Heliyon 9 (2023) e20116

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

The characteristics of particulate matter in different subway station environmental control systems

Xinru Wang [a,b,*], Liang Xia [c], Fei Pei [d], Zu Wang [c], Yiqiao Liu [d], Li Chang [d], Song Pan [b,e]

[a] College of mechanical engineering, Tianjin university of commerce, Tianjin 300134, PR China
[b] Key Laboratory for Comprehensive Energy Saving of Cold Regions Architecture of Ministry of Education, Jilin jianzhu University, Changchun 130118, PR China
[c] Research Centre for Fluids and Thermal Engineering, University of Nottingham Ningbo China, 315100, PR China
[d] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia
[e] Beijing Key Laboratory of Green Built Environment and Energy Efficient Technology, Beijing University of Technology, Beijing, 100124, PR China

ARTICLE INFO

Keywords:
Particulate matter
PM10
PM2.5
Environmental control system
Subway station

ABSTRACT

Particulate matter (PM2.5, PM10) in urban subway stations can significantly impact passengers' health. The particle concentration in subway stations is influenced by many factors. However, few existing studies have explored the impact of environmental control systems in-depth, especially under different outdoor pollution conditions. To address this research gap, this study focused on measuring and comparing the characteristics of PM2.5 and PM10 at subway stations with three control systems (open, closed, and screen door) under varying pollution conditions in Beijing. Particle concentrations from platforms, carriages, and outdoors were monitored and analyzed using statistical methods. The results showed that the particle concentration in the closed system was generally 20–40 $\mu g/m^3$ higher than that in the screen system at the platform, which might be attributed to the piston wind, as the air from the tunnel with a lot of dirt. The pollution in the carriage was more severe for the open system than that of the screen system. The PM2.5/PM10 ratio in the carriage was 91%, 90%, and 83.84% for the closed, open, and screen systems, respectively. This indicates that the screen door could reduce the particle concentration in the platform to 10%–50%. The particle concentration varied among subway stations with different environmental control systems, suggesting that the prevention and control strategies for particulate matter pollution should be different for stations with different systems.

1. Introduction

The recent large-scale urbanization in China and other regions worldwide has significantly increased traffic volume in large and medium-sized cities. With the development of modern subway systems, these networks now extend to more distant suburbs, covering greater distances and resulting in passengers spending considerably more time in them. The United States Environmental Protection Agency (EPA) found that the average time people spend in subways accounted for 7.2% of their daily lives [1].

A consequence of this that has caused particular concern is the substantial increase in personal exposure to inhalable particulate

* Corresponding author. College of mechanical engineering, Tianjin university of commerce, Tianjin 300134, PR China.
E-mail address: xinru5263@tjcu.edu.cn (X. Wang).

https://doi.org/10.1016/j.heliyon.2023.e20116
Received 4 December 2022; Received in revised form 11 September 2023; Accepted 12 September 2023
Available online 13 September 2023

matter (PM) due to commuting by subway. Particulate matter can be divided into coarse particulate (PM10 > 2.5 μm), fine particulate (PM2.5 > 0.1 μm), and ultrafine particulate (PM < 0.1 μm). Coarse particulate matter can become trapped in the trachea and bronchi of humans, resulting in it either being swallowed or discharged from the respiratory system via coughing [2–7].

Three types of environmental control systems are widely utilized in subway stations globally: open system, closed system, and screen door system. In a subway station employing an open environmental control system as illustrated in Fig. 1(a), the indoor public area is directly linked to the outdoors. Typically, a piston wind shaft and the entrances serve as ventilation for air exchange. In a closed system, as shown in Fig. 1(b), when a train car passes through the tunnel, it is virtually isolated from the outside environment. In a screen door system, as depicted in Fig. 1(c), the wall spans from the ceiling to the floor, thus preventing air from the platform from entering the tunnel. The crucial difference between a closed system and a screen door system lies in the fact that the platform is entirely isolated from the tunnel in the latter.

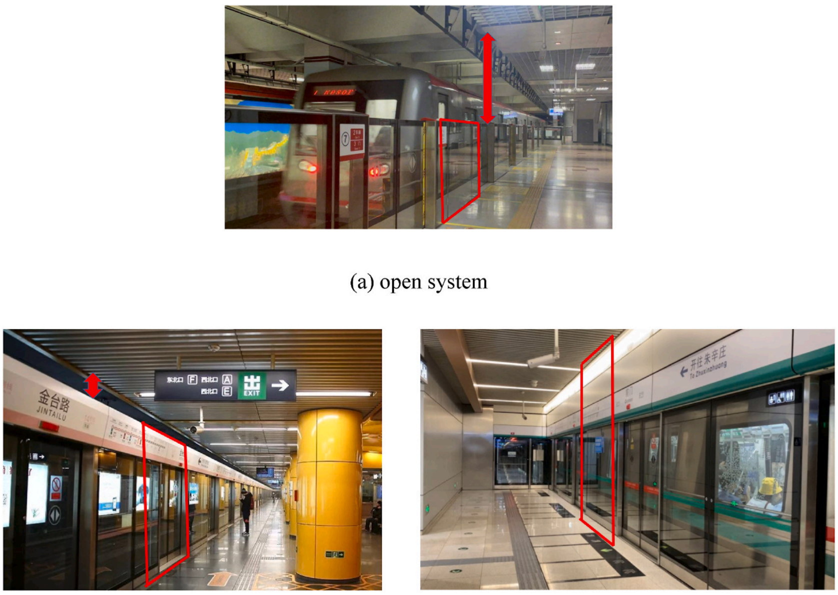
These different systems are designed to meet various needs and requirements of subway stations, depending on factors such as geographical location, climate, and passenger flow. Each system has its advantages and disadvantages, and the choice of which system to use depends on the specific circumstances and priorities of each subway station.

The environment control system plays a pivotal role in maintaining air quality in subway stations. Firstly, the volume of fresh air provided to different locations, such as platforms and carriages, varies under different control systems. Secondly, it also indicates that the supply or required air parameters, such as air temperature, differ between systems. Thirdly, the strategies employed to achieve the desired air quality under different environment control systems are distinct. Therefore, identifying the characteristics and differences of PM2.5 and PM10 at subway stations with various environment control systems holds significant implications for future control strategies and equipment research.

A lot of research has already studied the presence of PM2.5 and PM10 in subway stations [8–50]. The geographical locations covered by this research are shown in Table 1.

