Line 1: The platform is above-ground and ventilated with outdoor air. Trains have five cars, arrive from the left, stop, then depart towards the left side of the figure. The readings were taken at three positions (Figure 2) to measure PM levels at the two extremes positions on the platform and at its center.

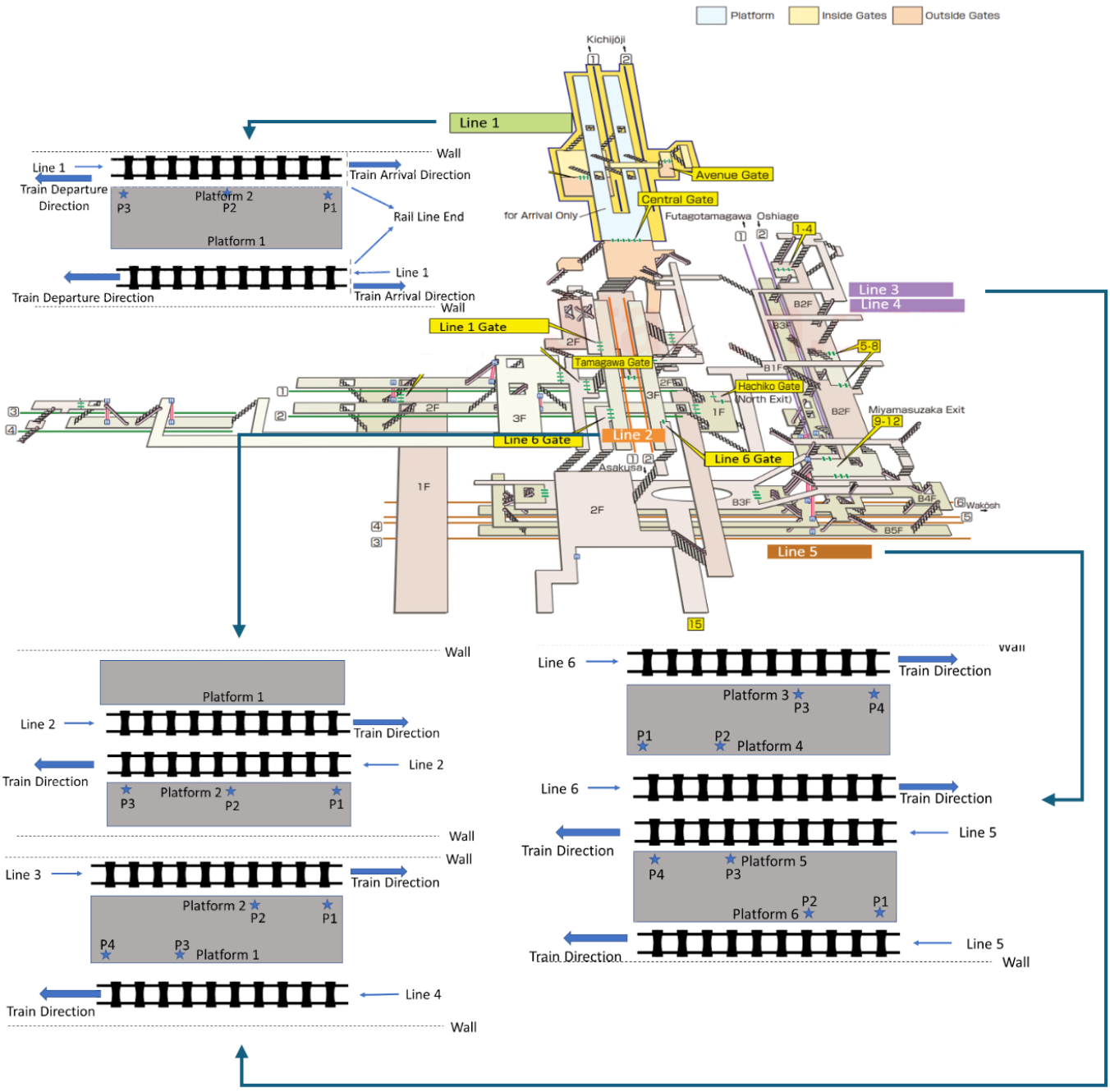

Figure 2. Map of Shibuya Station as of 2019, with the names of Lines 1–6 anonymized [29], ★P1–P4 are positions where the measurements were taken at each line.

Line 2: The platform is above-ground and ventilated with outdoor air. Trains have six cars; inbound trains arrive at Platform 2 from the right and continue without passengers towards the left. Outbound trains arrive at Platform 1 from the left and depart towards the right. The readings were taken at three positions, as shown in Figure 2.

Line 3 and Line 4 are underground lines located opposite each other in the same tunnel at the B3 level, without any ventilation facilities. Trains on both lines have 10 cars each, trains on Line 3 run from left to right and vice versa for Line 4. PM2.5 and PM10 readings were taken at four positions (Figure 2): Positions 1 and 2 on Line 3's platform, and Positions 3 and 4 on Line 4's platform. Positions 1 and 4 are at the ends of their respective platforms, while Positions 2 and 3 are located three cars away from the ends toward the center of the platform.

Line 5 and Line 6: The platforms are underground (B5 level) and ventilated with air conditioners. These two lines have two platform each, totaling four rail lines sharing the same space, with one platform for rail line. Trains have 8–10 cars, trains of Line 5 run from right to left, and vice versa for trains of Line 6. Occasionally, the train may run continuously pass the station without stopping. The readings were taken at four positions for each line, as shown in Figure 2.

Data of PM2.5 and PM10 were collected for 15 min at each position, with readings recorded every 5 s to observe the change in the readings with respect to the arrival and departure of the train (Table 1). It was also observed previously by [30] that PM values are not only affected by train arrival and departure at the nearby rail line but also by train arrival and departure at the far away rail line. We define our terms as follows: for measures taken at P1, a train arriving and departing on Line 1 is a Train Arrival Near (TAN) and Train Departure Near (TDN); and a train arriving and departing on Line 2 is a Train Arrival Far (TAF) and Train Departure Far (Figure 3). Two identical devices were used simultaneously to measure in a part of the measurement campaign. A sample recording is shown in Figure 4, and the rest of the recording is shown in Figures S1–S9.

Table 1. Description of the train lines and platforms of Shibuya station.

