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

xinru Wang (✉ xinru5263@tjcu.edu.cn)

Tianjin University of Commerce

liang xia

University of Nottingham - Ningbo China

fei pei

Universiti Malaya

zu wang

University of Nottingham - Ningbo China

yi qiao liu

Universiti Malaya

li chang

Universiti Malaya

song pan

Beijing University of Technology

Research Article

Keywords: Particulate matter, PM10, PM2.5, environmental control system, subway station

Posted Date: September 10th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-874591/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Abstract

The characteristics of inhalable particulate matter (PM_{2.5}, PM₁₀) in urban subway stations can have a major impact on passengers' health. Existing research largely fails to focus on different environmental control systems and there are few studies focused on different pollution conditions. This study therefore focused on measuring and comparing the characteristics of PM_{2.5} and PM₁₀ at subway stations with three control systems in Beijing different pollution conditions. Stations including three types of control system (open, closed and screen door) and outside were monitored and analyzed using a general linear model. The concentration of PM_{2.5} and PM₁₀ at different locations, such as on platforms, in carriages and in working areas, was compared and analyzed under different external pollution conditions. The results show that at different environment control systems the characteristics of PM_{2.5} and PM₁₀ are different. The concentrations of particles in closed system are generally higher than screen system at platform. While the pollution in carriage is heavier for open system than that of screen system. The PM_{2.5}/PM₁₀ ratio was 91%, 90% and 83.84% at closed, open and screen system, respectively. While, the PM_{2.5} and PM₁₀ levels inside the stations were strongly correlated with the outdoor conditions regardless of the environmental control system. This is the first study to show the PM concentration characteristics for different subway environmental control systems. As such, it provides a solid foundation for air clean studies at subway stations with different control systems.

1 Introduction

The recent large-scale urbanization of China and other places around the world has significantly increased the volume of traffic in large and medium-sized cities. This has had a number of notable convenient outcomes for commuters. In particular, as modern subway systems have developed, they have encompassed ever more far-flung suburbs, increasing the distances they cover and meaning that the average time passengers spend in them has been greatly augmented. The United States Environmental Protection Agency (EPA) found that the average amount of time people spent in subways accounted for 7.2% per day (Qiao, 2015).

A consequence of this that has caused particular concern is that commuting by subway substantially increases people's personal exposure to inhalable particulate matter. 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 (Araji, 2017). According to the sizes, particulates can be subdivided into coarse particulate (PM₁₀ > 2.5 microns), fine particulate (PM_{2.5} > 0.1 microns) and ultrafine particulate (PM < 0.1 microns). Many epidemiological studies have found a positive correlation between the concentration of particulate matter and morbidity from respiratory, heart and lung disease. It has been reported that the risk of cardiopulmonary disease rises by 4% and of lung cancer by 8% when PM_{2.5} concentrations reach a level of 10 µg/m³ (micrograms per cubic meter) (Aarnio, 2005).

A number of researchers have found that long-term exposure to high concentrations of PM_{2.5} in subways can seriously harm human health (Cheng, 2012; Janssen, 2013). Some results suggest that the hazard

from PM_{2.5} in subways is up to ten times greater than it is at ground level (Aarnio, 2005). A comparison of the genotoxic and inflammatory effects of particles generated by wood combustion, on highways, in ordinary city streets and in subways, found that the particles in subways cause more damage to DNA than any other particles ($p < 0.001$). This was put down to the greater presence of redox-active iron (Karlsson, 2006).

Understanding and controlling the impact of particulate matter in subways on people's health and safety is clearly now of vital concern. Monitoring and analyzing PM concentrations and their patterns of variation in subway stations is an essential step towards improving the overall air quality within them and supporting the development of healthy city transportation systems. This can then support the design of more effective filtration equipment and form the basis of further study. We conducted a study that compared different control systems described following in subway stations by measuring the PM_{2.5} levels in different locations within them.