The majority of these studies were conducted through on-site testing of particulate matter (PM) at various locations within subway stations, including the station hall and train carriage [4,9–11]. Lepeule et al. [11]measured the concentration of particles in six different cities over eight years in eastern America. Guo et al. [12]discovered that the concentration of particles in the subway was significantly higher than in the surrounding environment. The factors that affect the concentration and distribution of particulate matter (PM) in subway stations include seasonal weather, time of day, traffic density, braking systems, ventilation systems, passenger density, depth, station design, being above ground or underground, duration of station operation, location, piston effects, and outdoor traffic [3,12–14]. In China, there are now thousands of kilometers of subway systems in large and medium-sized cities [14]. Regrettably, there are very few studies that concentrate on the distribution and control of particulate matter (PM) in subways. Additionally, the discontinuous measurements over time in their results, with only a few days of data and sometimes even fewer data in some studies, make any proposed findings rather inconclusive [4,12,15–19].

Despite the scope of the aforementioned research, several issues persist regarding our comprehension of particulate pollution in subway stations. Primarily, nearly all the studies concentrate solely on the characteristics of PM2.5 and PM10, overlooking the impacts



(a) open system

(b) Closed system (c) Screen door system

Fig. 1. Different environmental control systems (the red blocks indicate the platform door and the red arrows indicate the distance from the top of the platform door to the ceiling).

Table 1
The current research regarding PM2.5 and PM10 in subways.

Area	City	Country	Studies
North America	Montreal	Canada	[8]
	New York	America	[10]
	Los Angeles	America	[20]
	Puna	America	[23]
	Philadelphia	America	[44]
	Mexico city	Mexico	[16,24,25]
Europe	Stockholm	Sweden	[26]
	London	England	[15]
	Birmingham	England	[27]
	Paris	French	[21]
	Barcelona	Spanish	[28]
	Milan	Italy	[29]
	Naples	Italy	[45]
	Lisbon	Portugal	[47]
	Istanbul	Turkey	[30]
Asia	Tehran	Iran	[31]
	Seoul	Korean	[9,32,46]
	Fukuoka	Japan	[22]
	Shanghai	China	[12,13,44,49]
	Beijing	China	[7,33,34]
	Guangzhou	China	[35]
	Xi'an	China	[36,50]
	Suzhou	China	[37]
	Tianjin	China	[39]
	Chongqing	China	[48]
	Taipei	China	[38]

of subway station control systems. An exception is He et al. [43], from several years ago who studied the effects of different environmental control systems. Nonetheless, this research was carried out without taking external conditions into account, and primarily centered around health risks, resulting in the omission of crucial data. Additionally, the absence of a clear comparison between various control systems and different types of particulate pollution implies a limited understanding of the effects that different control systems can have.

Nowadays, understanding and controlling the impact of particulate matter in subways on people's health and safety has become a matter of vital concern. Monitoring and analyzing the concentrations and patterns of variation of particulate matter in subway stations is a crucial step towards improving the overall air quality within these transportation hubs and supporting the development of healthy urban transportation systems. This research can contribute to the design of more effective filtration equipment and serve as the basis for further studies.

We conducted a comparative study of different control systems used in subway stations by measuring the particulate matter concentration levels at various locations within them. In Beijing, we monitored particulate matter concentration levels in subway

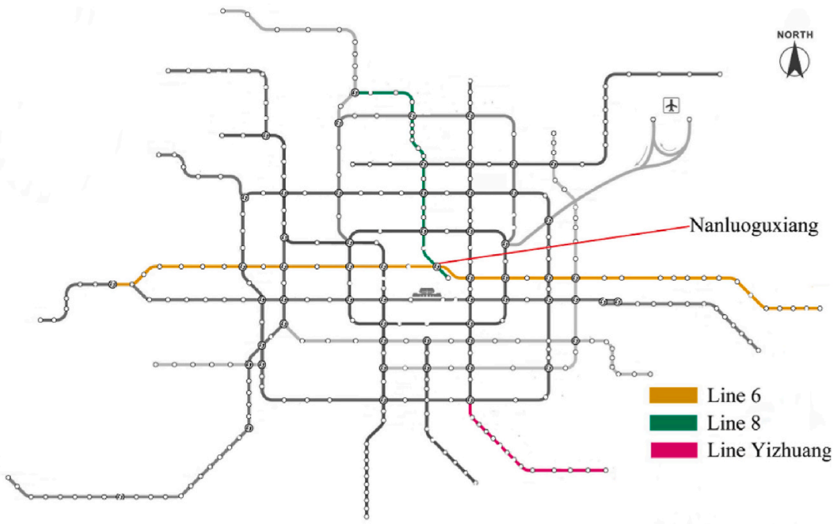


Fig. 2. Monitored subway lines in Beijing: line 6 (green), line 8 (yellow) and Yizhuang (red).

stations across three different lines, each with distinct environmental control systems. To gain a more in-depth understanding of pollution patterns, measurements were also taken at various locations within the stations under a variety of outdoor conditions. This comprehensive approach allowed for a more detailed analysis of how pollution levels vary within these transportation hubs.

2. Background and methodology

2.1. Monitored subway stations and measurement sites

Taking into account the environmental control systems and outdoor conditions, we selected subway stations from Lines 6 (green), 8 (yellow), and Yizhuang (red) in Beijing for monitoring (see Fig. 2). This decision was based on the proximity of these lines and their similar outdoor conditions. All stations on Line 6 have closed environmental control systems, with a total line length of 42.8 km and 26 stations. We chose six stations for monitoring. Line 8 spans a total of 45.6 km with 35 stations, excluding Zhuxinzhuang (ZXZ), which has an open system; the rest have screen door systems. We monitored nine stations on Line 8. As Nanluoguxiang (NLGX) serves as an interchange station for Lines 6 and 8, it was also included in our study. The Yizhuang line has 14 stations and a length of 23.3 km. We only monitored the above-ground stations on this line to provide a comparison with the underground stations.

The measurement sites for all stations are displayed in Fig. 3. We simultaneously tested the four measurement sites at each platform, positioned at a height of 1.5 m. The distance from the screen door or safety door was also set at 1.5 m, with the side wall being 10 m away. Consistent with this method, we used the same measurement points for the platforms of all other stations.

2.2. Measurement parameters and equipment

The monitoring period spanned from December 2016 to January 2017, with additional measurements carried out in March 2017 in working areas. Due to safety concerns, the measurements were only conducted during non-peak hours between 13:00 and 15:00. The testing duration at each measurement site was approximately 30 min per day, with a 1-min interval. The primary parameters monitored both inside and outside the station included the concentrations of PM2.5 and PM10 at various locations such as the platform, passenger hall, outside the station, carriages, and the work area. A portable Dusttrak II aerosol monitor (Model 8532, TSI, USA) was employed to measure the concentrations of PM10 and PM2.5, as well as temperature and humidity, with a resolution of ±0.1%. This device features data logging and a light-scattering laser photometer for real-time aerosol mass readings. During the testing process, the instrument was mounted at a height of 1.5 m from the ground, which corresponds to the breathing zone of a standing individual. The test equipment was calibrated before each measurement was conducted [7] and got regular maintenance in a professional institution. All tests were conducted in strict accordance with the guidelines provided by the subway authorities.