Line No.	Line Location	Number of Measurement Positions	Measurement Date	Day Type	Measurement Time	Average Intervals Between Trains (Minutes)	Tokyo's Hourly Average Tempearture (°C) [31]	Tokyo's Hourly Humidity (%) [31]	Shibuya's Daily Average SPM (μg/m^3) [32]
1	Above-ground	3	15 August 2019	Weekday	14:02–14:46	4	31.1	72	29
			17 August 2019	Weekend	15:34–16:19	4	34.2	60	34
2	Above-ground	3	15 August 2019	Weekday	20:17–20:46	1.7	27.8	92	29
			18 August 2019	Weekend	16:21–17:22	1.5	32.7	56	34
3 and 4	Underground (B3F)	4	15 August 2019	Weekday	19:16–19:54	1.6	27.5	94	29
			18 August 2019	Weekend	17:37–18:18	2.3	31.7	60	34
5	Underground (B5F)	4	15 August 2019	Weekday	15:21–16:01	1.9	30.4	76	29
			18 August 2019	Weekend	18:57–20:21	1.9	30.2	65	34
6	Underground (B5F)	4	15 August 2019	Weekday	16:15–16:55	1.9	30.3	76	29
			18 August 2019	Weekend	20:45–22:35 (with 25 min rest)	1.9	27.8	84	34

Data from the Japan Meteorological Agency's past weather records show the hourly temperature (27.5–34.2 °C) and humidity levels (56–94%) at Tokyo station but do not include PM2.5 or PM10 values for the observation dates [31]. These conditions suggest near-standard ambient air during the observation period.

The Suspended Particulate Matter (SPM) levels recorded by ground observation stations in Shibuya district [32] were within a similar range as the PM values measured by the portable sensor for above-ground lines. On 15, 17, and 18 August, the daily average SPM values recorded by the ground station were 29 μg/m^3, 34 μg/m^3, and 34 μg/m^3, respectively, with the highest 1 h values reaching 40 μg/m^3, 48 μg/m^3, and 53 μg/m^3. The average PM2.5 and PM10 values recorded using the portable sensor above the ground lines were 18 μg/m^3 and 22 μg/m^3, respectively.



Figure 3. Schematic diagram explaining the terminology at the platform, ★P1 is a sample measurement position.

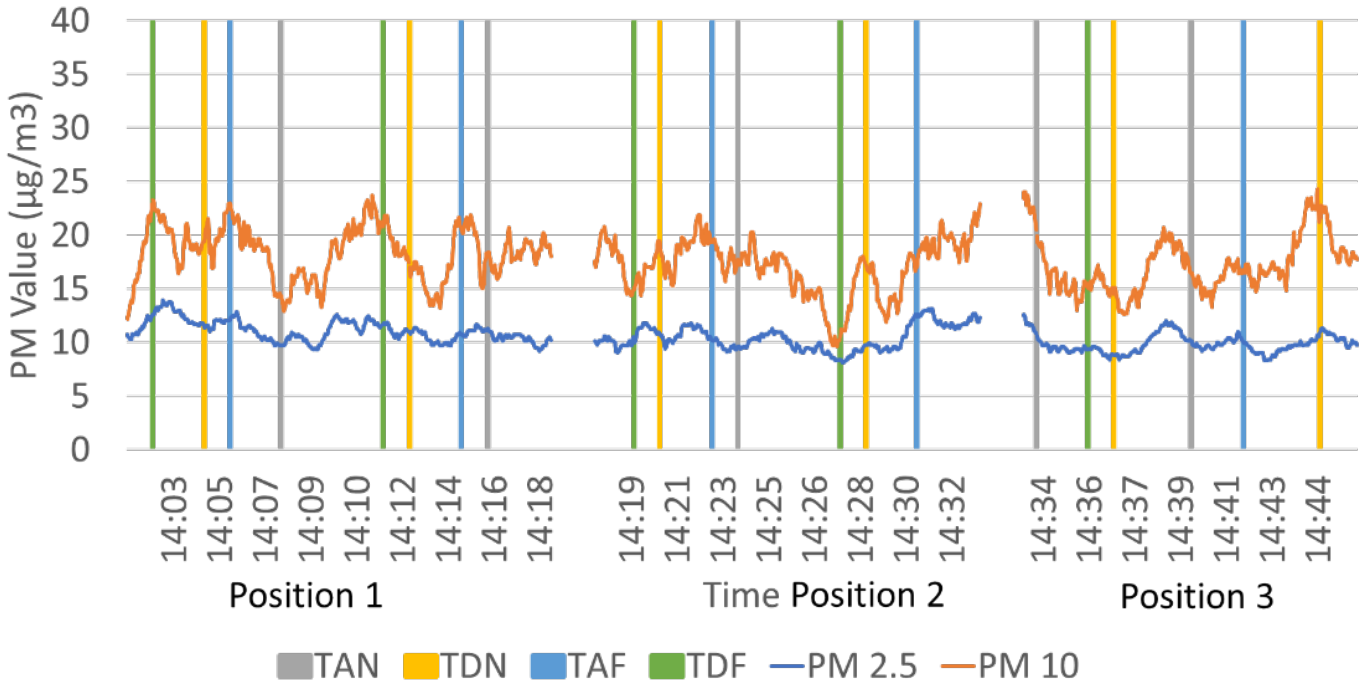

Figure 4. Example of recorded data. Concentration profiles of PM2.5 and PM10 on different positions on Line 1 on a weekday (15 August 2019) (TAN: Train Arrival Near; TDN: Train Departure Far; TAF: Train Arrival Far; TDF: Train Departure Far).

Figure 4 shows the PM levels for an above-ground train line, which is expected to have a stable PM level across positions on the platform. However, for underground lines like Line 5, as demonstrated in Figure S6 and Table S1, the PM 2.5 levels vary significantly, ranging from 29 μg/m^3 (position4) to 47 μg/m^3 (position 1) μg/m^3, while PM 10 levels range from 39 μg/m^3 (position 4) to 86 μg/m^3 (position 1). While the device's accuracy is ±10 μg/m^3 or 15%, these variations are more significant than just a reading error.

2.3. Parameter Selection

Air quality within subway stations is influenced by various factors. This study focuses on two key parameters—platform location (above ground vs. underground) and positions on the platform—to examine their effects on particulate matter (PM) concentrations.

Platform location plays a significant role in determining the PM2.5 inside subway stations. Underground stations tend to have higher PM concentrations compared to above-ground stations due to limited natural ventilation and reduced air exchange with the external environment [17]. The confined spaces of underground platforms can lead to the accumulation of pollutants, whereas above-ground stations benefit from open-air conditions that facilitate pollutant dispersion. By comparing PM levels at different platform locations, we aim to understand how structural differences influence air quality.

It is noted that each train line has a different operation frequency. Train frequency affects PM concentrations and varies depending on weekdays, weekends, and the time of day. During peak hours on weekdays, trains run more frequently to accommodate higher passenger volumes, which can lead to increased turbulence and resuspension of settled particles [12]. Conversely, reduced train frequency during off-peak hours or weekends may result in lower PM levels. By analyzing PM concentrations in relation to train schedules, we can assess how operational patterns influence air quality within the stations.