1.1 Subway station environmental control systems

Three types of environmental control system are commonly used in subway stations around the world: an open system, a closed system and a screen door system. In a subway station with an open environmental control system in Fig. 1 (a), the inside public area is directly connected with the outside. Typically, a piston wind shaft and the entrances are used as ventilation for air exchange. These types of subway station are usually above ground or elevated. In a closed system (see Fig. 1 (b)), when a carriage runs through the tunnel, it is almost completely isolated from the outside. The station itself uses a ventilation and air conditioning system and the piston wind caused by the carriage carries cold air into the tunnel to reduce the tunnel temperature. In a screen door system, the tunnel is completely isolated from the station platform by a screen door or glass. In the red circle in Fig. 1 (c), we can see that the wall runs from the roof to the floor, so the air in the platform cannot go into the tunnel and vice versa. The station platform and other public areas are controlled by a ventilation and air conditioning system, while, in the tunnel, the heat has to be carried out or exchanged with the outside air by means of the piston wind generated by the trains when they are moving. The difference between a closed system and a screen door system is that, in the latter, the platform is completely isolated from the tunnel. When compared to a screen door system, a closed system offers greater energy savings, while a screen door system can maintain a more stable environment on the platform, with less fluctuation being caused by the piston wind. Open systems are the most energy-saving of the three, as there is no air conditioning system and fresh air moves directly from outside through the tunnel. The downside of this system is that the air quality varies a lot, according to the outside conditions.

1.2 State of the art

A lot of research has already studied the presence of PM_{2.5} and PM₁₀ in subway stations. The geographical locations covered by this research are shown in Table 1 (Song, 2019). Related studies have taken place in over 10 countries, with the research mostly concentrating on big cities where large numbers of passengers take the subway every day.

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

Area	City	Country	Studies
North America	Montreal	Canada	Boudia N, 2006
	New York	America	Ruzmyn, 2015
	Los Angeles	America	Kam W. Z., 2011
	Puna	America	Delbari1, 2016
	Mexico city	Mexico	Hernandez-Castillo CR, 2014.; Gomez-Perales, 2004; Mugica-Alvarez, 2012
Europe	Stockholm	Sweden	Midander, 2012
	Helsinki	Finland	Aarnio, 2005
	London	England	Adams, 2001
	Birmingham	England	Harrison, 1997
	Paris	French	Bachoual, 2007; Tokarek, 2006
	Bracelona	Spanish	Moreno, 2014
	Milan	Italy	Colombi, 2013
	Istanbul	Turkey	Şahin, 2012
Asia	Tehran	Iran	Hosein, 2014
	Seoul	Korean	Kim K. Y., 2008; Son, 2012
	Fukuoka	Japan	Huang, 2012
	Shanghai	China	Guo, 2014; Ma, 2014)
	Beijing	China	Huang, 2012; Guan, 2018; Pan, 2019
	Guangzhou	China	Chan, 2002
	Xi'an	China	Gao, 2015
	Suzhou	China	Cao, 2017
	Tianjin	China	Wang B. L., 2016
	Taipei	China	Kam W. K., 2011

The majority of this research was conducted via on-site testing of PM at different places in the subway stations, i.e. the station hall, carriages, etc (Cheng, 2012; Kim K. Y., 2008; Ruzmyn, 2015). Corresponding

analysis was then conducted regarding the distribution and physicochemical properties of the PM_{2.5} in each location. Lepeule et al.(Lepeule, 2012) measured the concentration of particles in six different cities over a period of eight years in eastern America. Guo et al.(Guo, 2014) found that the concentration of particles in the subway was much higher than in the outside environment. The factors influencing the concentration and distribution of 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 (Guo, 2014; Ma, 2014; Aarnio, 2005; Boudia N, 2006, Cheng, 2012).

In China there are now thousands of kilometers of subway systems in large-and medium-sized cities (Yang, 2018). In Beijing, over ten million people use the subway every day and spend an hour or more in the underground. Increasing passengers flow in subway transportation are making it increasingly urgent to investigate air quality issues in local stations. Unfortunately, very few studies focus on PM distribution and its control in subways. Besides, the time discontinuous measurements in their results with few days even few data in some studies make any of the proposed findings rather inconclusive (Adams, 2001; Cheng, 2012; Mugica-Alvarez, 2012; Guo, 2014).