2.3. Data analysis

Different countries have different evaluation standards for concentrations of PM2.5 and PM10. The Chinese standard [51] divides the PM2.5 and PM10 concentration limits into two levels. In this study, we adhered to the second level of standards. Consequently, the mean daily concentration limits for PM2.5 and PM10 were set at 75 μg/m^3 and 150 μg/m^3, respectively.

As is customary in studies such as this, we employed SPSS (Statistical Package for Social Science) to analyze the monitoring data. A general linear model (GLM) was applied to investigate the potential effects of particulate matter concentration in the subway. A general linear model, also known as a multivariate regression model, can be represented as follows:

$$Y = XB + U \tag{1}$$

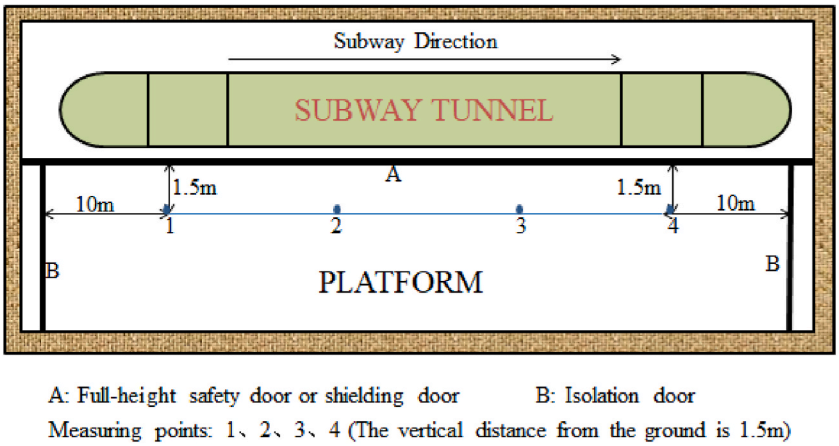


Fig. 3. Schematic of the measurement points on the platforms.

where Y is a matrix with a series of multivariate measurements relating to the dependent variables; X is a matrix of observations regarding the independent variables; B is a matrix containing parameters that are typically estimated; and U is a matrix that is used to capture errors. The relationship between PM10 and PM2.5 at different locations was principally tested using correlation analysis. This form of analysis is a statistical approach that can be used to study the strength of a relationship between two, numerically measured, continuous variables. Pearson's sample correlation coefficient was adopted as the calculation model, i.e.:

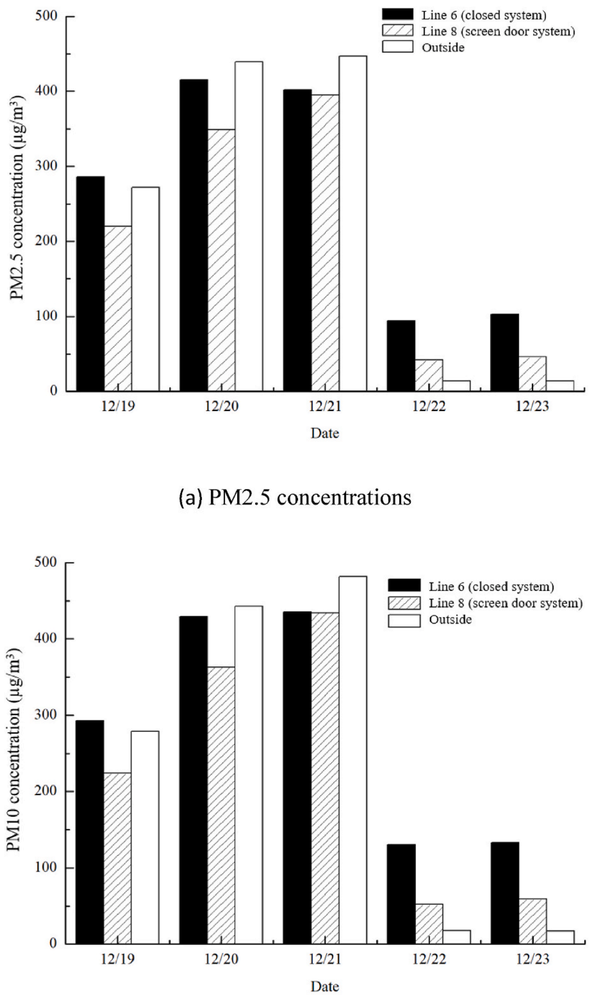
$$\rho = \frac{E[X - E(X)][Y - E(Y)]}{\sqrt{D(X)}\sqrt{D(Y)}} \tag{2}$$

$$\gamma = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}} \tag{3}$$

where, E and D are the mathematical expectation and variance, respectively. ρ is the overall correlation coefficient and γ is the sample correlation coefficient (Pearson's sample coefficient). X and Y are random variables, with x_i and y_i representing the observations.

3. Results and discussion

As previously mentioned, the concentrations of PM2.5 and PM10 for both lines 6 and 8 were carefully monitored. By comparing



(a) PM2.5 concentrations

(b) PM10 concentrations

Fig. 4. Platform measurement results for closed systems and screen door systems.

various stations, our aim was to determine the influence of different environmental control systems on particulate matter concentrations. These findings would then hold significant value for future projections.

3.1. Particulate matter concentration and characteristic at platform

Fig. 4 displays the concentration of PM2.5 and PM10 in closed systems (Line 6) and screen door systems (Line 8) over a week. Six stations with similar passenger flows (approximately 60 passengers/hour) and train frequencies per 5-min interval were selected for each line. Measurements for the two different systems were conducted simultaneously, and an outdoor monitoring point was chosen at NLGX, which is where the two lines intersect. Fig. 4 shows the average values across all the measurement points. The total number of data points exceeds 1000, including outdoor measurements.

Fig. 4 illustrates that, regardless of external concentration or date, particle concentrations of both PM2.5 and PM10 were consistently higher in the closed system (Line 6) compared to the screen door system (Line 8). In Fig. 4(a), in the closed system, the highest concentration of PM2.5 reached 415 μg/m^3, while the lowest was 94 μg/m^3, both of which exceed the standard value of 75 μg/m^3. For the screen door system (Line 8), the maximum concentration of PM2.5 was 395 μg/m^3, and the lowest value was 42 μg/m^3, which is below the standard. In Fig. 4(b), the lowest concentrations of PM10 for both systems were also below the standard limit of 150 μg/m^3.