Positions on the platform impact passenger exposure to PM due to spatial variations in pollutant distribution. Studies have shown that certain areas on the platform, such as those near the front of incoming trains, experience higher PM concentrations. This is attributed to the piston effect [13,27]. By measuring PM levels at different positions, we can identify hotspots of higher pollution and propose strategies to mitigate exposure in these areas.

While our research focuses on these two parameters, other factors may also affect PM concentrations but are beyond the scope of this paper. Ventilation conditions, including the design and efficiency of mechanical and natural ventilation systems, significantly influence air quality by controlling pollutant removal and fresh air intake [33]. Train design elements, such as materials used in wheels and braking systems, contribute to PM through abrasion and wear, releasing metals and other particles into the [8,34]. Atmospheric conditions like wind speed, humidity, temperature, and ambient air quality also impact PM levels within subway stations [35,36]. The Suspended Particulate Matter (SPM) levels recorded by a nearby ground observation station [32] were within a similar range as the PM values measured by the portable sensor for above-ground lines. On August 15, 17, and 18, the average SPM values recorded by the ground station were 29 $\mu g/m^3$, 34 $\mu g/m^3$, and 34 $\mu g/m^3$, respectively, with the highest 1 h values reaching 40 $\mu g/m^3$, 48 $\mu g/m^3$, and 53 $\mu g/m^3$. The corresponding average humidity levels were 72%, 57%, and 58%; average temperatures were 29.5 °C, 31.4 °C, and 31.2 °C; and wind speeds were 1.6 m/s, 1.9 m/s, and 1.1 m/s. These conditions suggest near-standard ambient air during the observation period.

Data from the Japan Meteorological Agency's past weather records did not include PM2.5 or PM10 values for the observation dates [31]. The average PM2.5 and PM10 values recorded using the portable sensor above the ground lines were 18 $\mu g/m^3$ and 22 $\mu g/m^3$, respectively. Future studies could incorporate these parameters for a more comprehensive analysis of factors affecting air quality in subway systems.

3. Results

3.1. Comparison of Particulate Matter Measurements Above-Ground and Underground Lines

Figure 5 shows that the underground lines (Line 3, 4, 5, and 6) have more particulate matter compared to the ones above ground (Line 1 and 2). Notably, the PM2.5 and PM10 concentrations are near—or exceed—safety 24 h standards for underground lines, averaging at 39.54 and 56.98 $\mu g/m^3$ respectively, while above-ground lines are within safe limits, averaging at 17.09 and 22.73 $\mu g/m^3$ respectively (Table 2). Additionally, above-ground platforms have lower PM levels than underground platforms. However, while Lines 3 and

4 are at Basement Level 3, and Lines 5 and 6 are at Basement Level 5, Lines 5 and 6 have lower PM levels than Lines 3 and 4.

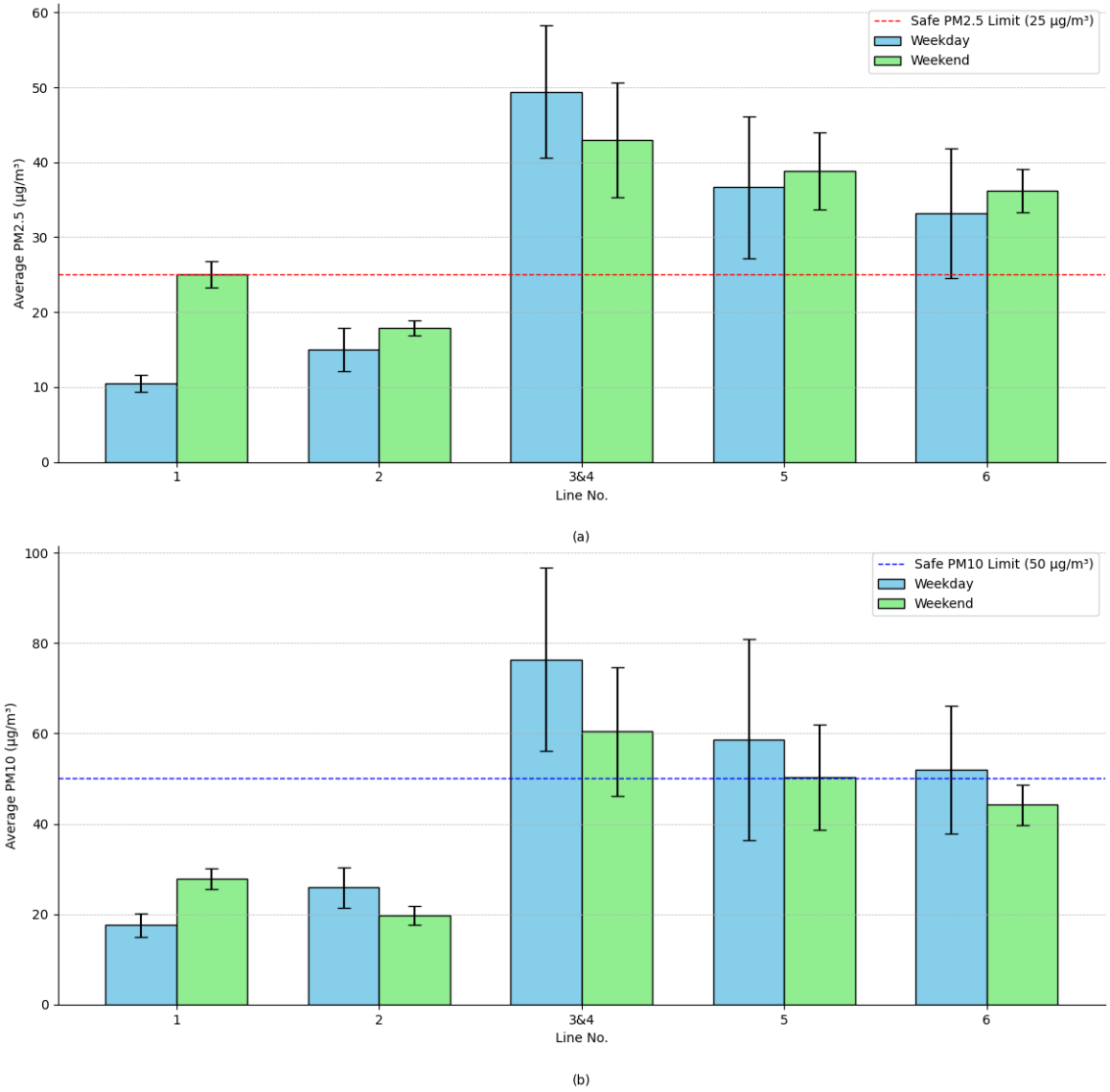

Figure 5. Average values of (**a**) PM2.5 and (**b**) PM10 for above-ground (Line 1 and 2) and underground lines (Lines 3–6).