Despite the extent of the above-mentioned research, a number of problems remain regarding our understanding of particulate pollution in subway stations. First, almost all of the research focuses solely on the PM_{2.5} and PM₁₀ characteristics, ignoring the effects of subway station control systems. An exception, here, is He et al. (2018), from several years ago who studied the effects of different environmental control systems. However, this research was conducted without consideration of the outside conditions and was mainly focused on health risks, so important data was overlooked. At the same time, the lack of clear comparison of different control systems in relation to different kinds of particulate pollution means that there is not a comprehensive awareness of the impact different kinds of control systems can have.

The environment control system is significant for air quality at subway stations. Firstly, at the different environment control systems, the fresh air volume for different locations such as platform, carriage and so on is different. Secondly, it also represents that the supplied or required air parameters are different, i.e., the air temperature. These two aspects are both mean that the concentration characteristics at different environment control systems are different. Thirdly, different environment control systems also mean the strategies for control to achieve the air quality demand are different. So clearing the characteristics and the differences of PM_{2.5} and PM₁₀ at different subway stations is meaningful for future control strategy and equipment study.

1.3 Contribution and structure of the paper

This paper aims to fill the research gaps mentioned above by comparing the characteristics of PM_{2.5} and PM₁₀ under different conditions at a number of different environmental control systems subway stations, drawing upon newly measured data. We monitored levels of particulate matter in the subway stations on three separate lines in Beijing, with different kinds of environmental control systems. The

measurements at different locations in the stations were also collected under a range of different outside conditions, enabling a much richer analysis of changing patterns of pollution. A further contribution of the paper is its measurement and analysis of the particulate matter conditions in working areas. The health impact of particulate matter for workers in subway stations is an important topic in its own right and this is the first time such measurements have been made because these areas are typically not open to public access.

The structure of this paper is as follows: First, in Sect. 2, it presented the methodology and introduce the different environmental control systems, the monitored stations, the equipment and how to analyze the data. The results of our measurements for different environmental control systems are presented and discussed in Sect. 3. Section 4 provides the study limitation and the future work, and finally, our overall conclusions is presented in Sect. 5.

2 Background And Methodology

2.1 Monitored subway stations and measurement sites

Taking into consideration their environmental control systems and the outside conditions, stations on subway lines 6 (green), 8 (yellow) and Yizhuang (red) in Beijing were selected for monitoring (see Fig. 2), as the locations for these three lines are near, the outside condition is similar whichever it is. All the stations on line 6 are closed environmental control systems. The overall length of the line is 42.8 km, encompassing 26 stations. Six of these were selected for monitoring. Line 8 has a total of 35 stations and a length of 45.6 km. Apart from Zhuxinzhuang station, which has an open system, all of the stations have screen door systems. We tested nine stations on line 8. As Nanluoguxiang (NLGX) station is an exchange station for lines 6 and 8. Yizhuang line has 14 stations and a length of 23.3 km. Only the above-ground stations were monitored on the Yizhuang line, which are described in Sect. 3.3, to provide a comparison with the underground stations.

Nanluoguxiang (NLGX), the exchange station for lines 6 and 8, is located at the junction of Nanluoguxiang street and Dianmen East street. NLGX has an east-west orientation for both lines 6 and 8, as shown in Fig. 3. The depth of lines 6 and 8 at NLGX is the same, but, for line 6, the station has a closed environmental control system and, for line 8, it uses a screen door system. The platforms for both lines allow boarding from both sides.

The measurement sites for all stations are shown in Fig. 4. The four measurement sites were tested simultaneously, at a height of 1.5m. The distance from the screen door or safety door was also 1.5m, while the distance from the side wall was 10m. The same measurement points were used on the platforms at all of the other stations.