The PM2.5 and PM10 concentrations of the platform in the screen door system are consistently lower by 10%–50% compared to those in the closed system, regardless of external conditions. This may be attributed to the piston wind effect. In the closed system (Line 6), the platforms are connected to the tunnel, and the concentration of particles on the platform is significantly influenced by the piston wind. In contrast, screen door systems (Line 8) have platforms that are virtually isolated from the tunnel, minimizing the impact of piston wind. Although other factors, such as run time, passenger flow, train frequency, measurement time, and structure, are similar or identical for both lines, the environmental control system appears to be the primary reason for this phenomenon.

Another noteworthy observation from the above results is that outdoor conditions have a considerable impact on subway stations. Regardless of the system, an increase in particle concentration outside led to a corresponding increase in concentration on the platform, and vice versa. This suggests that effective environmental control is crucial to maintaining optimal air quality in subway stations.

To compare the influence of trains on platform particle concentration among different environmental control systems, three types of systems were monitored at Line 6 (closed), Line 8 (screen door), and ZXZ station (an open system at the end of Line 6), before and after trains entered the station. The selection of these stations was based on their similar structure to many other stations of the same type, making them representative of the majority of Beijing stations using the three distinct control systems. The changes in PM2.5 and PM10 concentrations on the platform are presented in Tables 2 and 3. Measurements were taken simultaneously for the three systems, with data recorded 1 min prior to the carriage door opening and 1 min after the door had closed, in order to examine the impact of air from the train on the platform.

As illustrated in Tables 2 and it can be observed that when trains entered the stations and the external conditions were favorable, the concentrations of PM2.5 and PM10 increased. This is because the platform's concentration is higher than in the tunnel, which is directly connected to the outdoors. The percentage increases in PM2.5 for the closed, screen door, and open systems were 29%, 22%, and 0%, respectively. Similarly, the percentage increases in PM10 for each system were 33%, 28%, and 9%, respectively. The highest percentage increase was observed in the closed system, while the lowest was noted in the open system.

However, when there was severe pollution outside, the trend reversed (Table 3). The pollution in the tunnel was heavier than that on the platform. In this case, the open system experienced the highest percentage increase (1.7% and 1.9% for PM2.5 and PM10, respectively), while the lowest increase was recorded for the closed system (−1.7% and −2.8% for PM2.5 and PM10, respectively). The screen door system displayed an intermediate increase under both conditions (1.4% and 0.4% for PM2.5 and PM10, respectively, under the most severe conditions).

In the case of an open system, the station is directly connected to the external environment, making it more susceptible to its influence. Indeed, the impact of the external environment is even greater than that of the tunnel, as the changes outside are more pronounced. On the other hand, both the closed and screen door systems are primarily affected by the internal environment, which includes the tunnel and the passenger hall. As a result, the fluctuations in the concentrations of PM2.5 and PM10 in these systems follow an opposite trend to that of the open system.

A correlation analysis was conducted among the results for the three representative stations. The findings (presented in Table 4) revealed a significant correlation in different systems, with the R-values all less than 0.02, approaching zero. The linear regression equations for PM2.5 concentration in the closed, screen door, and open systems were $Y = 0.622X+91.093$, $Y = 0.602X+41.534$, and $Y = 0.895X+0.522$, respectively. Similarly, the equations for PM10 concentration were $Y = 0.641X+123.335$ in closed systems, $Y = 0.708X+46.103$ in screen door systems, and $Y = 0.902X-7.000$ in open systems. The revised R-squared values ranged from 0.697 to

Table 2
Variations in PM2.5 and PM10 when outside was good (μg/m^3).

	Outside		Closed system		Screen door system		Open system	
	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10
Before train entered	62	68	102	103	81	91	56	62
After train left			143	153	104	126	56	68
Percentage increase			29%	33%	22%	28%	0%	9%

Table 3
Variations in the PM when outside was heavy pollution (μg/m^3).

	Outside		Closed system		Screen door system		Open system	
	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10	PM2.5	PM10
Before train entered	549	573	544	539	438	446	328	359
After train left			535	524	444	448	337	366
Percentage increase			−1.7%	−2.8%	1.4%	0.4%	2.7%	1.9%

Table 4
Correlation analysis for PM levels inside and outside subway stations.

Station	PM	Equations	R	Revised R^2	Sig.
Closed system	PM2.5	Y = 0.622X+91.093	0.880	0.742	0.020
	PM10	Y = 0.641X+123.335	0.992	0.981	0.000
Screen door system	PM2.5	Y = 0.602X+41.534	0.940	0.866	0.000
	PM10	Y = 0.708X+46.103	0.991	0.980	0.000
Open system	PM2.5	Y = 0.895X+0.522	0.857	0.697	0.003
	PM10	Y = 0.902X-7.000	0.963	0.916	0.000

0.981, indicating a strong correlation between PM2.5 and PM10 concentrations in subway stations and external conditions, regardless of the environmental control system in place.

The variable coefficients in the equations represent the degree of variation. In this case, the variable coefficients for the open system were the highest (0.895 for PM2.5 and 0.902 for PM10). This suggests that the open system is most susceptible to external environmental conditions.