Table 2. Average values of PM values in different lines in the Shibuya station.

Position	Line No.	Average PM2.5 Levels (µg/m^3)			Average PM10 Levels (µg/m^3)		
		Weekday	Weekend	Average	Weekday	Weekend	Average
Above-ground	1	10.45	25.03	17.09	17.57	27.79	22.73
	2	15.00	17.87		25.89	19.66	
Underground	3 & 4	49.43	42.98	39.54	76.35	60.47	56.98
	5	36.66	38.84		58.58	50.28	
	6	33.17	36.18		51.99	44.22	

For Line 1, it was observed that even though PM2.5 and PM10 concentration was within WHO safety limits, the values were higher on weekends compared to weekdays (Figure 5). For Line 2, PM2.5 concentration levels were almost the same for both weekdays and weekends, and PM10 were higher on weekdays. For Line 3 and Line 4, the average

PM2.5 and PM10 concentration levels were higher on weekdays. For Line 5 and 6, PM2.5 levels were slightly higher on weekends, but PM10 levels were higher on weekdays.

3.2. Comparison of PM Level at Different Positions on the Platform

First, the PM2.5 and PM10 concentrations during weekdays and weekends appear consistent across different positions on the above-ground lines (Lines 1 and 2). For Line 1, the values remain relatively uniform throughout all positions (Figure 6a–d; Tables S1–S4). However, on Line 2 during weekdays, there is a slight elevation in PM2.5 and PM10 levels at Position 3 (Figure 6a,c; Tables S1 and S3). Also, the humidity in the ambient air was higher on weekdays (94%) than on the weekend (60%), which reflects higher readings of PM values (PM2.5: 49 μg/m^3 (weekday), 43 μg/m^3 (weekend); PM10: 76 μg/m^3 (weekday), 60 μg/m^3 (weekend)) for Lines 3 and 4 on weekdays than on the weekend. However, this impact of high humidity was not observed for other lines.

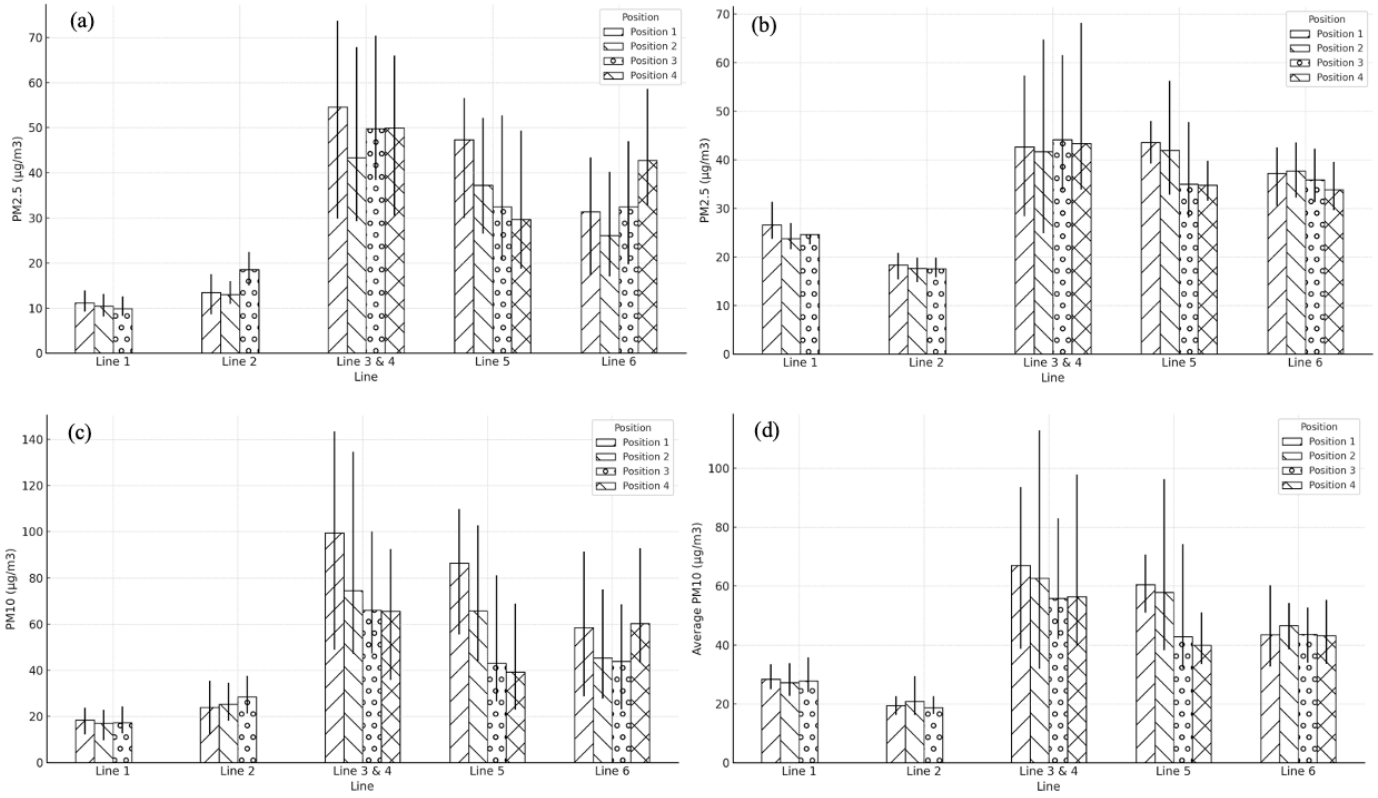

Figure 6. PM levels at different positions, with (**a**) Average PM2.5 on weekdays at different positions, with whiskers showing the range of values. (**b**) Average PM2.5 on weekends at different positions, with whiskers showing the range of values. (**c**) Average PM10 on weekdays at different positions, with whiskers showing the range of values. (**d**) Average PM10 on Weekends at different positions, with whiskers showing the range of values.

In contrast, the underground lines (Lines 3–6) exhibit variations in PM levels among different positions, though these variations are not consistent across all lines. One observable pattern is that the extreme positions—Positions 1 and 4—tend to have higher PM concentrations than the middle positions (Positions 2 and 3). For instance, on Line 6 during weekdays, the PM10 readings at the extremes are significantly higher: Position 1 records 58.52 μg/m^3, and Position 4 records 60.20 μg/m^3, which are approximately 33% higher than the readings at Position 2 (45.32 μg/m^3) and Position 3 (43.93 μg/m^3) (Table S3). Another pattern is that Position 1 consistently shows higher PM levels than the other positions, while Position 4 sometimes has lower PM levels, as observed on Line 5 and, to some extent,

on Line 4 (Figure 6). For example, on Line 5 during weekdays, the PM10 level at Position 1 is 86.44 μg/m^3, which is 120% higher than the level at Position 4, 39.25 μg/m^3 (Table S3).