2.2 Measurement parameters and equipment

The monitoring period was December 2016 to January 2017, with a few additional days in March 2017 when measurements in working areas were undertaken. For safety reasons, the measurements were only able to take place during non-peak hours between 13:00 and 15:00. The main monitored parameters, both inside and outside of the station, included the concentration of PM2.5 and PM10, the temperature and the humidity, at different sites including the platform, the passenger hall, outside the station, carriages and the work area. A portable Dusttrak II aerosol monitor (Model 8532, TSI, USA - see Fig. 5) was used to monitor the concentrations of PM10 and PM2.5, the temperature, and the humidity, with $\pm 0.1\%$ resolution. This device incorporates data-logging and a light-scattering laser photometer for real-time aerosol mass readings. The data logging interval was set at 1 minute. The test equipment was calibrated before conducting the measurements (Song, 2019) and the testing had to take place following strict instructions from the subway authorities.

2.4 Data analysis

Different countries have different evaluation standards for concentrations of PM2.5 and PM10. The United States uses the Environmental Protection Agency (EPA) standard published in 2006. The Chinese standard (GB3095-2012, 2012) divides the PM2.5 and PM10 concentration limits into two levels. The first level is similar to the EPA standard, the second level is lower. In this study, we adopted the second level. Thus, the mean daily concentration limit for PM2.5 was taken to be $75\mu\text{g}/\text{m}^3$ and $150\mu\text{g}/\text{m}^3$ for PM10.

As is commonplace with studies of this nature, SPSS (the Statistical Package for Social Science) was used to analyze the monitoring data, with a general linear model (GLM) being applied to examine the potential effects of the particulate matter concentration in the subway. A general linear model, or multivariate regression model, is a statistical linear model that can be written as follows:

$$Y = XB + U \quad (1)$$

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 errors are usually assumed to be uncorrelated across the measurements and to follow a multivariate normal distribution. If the errors do not follow a multivariate normal distribution, the assumptions about Y and U can be relaxed.

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.:

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

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

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. The results of applying this analytic approach are described in Chap. 3.

3 Results And Discussion

As noted above, we monitored the concentration of PM2.5 and PM10 for both lines 6 and 8. By comparing different stations, we wanted to identify the impact of different environmental control systems on particulate matter concentration. The results should then be meaningful for future forecasts.

3.1 Platform particulate matter concentration for different conditions

Figure 6 shows the platform concentration of PM2.5 and PM10 for closed systems (line 6) and screen door systems (line 8) over a week. Six stations with similar passenger flows (about 60) and train frequencies per five minutes interval were selected for each line. Measurements for the two different systems were made at the same time and an outside monitoring point was chosen at NLGX, which is where the two lines cross. The measurements were taken at a non-peak time, from 13:00 to 15:00. The values in Fig. 6 are the average values across all the measurement points shown in Fig. 5. The total number of data is over 1000 including outside measurement.

Figure 6 shows that, no matter what the concentration outside or the date, the particle concentrations for both PM2.5 and PM10 were higher for the closed system (line 6) than for the screen door system (line 8). For the closed system, the highest concentration of PM2.5 was $415 \mu\text{g}/\text{m}^3$, while the lowest was $94 \mu\text{g}/\text{m}^3$. Both of these are higher than the standard ($75 \mu\text{g}/\text{m}^3$). The highest concentration of PM2.5 for the screen door system (line 8) reached $395 \mu\text{g}/\text{m}^3$ and the lowest value was $42 \mu\text{g}/\text{m}^3$ (below the standard). The lowest concentration of PM10 for both systems was below the standard of $150 \mu\text{g}/\text{m}^3$.

The concentrations of PM2.5 and PM10 at platform in screen door system is lower than that in closed system whatever the outside it is. This maybe caused by the piston wind which is related to control system. The platforms on line 6 (with a closed system) are connected with the tunnel and the concentration of the particles on the platform is significantly affected by the piston wind caused by trains, with particles in the tunnel being driven onto the platform by the piston wind. For screen door systems (line 8), the platforms are almost completely isolated from the tunnel, the piston wind has little effect. While for all other factors, including run time, passenger flow, train frequency, measurement time

and structure, the two lines are similar or the same. So, the environmental control system maybe the main reason for this phenomenon.