3.2. Concentrations and characteristic in the carriages

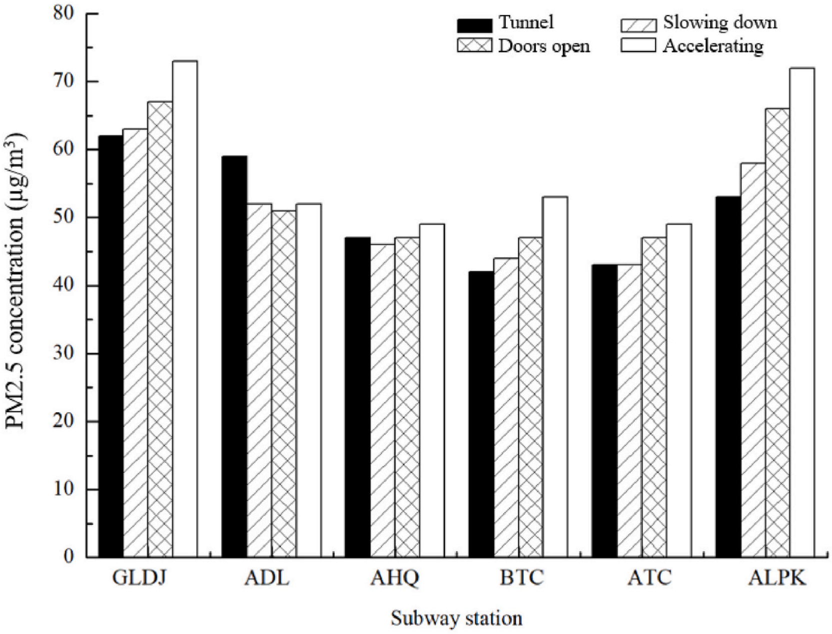
To investigate how airflow from public areas in screen door and open systems may affect particle concentration inside train carriages, we monitored trains running on Line 8 (screen door system) and Yizhuang Line (open system). The environment inside the carriage is similar at both closed system stations and screen door systems, which are controlled by the HVAC system. Therefore, we only present the results for the screen door and open system. On Line 8, six stations including Guloudajie (GLDJ), Andelibeijie (ADL), Anhuaqiao (AHQ), Beitucheng (BTC), Aoti Center (ATC), and Olympic (ALPK) were monitored. On the Yizhuang Line, seven stations were monitored, including Jiugong (JG), Yizhuangqiao (YZQ), Wenhuayuan (WHY), Wanyuanjie (WYJ), Rongjing East Street (RJD), Rongchuang East Street (RCD), and Tongji South Road (TJN). The data was recorded when the carriage was in the tunnel, entering the platform (slowing down), stopping at the platform (doors open), and leaving the platform (accelerating). Measurements were taken over a period of 30 min. The results are averaged across the 30-min period.

Fig. 5 displays the results for Line 8 (screen door system) under two distinct external conditions. When the external environment was favorable, the average PM2.5 concentration measured 18 μg/m^3. The PM2.5 concentration inside all carriages was higher than the external level but below the standard limit (75 μg/m^3). As observed in Fig. 5(a), the PM2.5 concentration generally exhibited a slight increase when the carriage doors were opened; however, this increment was not substantial. In contrast, when the external pollution level was severe (549 μg/m^3) as depicted in Fig. 5(b), the carriage's PM2.5 concentrations at all stations were lower than the external values. The minimum value of 215 μg/m^3 was recorded at ALPK when the doors were open, while the maximum of 292 μg/m^3 occurred at ADL during acceleration. Although these levels were still significantly higher than the standard (75 μg/m^3), they were lower than the external pollution concentrations. Unlike the scenario with good external conditions, a notable decrease in PM2.5 concentration was observed in most stations when the carriage doors were opened. This phenomenon may have been caused by the movement of air between the carriage and the platform, with changes in passenger flow and pressure contributing to the effect.

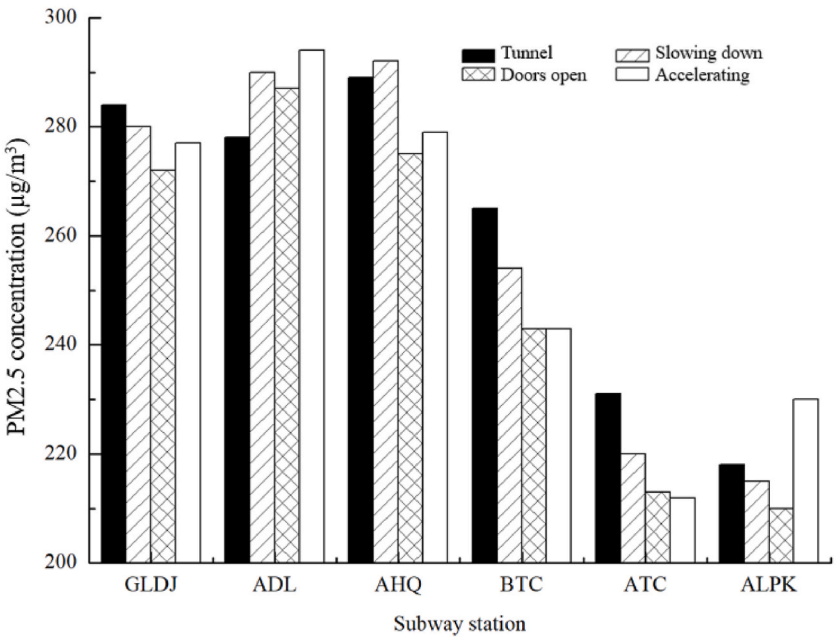
Fig. 6 presents the results for an open system. The patterns of PM2.5 concentration in this case were opposite to those observed in a screen door system (Line 8). When the train was in operation, the concentration typically decreased under favorable external conditions (around 77 μg/m^3) as shown in Fig. 6(a). However, the concentration increased when there was severe external pollution (630 μg/m^3). In Fig. 6(b), in an open system, the platform and tunnel are directly connected to the external environment, hence the particle concentration inside the carriages is significantly influenced by external pollution. As the train operates, infiltration occurs continuously, leading to a noticeable increase or decrease in accordance with the external conditions.

Comparing the findings in Figs. 5 and 6, it can be observed that regardless of the external conditions, the pollution level inside the carriage is consistently higher in the open system compared to the screen door system, especially when the external environment is severely polluted. The PM2.5 pollution in the carriage of the open system is 40%–70% higher than that in the screen door system. This discrepancy is attributed to the differing environmental control systems employed. In the open system, the carriage is directly connected to the tunnel, which in turn, is directly linked to the external environment through an air shaft. Conversely, in the screen door system, the carriage is connected to the tunnel via the HVAC system, which has the capability to filter pollutants within the tunnel.

The PM2.5/PM10 ratio is elevated, posing a greater risk to passengers. The ratio of PM2.5 to PM10 for different environmental control systems under favorable external conditions was calculated and analyzed, as shown in Table 5. With external PM2.5 and PM10



(a) Good outside conditions (PM2.5 was 18μg/m^3)



(b) Heavy pollution outside (PM2.5 was 549μg/m^3)

Fig. 5. p.m.2.5 concentration in the carriages for a screen door system.

levels of 34 μg/m^3 and 37 μg/m^3, respectively, the highest ratio was observed outdoors, at 91.89%. This was followed by the closed system and open system, at 91% and 90%, respectively. The screen door system registered the lowest ratio at 83.84%. This outcome also indicates that the environmental conditions in the screen door system are superior to the others, as the environment is largely influenced by the air control system, and the impact of external and tunnel factors is minimal. In contrast, the open system is directly