In these cases, positions with lower PM concentrations fall within safety standards, whereas higher PM levels at the extremes tend to exceed these standards. The variation among different positions on the platforms suggests that air quality may be better at certain locations, while other areas may require enhanced ventilation or air purification measures.

4. Discussion

4.1. PM2.5 Levels at Different Platforms

According to WHO guidelines (WHO Air Quality Guideline Values), the concentration of fine particulate matter (PM2.5) should be less than 25 μg/m^3 for the 24 h mean, and the concentration of coarse particulate matter (PM10) should be less than 50 μg/m^3 for the 24 h mean. At the time of the research, no specific limits for particulate matter in indoor air were established, with recommendations to follow ambient air quality guidelines. The 2021 WHO guidelines for indoor air quality also support this approach. Understanding PM levels on platforms per WHO standards is crucial as they may pose health risks to commuters and station staff [37]. Based on these guidelines, above-ground lines (Lines 1 and 2) are within the limits (assuming the 24 h mean for these lines would be the average value for the period of observation), and is better than most stations globally (Table S5). We acknowledge that additional measurements could have improved the representation of the 24 h mean, but practical constraints during the study made this infeasible.

However, while it is better than most stations globally (Table S5), the PM levels of underground lines (Lines 3, 4, 5, and 6) are equal to or exceed the safety limits. PM levels are lower in Lines 5 and 6 compared to Lines 3 and 4, perhaps because Lines 5 and 6 are in a wider tunnel with four platforms, while the latter are in a narrower tunnel with only two platforms [37]. Furthermore, despite Line 5 and Line 6 being in the same tunnel (i.e., Platform 3 and 4; see Figure 2), Line 6's platforms have lower PM levels. This is perhaps due to the air conditioners equipped on Line 6's platforms, which are absent from Line 5. This suggests that better ventilation and air filtering lowered PM levels, which, in turn, improved air quality.

It can be noted that train frequency does not affect the average PM values. The lowest count for train arrival and departure times is 1 min, which is not very precise. If it were more accurate, it would provide a better understanding of its effect on PM values. However, it was noted that when the train doors open (with the air inside the train initially having lower PM values compared to the platform), there is an exchange of air between the train and the platform. It was observed that the PM value of the air inside the train gradually increases, while the PM value on the platform gradually decreases.

Ventilation plays a critical role, as poor ventilation can lead to higher PM concentrations, particularly in deeper stations [37,38]. The "piston effect", caused by train movement, pushes air through tunnels, influencing PM distribution [22]. Effective mitigation strategies include improved ventilation, the use of electric brakes, and air conditioning systems to reduce exposure and improve air quality [30,35,39]. Understanding and managing these factors is essential for minimizing health risks in subways [40,41]. Effective air conditioning reduced PM exposure inside trains [8].

4.2. PM2.5 Levels at Different Positions on the Platform

Train arrivals and departures have a major impact on PM levels on the platforms. Additionally, train arrivals and departures at distant platforms also significantly influence PM peaks, not just those at nearby platforms. This phenomenon can be explained by the

train piston effect. Although this effect helps reduce PM levels inside the station since, when a train enters the tunnel, it drags air along with it due to fluid viscosity and draws in fresh air from the other end (provided there is ventilation), it eventually accumulates PM at the train exit point. This is consistent with the findings of [37] in the Barcelona subway system.

For instance, in Line 1, at Position 1 on a weekday (Figure 6c, Table S3), the peak PM10 value is 23.2 $\mu g/m^3$, whereas the average value at that position is 18.4 $\mu g/m^3$. There are also more peaks observed at or near train arrivals and departures. A similar observation is seen for Line 2. At Position 1 on Line 3 on a weekday (Figure 6c, Table S3), the PM10 value reaches up to 142.8 $\mu g/m^3$ during a train arrival at another platform, while the average value at the same location is 99.4 $\mu g/m^3$. Similarly, for Line 5, the peak at Position 1 during a train departure at a distant platform is 107.3 $\mu g/m^3$, whereas the average is 86.4 $\mu g/m^3$. Moreover, on Line 6, at Positions 1 and 4, the peak is observed at 91.7 $\mu g/m^3$ during a train departure at another platform, whereas the average value is around 60 $\mu g/m^3$ for both. It is challenging to explain why the train piston effect due to train arrivals and departures at distant platforms is more pronounced compared to nearby platforms.

It can be noted that on above-ground rail lines (Line 1 and Line 2), there is very little difference in PM levels at various positions on the platform (Positions 1, 2, and 3). This is because the train piston effect is more prominent in closed tunnels. However, on the underground rail lines (Line 3, 4, and 5), there are some differences at various position; in particular, PM levels are higher at Position 1 (the train exit point for Lines 3, 4, and 5) compared to other positions. On Line 6, PM levels are almost the same at all positions; this line's platforms are equipped with air conditioners, unlike any other line.

However, there is an irregularity in average PM10 concentrations at different positions on the underground lines, namely, Line 5 and Line 6. In these lines, for Line 5, Positions 1 and 2 experience higher average PM levels than the desired permissible limits, while Positions 3 and 4 are within the safety limits. This is predominantly due to the train piston effect; at these positions, PM accumulates when the train arrives, carrying PM along with the wind, and it accumulates over that region when the train stops. PM can be generated by friction between rail lines and wheels (depending on their material properties) and between catenaries and pantographs. Train piston effects are influenced by various factors, including tunnel structure and platform design. For Lines 3 and 4, the platforms are connected by two tunnels, resulting in a narrower platform space on Basement Level 3. In contrast, for Lines 5 and 6, the platforms are connected by four tunnels, which allows for a wider platform space on Basement Level 5. There is also a possibility of PM accumulating from ambient air through ventilation shafts. However, it was observed that ambient air had much lower concentrations for both PM2.5 and PM10.