Something else to notice about the above results is that, whatever the system, when the particle concentration outside increased, the concentration on the platform increased as well, and vice versa. Thus, the outdoor conditions have a significant effect on subway stations. However, when the concentration outside was very low, for instance on the 22nd and 23th, with a PM2.5 concentration of just 14 $\mu\text{g}/\text{m}^3$, the platform pollution was higher than it was outside, which contradicts the measurements made on the 20th and 21st. This may have been caused by an accumulation of these particles, as the subway is half-enclosed and the ventilation system is closed at night, preventing the particles from being effectively removed.

To compare the impact of trains on platform particle concentration in relation to the different environmental control systems, the three different kinds of system were monitored on line 6 (closed), line 8 (screen door) and at Zhuxinzhuang station (an open system at the end of line 6), before and after trains had entered the station. The reason for choosing these stations was that they had a similar structure to many other stations of their type. Thus, they could be considered representative of the majority of stations in Beijing using the three different control systems. The changes in PM2.5 and PM10 concentrations on the platform are shown in Tables 2 and 3. The measurements were taken at the same time for the three different systems, with the data being recorded one minute before the carriage door opened and one minute after the door had closed, to test the impact of the air in the train on the platform. Each state was monitored 30 times. The results are the average of the 30 measurements.

Table 2

Variations in PM2.5 and PM10 for the different systems as trains passed through the stations when the outside conditions were good ($\mu\text{g}/\text{m}^3$)

	Outside		Closed system (Dongdaqiao line 6)		Screen door system (Anhuaqiao line 8)		Open system (Zhuxinzhuang line 8)	
	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 for the different systems as trains passed through the stations when there was heavy pollution outside ($\mu\text{g}/\text{m}^3$)

	Outside		Closed system (Dongdaqiao line 6)		Screen door system (Anhuaqiao line 8)		Open system (Zhuxinzhuan line 8)	
	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%

It can be seen in Table 2 that, when trains entered the stations and the outside conditions were good, the concentration of PM2.5 and PM10 increased. Because the concentrations at platform is higher than in tunnel, where is directly connected with outside. The percentage increase in PM2.5 for the closed system, screen door system and open system was 29%, 22% and 0%, respectively. The percentage increase in PM10 for each system was 33%, 28% and 9%, respectively. The percentage increase for the closed system was the highest and lowest for open door system. However, when there was heavy pollution outside, the trend was the opposite. As the pollution in tunnel is heavier than platform. The open system had the highest percentage increase (1.7% and 1.9% for PM2.5 and PM10, respectively) while the lowest increase was measured for the closed system (-1.7% and -2.8% for PM 2.5 and PM10, respectively). The screen door system was in the middle under both conditions (1.4% and 0.4% for PM2.5 and PM 10, respectively, under the worst conditions).

In the case of an open system, the station is directly connected with the outside, so the outside environment has an obvious effect upon it. Indeed, the effect of the outside environment is even greater than the tunnel, because the changes outside are more pronounced. In the case of both closed and screen door systems, they are chiefly affected by the inside environment. This includes both the tunnel and the passenger hall. So, the fluctuations in the concentrations of PM2.5 and PM10 follow an opposite trend to the open system.

3.2 Concentrations in the carriages

To understand how airflow from the public areas in the screen door and open systems may affect the concentration of particles in train carriages, we monitored inside trains running on line 8 (screen door system) and the Yizhuang line (open system). The environment in carriage is similar at closed system stations and screen door system, where are both controlled by HVAC system, so we only show the results of 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), Wenhua Yuan (WHY), Wanyuanjie (WYJ), Rongjing East street (RJD), Rongchuan East street (RCD) and Tongji South Road (TJN). The data was recorded when the carriage was in the tunnel, entering the platform (slowing down), stopped at the platform (doors open) and leaving the platform (accelerating). The measurements were taken over a period of thirty minutes. The results are averaged across the 30 minutes.