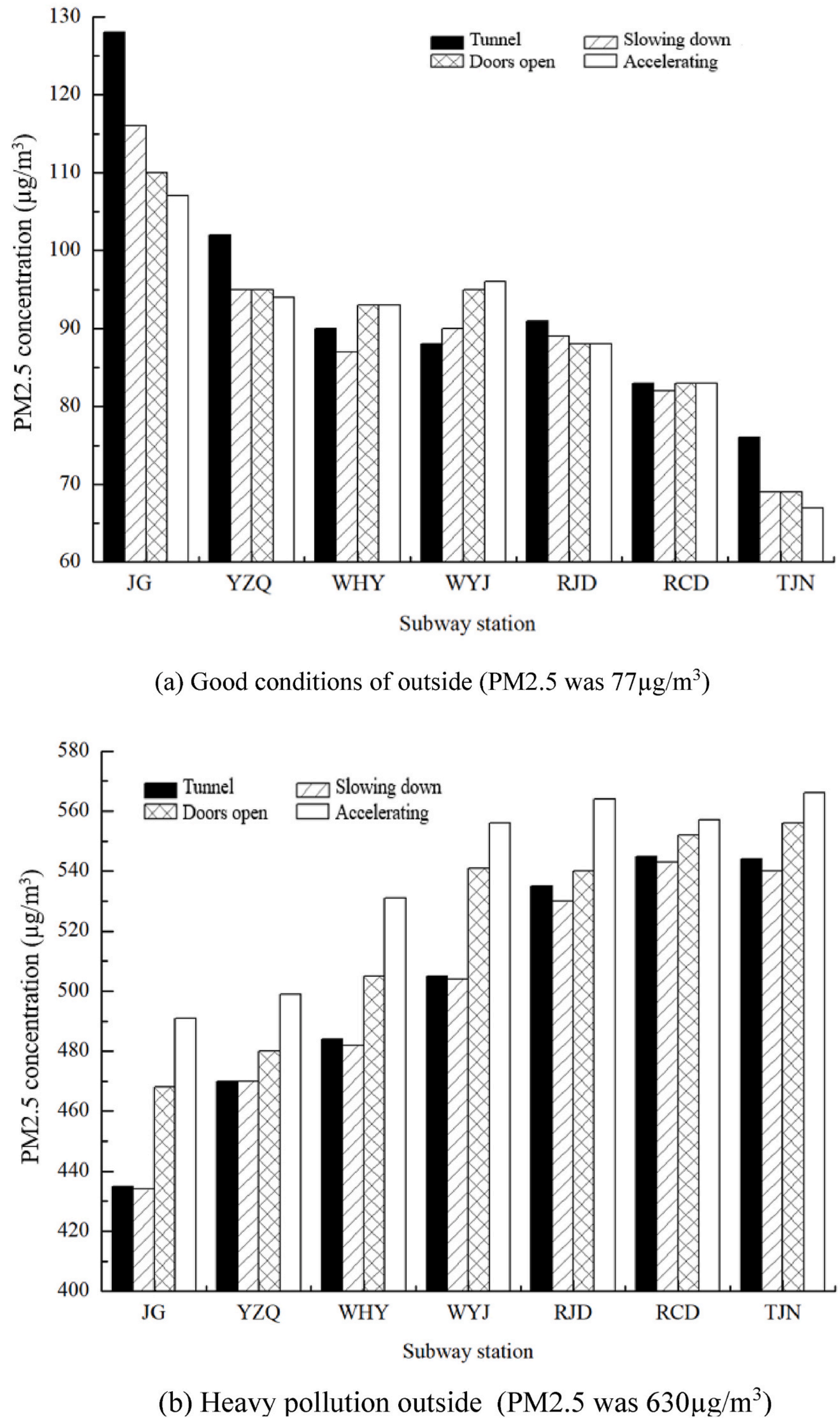


Fig. 6. p.m.2.5 concentration in the carriages for an open system.

connected to the outdoor environment, making it more susceptible to external influences.

4. Limitations

Due to the limitations of measurement conditions, considering the safety of the measured individuals, the convenience of passengers, and the requirements of the subway company, the dataset is not extensive. For future research, long-term measurements at

Table 5
The PM2.5 to PM10 ratio at carriages (μg/m^3).

	Outside	Screen door system	Closed system	Open system
PM2.5	34	83	91	36
PM10	37	99	100	40
PM2.5/PM10	91.89%	83.84%	91%	90%

various stations and locations are necessary for more comprehensive situation studies. Nevertheless, the existing data is statistically significant in demonstrating the general concentration characteristics of PM2.5 and PM10 in different environmental control systems at different locations. In these systems, the values of PM2.5 and PM10 are analyzed and compared under varying outdoor conditions.

The differences in station structure, such as length, width, and depth, passenger flow, seasonality, and operational frequency, were not taken into account in this study. The objective of this paper is to examine the impact of environmental control systems, and to minimize the influence of these factors, measurements were conducted at similar stations with close subway length and depth, and during non-peak periods when passenger flow and operational frequency are comparable. The methodology presented in this paper could be adopted and the results used as a reference for future studies that involve more in-depth and comprehensive measurements.

5. Conclusions

This paper presents the findings of the monitoring and analysis of PM2.5 and PM10 concentrations in subway stations with various environmental control systems in Beijing, China. The particle characteristics at subway stations with three distinct control systems were initially examined and compared at different locations, such as on platforms and within carriages. Furthermore, this study marks the first time that working areas within a closed system have been measured in such an investigation. The primary conclusions are as follows:

The concentration of particles varies at subway stations equipped with different environmental control systems. The PM2.5/PM10 ratio differs between subway stations and outdoor environments, with outdoors having the highest concentration, followed by closed systems and then open systems. This indicates that the screen door system can reduce the particle concentration on the platform to a certain extent. Regardless of the type of environmental control system, the pollution level inside the carriage is higher for the open system compared to the screen system. The PM2.5 and PM10 concentrations at the subway platform show a strong correlation with outdoor conditions. When trains enter the station under favorable outside conditions (PM2.5 was 62 μg/m^3), both PM2.5 and PM10 concentrations increase. However, when there is severe pollution outside, the trend reverses. This suggests that the prevention and control strategies for particulate matter pollution in stations with different systems should be tailored accordingly.

However, there are also limitations to the study, such as the need for more measurements during peak periods and different seasons in the future to further build upon these findings. The continuous accumulation of this type of data will aid in directing future monitoring efforts for the betterment of public health in rapidly evolving transportation systems in urban areas globally.

Author contribution statement

Xinru Wang: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
Liang Xia; Zu Wang; Yiqiao Liu: Contributed reagents, materials, analysis tools or data.
Fei Pei: Performed the experiments.
Li Chang: Analyzed and interpreted the data.
Song Pan: Conceived and designed the experiments.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant Number: 52278121). And the authors gratefully acknowledge the financial support from Key Laboratory for Comprehensive Energy Saving of Cold Regions Architecture of Ministry of Education, Jilin Jianzhu University in Changchun Province (No JLJZHDKF202206).