5. Conclusions

In Shibuya Station, which is the second busiest station in Japan, it was found that while above-ground train lines have healthy air quality, with an average PM2.5 and PM10 levels at 17.09 $\mu g/m^3$ and 39.54 $\mu g/m^3$ respectively, underground train lines have PM2.5 and PM10 levels that are nearly equal to or exceed the safety limit for daily exposure (22.73 $\mu g/m^3$ and 56.98 $\mu g/m^3$). This difference could be due to the above-ground platforms having better exchange of air with the environment. In addition, it was suggested that having proper ventilation facilities may significantly improve air quality in underground platforms, as we found that deeper platforms with better ventilation had better air quality than shallower ones with poorer ventilation. Also, it was observed that there was significant horizontal variation among positions at the underground platforms, with as much as 120% difference between two points on the same platform at in the same measurement session. This could be attributed to the piston effects, where in a tunnel, the extreme positions near the

entrances and exits of the train carriage have elevated PM concentration compared to those in the middle. There are positions on the underground subway platforms that exceed the safety standards, especially at the extremes of the platforms, necessitating improvements in ventilation. To summarize, this research revealed variations in PM levels within the Shibuya metro station, which can help in the further designing of trains and station structure to reduce the exposure of an individual commuting via the subway system.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/rs17020235/s1: Figure S1: Concentration profiles of PM2.5 and PM10 on different positions on Line 1 on a weekend [17 August 2019]; Figure S2: Concentration profiles of PM2.5 and PM10 on different positions on Line 2 on a weekday [15 August 2019]; Figure S3: Concentration profiles of PM2.5 and PM10 on different positions on Line 2 on a weekend [18 August 2019]; Figure S4: Concentration profiles of PM2.5 and PM10 on different positions on Line 3 and Line 4 on a weekday [15 August 2019]; Figure S5: Concentration profiles of PM2.5 and PM10 on different positions on Line 3 and Line 4 on a weekend [18 August 2019]; Figure S6: Concentration profiles of PM2.5 and PM10 on different positions on Line 5 on a weekday [15 August 2019]; Figure S7: Concentration profiles of PM2.5 and PM10 on different positions on Line 5 on a weekend [17 August 2019]; Figure S8: Concentration profiles of PM2.5 and PM10 on different positions on Line 6 on a weekday [15 August 2019]; Figure S9: Concentration profiles of PM2.5 and PM10 on different positions on Line 6 on a weekend [17 August 2019]; Table S1: Average, minimum, and maximum PM2.5 values on weekdays across various lines and positions; Table S2: Average, minimum, and maximum PM2.5 values on weekends across various lines and positions; Table S3: Average, minimum, and maximum PM10 values on weekdays across various lines and positions; Table S4: Average, minimum, and maximum PM10 values on weekends across various lines and positions; Table S5. Comparison between PM levels measured in this study and other studies [12,17,18,21–23,39,42–59].

Author Contributions: Conceptualization, D.A.; methodology, D.A.; software, D.A.; validation, D.A.; formal analysis, D.A.; investigation, D.A.; resources, D.A. and W.T.; data curation, D.A. and X.T.T.; writing—original draft preparation, D.A.; writing—review and editing, X.T.T. and W.T.; visualization, D.A. and X.T.T.; supervision, W.T.; project administration, W.T.; funding acquisition, W.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Raw data is available upon request to the author.

Acknowledgments: I am deeply grateful to my supervisors for their invaluable guidance and encouragement and to the lab members and staff for their support throughout this journey. Lastly, my heartfelt thanks go to my family for their unwavering support and to the Almighty for this blessing.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Sundell, J. On the History of Indoor Air Quality and Health History. *Indoor Air* **2004**, *14*, 51–58. [CrossRef] [PubMed]
2. Centnerová, L.H. On the History of Indoor Environment and It's Relation to Health and Wellbeing. *REHVA J.* **2018**, *55*, 14–20.
3. Brunekreef, B.; Holgate, S.T. Air Pollution and Health. *Lancet* **2002**, *360*, 1233–1242. [CrossRef] [PubMed]
4. Datta, A.; Suresh, R.; Gupta, A.; Singh, D.; Kulshrestha, P. Indoor Air Quality of Non-Residential Urban Buildings in Delhi, India. *Int. J. Sustain. Built Environ.* **2017**, *6*, 412–420. [CrossRef]
5. Baek, S.O.; Kim, Y.S.; Perry, R. Indoor Air Quality in Homes, Offices and Restaurants in Korean Urban Areas—Indoor/Outdoor Relationships. *Atmos. Environ.* **1997**, *31*, 529–544. [CrossRef]
6. Int Panis, L.; de Geus, B.; Vandenbulcke, G.; Willems, H.; Degraeuwe, B.; Bleux, N.; Mishra, V.; Thomas, I.; Meeusen, R. Exposure to Particulate Matter in Traffic: A Comparison of Cyclists and Car Passengers. *Atmos. Environ.* **2010**, *44*, 2263–2270. [CrossRef]
7. de Nazelle, A.; Fruin, S.; Westerdahl, D.; Martinez, D.; Ripoll, A.; Kubesch, N.; Nieuwenhuijsen, M. A Travel Mode Comparison of Commuters' Exposures to Air Pollutants in Barcelona. *Atmos. Environ.* **2012**, *59*, 151–159. [CrossRef]
8. Martins, V.; Moreno, T.; Minguillón, M.C.; Amato, F.; de Miguel, E.; Capdevila, M.; Querol, X. Exposure to Airborne Particulate Matter in the Subway System. *Sci. Total Environ.* **2015**, *511*, 711–722. [CrossRef]