Figure 7 shows the results for line 8 (screen door system) with two different outside conditions. When the outside conditions were good, the average PM_{2.5} concentration was 18 µg/m³. The carriage PM_{2.5} concentration in all stations was higher than outside but lower than the standard (75 µg/m³). It can be seen in Fig. 7(a) that the PM_{2.5} concentration generally increased slightly when the carriage doors opened, but the increase was not significant. When there was heavy pollution outside (549 µg/m³) in Fig. 7(b), the carriage levels in all stations, a minimum of 215 µg/m³ when the doors were open at ALPK and a maximum of 292 µg/m³ when the train was accelerating at ADL, were lower than outside, but still much higher than the standard (75 µg/m³). Unlike when the outside conditions were good, when the carriage doors opened, there was an obvious decrease in the PM_{2.5} concentration in most stations. This may have been caused by the movement of air between inside the carriage and the platform, with changes in the passengers and pressure adding to the phenomenon.

Figure 8 shows the results for an open system (the Yizhuang line). Here, the patterns of PM_{2.5} concentration were the opposite of those for a screen door system (line 8). While the train was running, the concentration generally decreased when the outside conditions were good (around 77 µg/m³) in Fig. 8(a), but the concentration increased when there was heavy pollution outside (630 µg/m³). In an open system, the platform and tunnel are directly connected with the outside environment, so the concentration of particles in the carriages is significantly affected by external pollution. While the train is running, the infiltration is continuous, so there is an obvious increase or decrease in keeping with the conditions outside.

Comparing the results in Figs. 7 and 8, the results showed that no matter what the outside it is, the pollution in carriage is heavier for open system than that of screen system, especially when the outside is heavy polluted, the values for open system is much higher than that of screen system. This is caused by the difference of environment control system. As carriage at open system is directly connected with tunnel, and tunnel is directly connected with outside through air shaft. While the carriage at screen door system is connected with tunnel through HVAC system, which could filter the pollution in the tunnel.

3.3 Working area concentrations

The work areas were almost totally located underground, which is closed off from the outside and the environment is controlled by HVAC system for all different control system at subway stations. The work areas in a subway station with a screen door system were monitored to assess the PM_{2.5} pollution conditions affecting station staff. The results are shown in Fig. 9. The station used an air conditioning system in the work areas and the outside conditions were good during our measurements, with PM_{2.5}

concentration of $54 \mu\text{g}/\text{m}^3$. It can be seen in Fig. 9, that the corridor had the highest concentration ($105 \mu\text{g}/\text{m}^3$), and most rooms at working areas is heavier polluted than outside. The staff remain for long periods in the work areas, so the quality of the environment has an important impact on their health. Combined with the results showed in Fig. 9, though the research undertaken here was preliminary and rather constrained as a result of subway regulations, but we strongly advocate the regular inclusion of work areas in future studies of this kind.

3.4 The ratio of PM2.5 to PM10 at carriage

The higher of ratio of PM2.5 to PM10 at carriage, the higher risk to passenger. The PM2.5 to PM10 ratio for different environmental control systems was also calculated and analyzed across when the outside condition was good. The results are shown in Table 4. The outside PM2.5 and PM10 were $34 \mu\text{g}/\text{m}^3$ and $37 \mu\text{g}/\text{m}^3$. The highest ratio was outside, at 91.89%. This was followed by the closed system and open system, respectively, at 91% and 90%. The lowest was for the screen door, at 83.84%. This result also reveals that environment in screen door is better than others, as the environment is almost related to air control system, the effects by outside and tunnel is the least. While the open system is directly related to outdoor environment, the outside environment has the highest influence.