References

[1] G.X. Qiao Ting, Yi Zheng, Jun Yang, Lina Wang, Jianming Yang, Zhongsi Huang, Preliminary investigation of PM 1, PM 2.5, PM 10 and its metal elemental composition in tunnels at a subway station in Shanghai, China, Transport. Res. Part D 41 (2015) 136–146.

[2] M.T. Araji, S.D. Ray, L. Leung, Pilot-study on airborne PM 2.5, filtration with particle accelerated collision technology in office environments, Sustain. Cities Soc. 28 (2017) 101–107.

[3] Y. Yin, J. He, L. Zhao, J.* Pei, X. Yang, Y. Sun, X. Cui, C.-H. Lin, D. Wei, Q. Chen, Identification of key volatile organic compounds in aircraft cabins and associated inhalation health risks, Environ. Int. 158 (2022) 106–109.

[4] Y.H. Cheng, Z.S. Liu, J.W. Yan, Comparisons of PM10, PM2.5, particle number, and CO2 levels inside metro trains traveling in underground tunnels and on elevated tracks, Aerosol Air Qual. Res. 12 (2012) 879–891.

[5] N. Janssen, den van, N. Hurk, G. Hoek, der van, S. Zee, M. Zuurbier, F. Cassee, Exposure to PM2.5, Black Carbon and ultrafine particles in above- and underground public transport, Proceedings of Environment and Health Bridging South, North, East and West, Basel, Switzerland 8 (2013) 19–23.

[6] L. Karlsson, A.G. Ljungman, J. Lindbom, L. Moller, Comparison of genotoxic and inflammatory effects of particles generated by wood combustion, a road simulator and collected from street and subway, Toxicol. Lett. 165 (3) (2006) 203–211.

[7] P. Song, Saisai Du, Xinru Wang, Xingxing Zhang, Liang Xia, Jiaping Liu, Fei Pei, Yixuan Wei, Analysis and Interpretation of the Particulate (PM 2.5 and PM10) Concentration at the Subway Stations in Beijing, China, Sustainable Cities and Society, 2019, pp. 366–377.

[8] e.a Boudia N, Manganese concentrations in the air of the Montreal (Canada) subway in relation to surface automobile traffic density, Sci. Total Environ. 366 (1) (2006) 143–147.

[9] K.Y. Kim, Y.S. Kim, Y.M. Roh, C.M. Lee, C.N. Kim, Spatial distribution of particulate matter (PM10 and PM2.5) in Seoul Metropolitan Subway stations, J. Hazard Mater. 154 (13) (2008) 440–443.

[10] M.J. Ruzmyn, Vilcassim, D. George, Richard Thurston, E. Peltier, Gordon Terry, Black carbon and particulate matter (PM2.5) concentrations in New York city's subway stations, ES T (Environ. Sci. Technol.) 48 (2015) 14738–14745.

[11] J. Lepeule, F. Laden, D. Dockery, J. Schwartz, Chronic exposure to fine particles and mortality: an extended follow-up of the harvard six cities study from 1974 to 2009, Environ. Health Perspect. 120 (7) (2012) 965–970.

[12] L. Guo, Y.J. Hu, Q.Q. Hu, J. Lin, C.L. Li, J.M. Chen, L.N. Li, H.B. Fu, Characteristics and chemical compositions of particulate matter collected at the selected metro stations of Shanghai, China, Sci. Total Environ. 496 (2014) 443–445.

[13] H. Ma, H.G. Shen, Z. Liang, L.C. Zhang, C. Xia, *Assengers' Exposure to PM2.5, PM10, and CO2 in typical underground subway Platforms in Shanghai.* proceedings of the 8th international symposium on heating, Ventilation and Air Conditioning 261 (2014) 237–245.

[14] L. Yang, Y. Zhang, J. Xia, Case study of train-induced airflow inside underground subway stations with simplified field test methods, Sustain. Cities Soc. 37 (2018) 275–287.

[15] H.S. Adams, M.J. Nieuwenhuijsen, R.N. Colvile, Determinants of fine particle (PM2.5) personal exposure levels in transport microenvironments, London, UK. Atmospheric Environment 35 (27) (2001) 4557–4566.

[16] V. Mugica-Alvarez, J. Figueroa-Lara, M. Romero-Romo, J. Sepulveda-Sanchez, T. Lopez-Moreno, Concentrations and properties of airborne particles in the Mexico City subway system, Atmos. Environ. 49 (2012) 284–293.

[17] GB3095-2012, Environmental air quality standard, 2012.

[18] https://www.datascience.com/blog/introduction-to-forecasting-with-arima-in-r-learn-data-science-tutorials.

[19] Y. Wang, J. Li, X. Li, Subway simulation of co 2, concentration during close mode operation, Sustain. Cities Soc. 28 (2017) 201–208.

[20] W. Kam, Z. Ning, M.M. Shafer, J.J. Schauer, C. Sioutas, Chemical characterization and redox potential of coarse and fine particulate matter (PM) in underground and ground-level rail systems of the Los Angeles metro, Environ. Sci. Technol. 45 (16) (2011) 6769–6776.

[21] R. Bachoual, J. Boczkowski, D. Goven, N. Amara, L. Tabet, D. On, V. Leçonmalas, M. Aubier, S. Lanone, Biological effects of particles from the Paris subway system, Chem. Res. Toxicol. 20 (2007) 1426–1433.

[22] S. Tokarek, A. Bernis, An exemple of particle concentration reduction in parisian subway stations by electrostatic precipitation, Environ. Technol. 27 (11) (2006) 1279–1287.

[23] A. Delbari, M. Hadavifar, H. Haghparast, Concentration and characterization of airborne particles in two subway systems of Islamic Republic of Iran and India, Journal of Air Pollution and Health 1 (2) (2016) 61–68.

[24] Hernandez-Castillo CR, e.a., Whole-brain Connectivity Analysis and Classification of Spinocerebellar Ataxia Type 7 by Functional MRI, Cerebellum Ataxias., 2014, pp. 32–38.

[25] Gomez-Perales, J., Covile, RN, Nieuwenhuijsen, MJ, Fernandez-Brem, Auntz, A, Gutierrez-Avedoy, VJ, Paramo-Figueroa, VH., Commuters' exposure to PM2.5, CO, and benzene in public transport in the metropolitan area of Mexico City. . Atmos. Environ. 38(1219-1229).