9. Rivas, I.; Kumar, P.; Hagen-Zanker, A. Exposure to Air Pollutants during Commuting in London: Are There Inequalities among Different Socio-Economic Groups? *Environ. Int.* **2017**, *101*, 143–157. [CrossRef]
10. Adams, H.S.; Nieuwenhuijsen, M.J.; Colvile, R.N.; McMullen, M.A.S.; Khandelwal, P. Fine Particle (PM2.5) Personal Exposure Levels in Transport Microenvironments, London, UK. *Sci. Total Environ.* **2001**, *279*, 29–44. [CrossRef]
11. Jung, H.J.; Kim, B.W.; Malek, M.A.; Koo, Y.S.; Jung, J.H.; Son, Y.S.; Kim, J.C.; Kim, H.K.; Ro, C.U. Chemical Speciation of Size-Segregated Floor Dusts and Airborne Magnetic Particles Collected at Underground Subway Stations in Seoul, Korea. *J. Hazard. Mater.* **2012**, *213–214*, 331–340. [CrossRef]
12. Mugica-Álvarez, V.; Figueroa-Lara, J.; Romero-Romo, M.; Sepúlvea-Sánchez, J.; López-Moreno, T. Concentrations and Properties of Airborne Particles in the Mexico City Subway System. *Atmos. Environ.* **2012**, *49*, 284–293. [CrossRef]
13. Martins, V.; Moreno, T.; Minguillón, M.C.; Van Drooge, B.L.; Reche, C.; Amato, F.; De Miguel, E.; Capdevila, M.; Centelles, S.; Querol, X. Origin of Inorganic and Organic Components of PM2.5 in Subway Stations of Barcelona, Spain. *Environ. Pollut.* **2016**, *208*, 125–136. [CrossRef] [PubMed]
14. Xu, B.; Yu, X.; Gu, H.; Miao, B.; Wang, M.; Huang, H. Commuters' Exposure to PM2.5 and CO_2 in Metro Carriages of Shanghai Metro System. *Transp. Res. D Transp. Environ.* **2016**, *47*, 162–170. [CrossRef]
15. Qiao, T.; Xiu, G.; Zheng, Y.; Yang, J.; Wang, L.; Yang, J.; Huang, Z. Preliminary Investigation of PM1, PM2.5, PM10 and Its Metal Elemental Composition in Tunnels at a Subway Station in Shanghai, China. *Transp. Res. D Transp. Environ.* **2015**, *41*, 136–146. [CrossRef]
16. Lu, S.; Liu, D.; Zhang, W.; Liu, P.; Fei, Y.; Gu, Y.; Wu, M.; Yu, S.; Yonemochi, S.; Wang, X.; et al. Physico-Chemical Characterization of PM2.5 in the Microenvironment of Shanghai Subway. *Atmos. Res.* **2015**, *153*, 543–552. [CrossRef]
17. Kim, K.Y.; Kim, Y.S.; Roh, Y.M.; Lee, C.M.; Kim, C.N. Spatial Distribution of Particulate Matter (PM10 and PM2.5) in Seoul Metropolitan Subway Stations. *J. Hazard. Mater.* **2008**, *154*, 440–443. [CrossRef]
18. Park, D.U.; Ha, K.C. Characteristics of PM10, PM2.5, CO_2 and CO Monitored in Interiors and Platforms of Subway Train in Seoul, Korea. *Environ. Int.* **2008**, *34*, 629–634. [CrossRef]
19. Vilcassim, M.J.R.; Thurston, G.D.; Peltier, R.E.; Gordon, T. Black Carbon and Particulate Matter (PM2.5) Concentrations in New York City's Subway Stations. *Environ. Sci. Technol.* **2014**, *48*, 14738–14745. [CrossRef]
20. Wang, X.R.; Oliver Gao, H. Exposure to Fine Particle Mass and Number Concentrations in Urban Transportation Environments of New York City. *Transp. Res. D Transp. Environ.* **2011**, *16*, 384–391. [CrossRef]
21. Kam, W.; Cheung, K.; Daher, N.; Sioutas, C. Particulate Matter (PM) Concentrations in Underground and Ground-Level Rail Systems of the Los Angeles Metro. *Atmos. Environ.* **2011**, *45*, 1506–1516. [CrossRef]
22. Barmparesos, N.; Assimakopoulos, V.D.; Assimakopoulos, M.N.; Tsairidi, E. Particulate Matter Levels and Comfort Conditions in the Trains and Platforms of the Athens Underground Metro. *AIMS Environ. Sci.* **2016**, *3*, 199–219. [CrossRef]
23. Cheng, Y.H.; Liu, Z.S.; Yan, J.W. Comparisons of PM10, PM2.5, Particle Number, and CO2 Levels inside Metro Trains between Traveling in Underground Tunnels and on Elevated Tracks. *Aerosol Air Qual. Res.* **2012**, *12*, 879–891. [CrossRef]
24. Wang, B.; Yuan, Q.; Yang, Q.; Zhu, L.; Li, T.; Zhang, L. Estimate Hourly PM2.5 Concentrations from Himawari-8 TOA Reflectance Directly Using Geo-Intelligent Long Short-Term Memory Network. *Environ. Pollut.* **2021**, *271*, 116327. [CrossRef]
25. Yang, Q.; Kim, J.; Cho, Y.; Lee, W.J.; Lee, D.W.; Yuan, Q.; Wang, F.; Zhou, C.; Zhang, X.; Xiao, X.; et al. A Synchronized Estimation of Hourly Surface Concentrations of Six Criteria Air Pollutants with GEMS Data. *Npj Clim. Atmos. Sci.* **2023**, *6*, 94. [CrossRef]
26. Zoogman, P.; Liu, X.; Suleiman, R.M.; Pennington, W.F.; Flittner, D.E.; Al-Saadi, J.A.; Hilton, B.B.; Nicks, D.K.; Newchurch, M.J.; Carr, J.L.; et al. Tropospheric Emissions: Monitoring of Pollution (TEMPO). *J. Quant. Spectrosc. Radiat. Transf.* **2017**, *186*, 17–39. [CrossRef]
27. Pan, S.; Fan, L.; Liu, J.; Xie, J.; Sun, Y.; Cui, N.; Zhang, L.; Zheng, B. A Review of the Piston Effect in Subway Stations. *Adv. Mech. Eng.* **2013**, *5*, 950205. [CrossRef]
28. Ishigaki, Y.; Tanaka, K.; Pradana, H.A.; Matsumoto, Y.; Maruo, Y.Y. Citizen Sensing for Environmental Risk Communication. In Proceedings of the Second International Conference on Cyber-Technologies and Cyber-Systems, Barcelona, Spain, 12–16 November 2017.
29. Keio Corporation Shibuya Station Map. Available online: https://www.keio.co.jp/global/routes/stations/shibuya/ (accessed on 8 January 2020).
30. Moreno, T.; Reche, C.; Minguillón, M.C.; Capdevila, M.; de Miguel, E.; Querol, X. The Effect of Ventilation Protocols on Airborne Particulate Matter in Subway Systems. *Sci. Total Environ.* **2017**, *584–585*, 1317–1323. [CrossRef]
31. Japan Meteorological Agency. Available online: https://www.data.jma.go.jp/stats/etrn/view/daily_s1.php?prec_no=44&block_no=47662&year=2019&month=08&day=13&view=p1 (accessed on 22 December 2024).
32. Shibuya Open Data. Available online: https://city-shibuya-data.opendata.arcgis.com/content/24585babf9e84868875ff8509bfad95b/about (accessed on 23 December 2024).
33. Yang, L.; Zhang, Y.; Xia, J. Case Study of Train-Induced Airflow inside Underground Subway Stations with Simplified Field Test Methods. *Sustain. Cities Soc.* **2018**, *37*, 275–287. [CrossRef]
34. Ripanucci, G.; Grana, M.; Vicentini, L.; Magrini, A.; Bergamaschi, A. Dust in the Underground Railway Tunnels of an Italian Town. *J. Occup. Environ. Hyg.* **2006**, *3*, 16–25. [CrossRef]