[26] K. Midander, K. Elihn, A. Wallen, L. Belova, A.K.B. Karlsson, I.O. Wallinder, Characterisation of nano- and micron-sized airborne and collected subway particles, a multi-analytical approach, Sci. Total Environ. 427 (2012) 390–400.

[27] R. Harrison, A.R. Deacon, M.R. Jones, Sources and processes affecting concentration of PM2.5 and PM10 particulate matter in Birmingham (U.K.), Atmos. Environ. 24 (21) (1997) 4103–4110.

[28] T. Moreno, N. Perez, C. Reche, V. Martins, E. de Miguel, M. Capdevila, S. Centelles, M.C. Minguillon, F. Amato, A. Alastuey, X. Querol, W. Gibbons, Subway platform air quality: assessing the influences of tunnel ventilation, train piston effect and station design, Sci. Total Environ. 427 (2014) 390–400.

[29] C.S. Colombi, V. Angius, M. Gianelle, Lazzarini. , Particulate matter concentrations, physical characteristics and elemental composition in the Milan underground transport system, Atmos. Environ. 70 (2013) 166–178.

[30] U. Şahin, B. Onat, B. Stakeeva, T. Ceran, P. Karim, PM10 concentrations and the size distribution of Cu and Fe-containing particles in Istanbul's subway system, Transport. Res. Transport Environ. 17 (1) (2012) 48–53.

[31] K. Hosein, C.Y.J. Mahdi, H.S. Gholam, Concentration and characterization of airborne particles in Tehran's subway system, Environ. Sci. Pollut. Control Ser. 21 (2014) 7319–7328.

[32] J. Son, J.T. Lee, K.H. Kim, K. Jung, M.L. Bell, Characterization of fine particulatematter and associations between particulate chemical constituents and mortality in Seoul, Korea, Environ. Health Perspect. 120 (2012) 872–874.

[33] J. Huang, F.R. Deng, ShW. Wu, X.B. Guo, Comparisons of personal exposure to PM2.5 and CO by different commuting modes in Beijing, China, Sci. Total Environ. 425 (2012) 52–59.

[34] B. Guan, T. Zhang, X. Liu, Performance investigation of outdoor air supply and indoor environment related to energy consumption in two subway stations, Sustain. Cities Soc. 41 (2018) 513–524.

[35] L.Y. Chan, W.L. Lau, S.C. Zou, Z.X. Cao, S.C. Lai, Exposure level of carbon monoxide and respirable suspended particulate in public transportation modes while commuting in urban, area of Guangzhou, China, Atmos. Environ. 36 (38) (2002) 5831–5840.

[36] M. Gao, J.J. Cao, Seto Edmund, A distributed network of low-cost continuous reading sensors to measure spatiotemporal variations of PM2.5 in Xi'an, China, Environ. Pollut. 199 (2015) 56–65.

[37] S. Cao, X.R. Kong, L. Li, W. Zhang, Z.P. Ye, Y. Deng, An investigation of the PM2.5 and NO2 concentrations and their human health impacts in the metro subway system of Suzhou, China, Environ Sci Process Impacts 19 (2017) 666–675.

[38] W. Kam, K. Cheung, N. Daher, C. Sioutas, Particulate matter (PM) concentrations in underground and ground-level rail systems of the Los Angeles Metro, Atmos. Environ. 45 (8) (2011) 1506–1516.

[39] B. Wang, J.F. Liu, Z.H. Ren, R.H. Chen, Concentrations, properties, and health risk of PM2.5 in the Tianjin City subway system, Environ. Sci. Pollut. Res. 23 (2016) 22647–22657.

[40] V.C. Pun, F. Kazemiparkouhi, J. Manjourides, H.H. Suh, Long-term PM2.5 exposure and respiratory, cancer, and cardiovascular mortality in older US adults, Am. J. Epidemiol. 186 (8) (2017) 961–969.

[41] L. Seung Chul, MinJeong Hongbin Liu, Jeong Kim, Kim Tai, Yoo ChangKyoo, Online monitoring and interpretation of periodic diurnal and seasonal variations of indoor air pollutants in a subway station using parallel factor analysis (PARAFAC), Energy and Building 68 (2014) 87–98.
[42] J.B. Kim, Kim Seyoung, Lee Gwang-Jae, Bae Gwi-Nam, Youngmin Cho, Duckshin Park, Duck-Hee Lee, Soon-Bark Kwon, Status of PM in Seoul metropolitan subway cabins and effectiveness of subway cabin air purifier (SCAP), Clean Technol. Environ. Policy 16 (2014) 1193–1200.
[43] L.J. Shengquan He, Le Tian, Chi Zhang, Xianan Liu, Xiaohong Ming, Commuter Health Risk and the Protective Effect of Three Typical Metro Environmental Control Systems in Beijing,China vol. 62, Transportation Research Part D, 2018, pp. 633–645.
[44] M. Kabindra, A.S. Shakya, Alex Aharonian, Commuter exposure to particulate matter at underground subway stations in Philadelphia, Build. Environ. 186 (2020) 107–122.
[45] Molitierno, A.C.F.C.I.H.C, The role of particle resuspension within PM concentrations in underground subway systems, Int. J. Environ. Sci. Technol. 17 (2020) 4075–4094.
[46] K.K. Jihwan Son, Seungmi Kwon, Seung-Myung Park, Kwangtae Ha, Yunmi Shin, Mijin Ahn, Seogju Cho, Jinho Shin, Yongseung Shin, Gangwoong Lee, Source quantification of PM10 and PM2.5 using iron tracer mass balance in a seoul subway station, South Korea, Aerosol Air Qual. Res. 21 (7) (2021) 1–12.
[47] C. Correia, M. V, I. Cunha-Lopes, T. Faria, E. Diapouli, K. Eleftheriadis, S.M. Almeida, Particle exposure and inhaled dose while commuting in Lisbon, Environ. Pollut. 257 (2020), 113547.
[48] Y.X. Qian Zhao, Jianquan Lin, Hongzhi Mao, Zhen Zeng, Yanan Liu, Measurement-based evaluation of the effect of an over-track-exhaust ventilation system on the particulate matter concentration and size distribution in a subway, Tunn. Undergr. Space Technol. 109 (2021), 103772.
[49] C.Y. Liping Pang, Xiaodong Cao, Qing Tian, Bo Li, Experimental investigation of air quality in a subway station with fully enclosed platform screen doors, Int. J. Environ. Res. Publ. Health 15 (5213) (2020) 1–15.
[50] Z.Q. Jinlong Zheng, H. Oliver Gao, Bing Li, Commuter PM exposure and estimated life-expectancy loss across multiple transportation modes in Xi'an, China, Ecotoxicol. Environ. Saf. 214 (2021) 112–117.