35. Nieuwenhuijsen, M.J.; Gómez-Perales, J.E.; Colvile, R.N. Levels of Particulate Air Pollution, Its Elemental Composition, Determinants and Health Effects in Metro Systems. *Atmos. Environ.* **2007**, *41*, 7995–8006. [CrossRef]
36. Miskell, G.; Salmond, J.A.; Williams, D.E. Use of a Handheld Low-Cost Sensor to Explore the Effect of Urban Design Features on Local-Scale Spatial and Temporal Air Quality Variability. *Sci. Total Environ.* **2018**, *619–620*, 480–490. [CrossRef] [PubMed]
37. Moreno, T.; Pérez, N.; Reche, C.; Martins, V.; de Miguel, E.; Capdevila, M.; Centelles, S.; Minguillón, M.C.; Amato, F.; Alastuey, A.; et al. Subway Platform Air Quality: Assessing the Influences of Tunnel Ventilation, Train Piston Effect and Station Design. *Atmos. Environ.* **2014**, *92*, 461–468. [CrossRef]
38. Kwon, S.B.; Jeong, W.; Park, D.; Kim, K.T.; Cho, K.H. A Multivariate Study for Characterizing Particulate Matter (PM10, PM2.5, and PM1) in Seoul Metropolitan Subway Stations, Korea. *J. Hazard. Mater.* **2015**, *297*, 295–303. [CrossRef] [PubMed]
39. Martins, V.; Minguillón, M.C.; Moreno, T.; Mendes, L.; Eleftheriadis, K.; Alves, C.A.; de Miguel, E.; Querol, X. Characterisation of Airborne Particulate Matter in Different European Subway Systems. Urban Transport Systems. 2017; pp. 89–110. Available online: https://www.intechopen.com/chapters/52468 (accessed on 20 November 2024).
40. Wen, Y.; Leng, J.; Shen, X.; Han, G.; Sun, L.; Yu, F. Environmental and Health Effects of Ventilation in Subway Stations: A Literature Review. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1084. [CrossRef]
41. Wang, Q. Urbanization and Global Health: The Role of Air Pollution. *Iran J. Public Health* **2018**, *47*, 1644.
42. Pan, S.; Du, S.; Wang, X.; Zhang, X.; Xia, L.; Liu, J.; Pei, F.; Wei, Y. Analysis and Interpretation of the Particulate Matter (PM10 and PM2.5) Concentrations at the Subway Stations in Beijing, China. *Sustain. Cities Soc.* **2019**, *45*, 366–377. [CrossRef]
43. Gerber, A.; Bohn, J.; Groneberg, D.A.; Schulze, J.; Bundschuh, M. Airborne Particulate Matter in Public Transport: A Field Study at Major Intersection Points in Frankfurt Am Main (Germany). *J. Occup. Med. Toxicol.* **2014**, *9*, 13. [CrossRef]
44. Aarnio, P.; Yli-Tuomi, T.; Kousa, A.; Mäkelä, T.; Hirsikko, A.; Hämeri, K.; Räisänen, M.; Hillamo, R.; Koskentalo, T.; Jantunen, M. The Concentrations and Composition of and Exposure to Fine Particles (PM2.5) in the Helsinki Subway System. *Atmos. Environ.* **2005**, *39*, 5059–5066. [CrossRef]
45. Yang, F.; Kaul, D.; Wong, K.C.; Westerdahl, D.; Sun, L.; Ho, K.-f.; Tian, L.; Brimblecombe, P.; Ning, Z. Heterogeneity of Passenger Exposure to Air Pollutants in Public Transport Microenvironments. *Atmos. Environ.* **2015**, *109*, 42–51. [CrossRef]
46. Şahin, Ü.A.; Onat, B.; Stakeeva, B.; Ceran, T.; Karim, P. PM10 Concentrations and the Size Distribution of Cu and Fe-Containing Particles in Istanbul's Subway System. *Transp. Res. D Transp. Environ.* **2012**, *17*, 48–53. [CrossRef]
47. Onat, B.; Stakeeva, B. Assessment of Fine Particulate Matters in the Subway System of Istanbul. *Indoor Built Environ.* **2014**, *23*, 574–583. [CrossRef]
48. Cartenì, A.; Cascetta, F.; Campana, S. Underground and Ground-Level Particulate Matter Concentrations in an Italian Metro System. *Atmos. Environ.* **2015**, *101*, 328–337. [CrossRef]
49. Ramos, M.J.; Vasconcelos, A.; Faria, M. Comparison of Particulate Matter Inhalation for Users of Different Transport Modes in Lisbon. *Transp. Res. Procedia* **2015**, *10*, 433–442. [CrossRef]
50. Vallejo, M.; Lerma, C.; Infante, O.; Hermosillo, A.G.; Riojas-Rodriguez, H.; Cardenas, M. Personal Exposure to Particulate Matter Less than 2.5 Mm in Mexico City: A Pilot Study. *J. Expo. Sci. Environ. Epidemiol.* **2004**, *14*, 323–329. [CrossRef]
51. Van Ryswyk, K.; Anastasopolos, A.T.; Evans, G.; Sun, L.; Sabaliauskas, K.; Kulka, R.; Wallace, L.; Weichenthal, S. Metro Commuter Exposures to Particulate Air Pollution and PM2.5-Associated Elements in Three Canadian Cities: The Urban Transportation Exposure Study. *Environ. Sci. Technol.* **2017**, *51*, 5713–5720. [CrossRef]
52. Braňí, M. The Contribution of Ambient Sources to Particulate Pollution in Spaces and Trains of the Prague Underground Transport System. *Atmos. Environ.* **2006**, *40*, 348–356. [CrossRef]
53. Kim, M.; Sankararao, B.; Kang, O.; Kim, J.; Yoo, C. Monitoring and Prediction of Indoor Air Quality (IAQ) in Subway or Metro Systems Using Season Dependent Models. *Energy Build* **2012**, *46*, 48–55. [CrossRef]
54. Ye, X.; Lian, Z.; Jiang, C.; Zhou, Z.; Chen, H. Investigation of Indoor Environmental Quality in Shanghai Metro Stations, China. *Environ. Monit. Assess* **2010**, *167*, 643–651. [CrossRef]
55. Johansson, C.; Johansson, P.Å. Particulate Matter in the Underground of Stockholm. *Atmos. Environ.* **2003**, *37*, 3–9. [CrossRef]
56. Mohsen, M.; Ahmed, M.B.; Zhou, J.L. Particulate Matter Concentrations and Heavy Metal Contamination Levels in the Railway Transport System of Sydney, Australia. *Transp. Res. D Transp. Environ.* **2018**, *62*, 112–124. [CrossRef]
57. Bolourchi, A.; Atabi, F.; Moattar, F.; Ehyaei, M.A. Experimental and Numerical Analyses of Particulate Matter Concentrations in Underground Subway Station. *Int. J. Environ. Sci. Technol.* **2018**, *15*, 2569–2580. [CrossRef]
58. Cheng, Y.H.; Lin, Y.L.; Liu, C.C. Levels of PM10 and PM2.5 in Taipei Rapid Transit System. *Atmos. Environ.* **2008**, *42*, 7242–7249. [CrossRef]
59. Chen, Y.Y.; Sung, F.C.; Chen, M.L.; Mao, I.F.; Lu, C.Y. Indoor Air Quality in the Metro System in North Taiwan. *Int. J. Environ. Res. Public Health* **2016**, *13*, 1200. [CrossRef] [PubMed]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.