Table 4

The PM2.5 to PM10 ratio for different environmental control systems ($\mu\text{g}/\text{m}^3$)

	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%

3.5 Correlation analysis at platform

As discussed in Sect. 2.4, a correlation analysis was undertaken between the results for the three representative stations mentioned in Sect. 3.2 and outside conditions using the data in Sect. 3.2. The results show that the correlation in different systems is all obvious, as the significant values are less 0.02, near 0. The PM2.5 linear regression equation for the closed systems was $Y = 0.622X + 91.093$. For the screen door systems, it was $Y = 0.602X + 41.534$. For the open systems it was $Y = 0.895X + 0.522$. The PM10 linear regression equation was $Y = 0.641X + 123.335$ for the closed systems, $Y = 0.708X + 46.103$ for the screen door systems and $Y = 0.902X - 7.000$ for the open systems. The range for the revised R^2 was 0.697–0.981. As this is approaching 1, it suggests that, regardless of the environmental control system, PM2.5 and PM10 concentrations in subway stations have a strong correlation with the outside conditions. The variable coefficients in the equations represent the degree of variation. The variable

coefficients for the open system were the highest (0.895 for PM2.5 and 0.902 for PM10). This means that the open system is the most easily affected by the outside conditions.

Table 5
Correlation analysis for PM levels inside and outside subway stations with different environmental control systems

Station	PM	Equations	R	Revised R ²	Sig.
Closed system (Dongdaqiao)	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 (Anhuaqiao)	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 (Zhuxinzhuang)	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

4 Limitations

Limited by measurement conditions, as the measurement is very difficult considering the measured people's safety, passengers' convenience and requirement from subway company, the number of data is not big. Especially for working areas, where is forbidden except workers, the data is small, only one station. For future study, longtime measurement at different stations and locations is need for more situation studies. However, the existed data are statistically significant to show the general concentration characteristics of PM2.5 and PM10 at different environment control systems as different location. In these systems, the values of PM2.5 and PM10 are analyzed and the comparison are conducted under different outside conditions.

The differences of station structure such as length, width, and depth, the passengers' flow and the operation frequency are not considered in this study. As the objective for this paper is to study the influence of environment control system, to reduce these factors' effects, the measurement is conducted at one line or similar stations where the subway length and depth are near, and the measurement time is non-peak period, when the passengers' flow and the operation frequency are similar. And method in this paper could be co-opted and the results could be reference for future deeper and boarder measurement studies.

5 Conclusions

This paper has presented the results of the monitoring and analysis of PM2.5 and PM10 concentrations in subway stations with different environmental control systems in Beijing, China. SPSS was used to

analyze potential correlations between particulate matter concentrations. The particle characteristics at subway stations with three different control systems were first studied and compared at different locations, such as on the platforms and in the carriages. In addition, the working areas in a closed system were measured for the first time in such a study. The ratios of PM_{2.5}/PM₁₀ at different stations and the correlations between stations with different systems and the outside were analyzed and compared. The main conclusions were as follows:

- When trains entered the station under good outside conditions (PM_{2.5} was 62 µg/m³), the PM_{2.5} and PM₁₀ concentrations both increased. The percentage increase for closed systems was the highest, at 29% and 33%, respectively, while the open system had the lowest increase at 0% and 9%. However, when there was heavy pollution outside, the trend was the opposite.
- When the outside conditions were good (PM_{2.5} was 18 µg/m³), the PM_{2.5} concentration in carriages in all stations was higher than it was outside. When there was heavy pollution outside (PM_{2.5} was 549 µg/m³), the carriage concentrations were lower than outside.
- The results showed that no matter what the outside it is, the pollution in carriage is heavier for open system than that of screen system, especially when the outside is heavily polluted.
- The PM_{2.5} to PM₁₀ ratio was highest outside, at 91.89%. This was followed by the closed system, then the open system. While the screen door system ratio was 83.84%, which reveals that the particle content is different.
- Correlation analysis between inside and outside the subway stations showed that, regardless of the kind of environmental control system, the PM_{2.5} and PM₁₀ concentrations at subway platform have a strong correlation with the outside conditions.

But there are also limitations, i.e., more measurements are required in the future to build upon this work, including a wider range of measurements in working areas in stations with different environmental control systems. The ongoing assembly of this kind of data will help to drive future monitoring for the greater benefit of public health in evolving transport systems in urban areas around the world.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant Number: 51578011), the Ningbo Innovation Team Project (2017C510001), the International Cooperation project of Hebei province (18394317D) and the NCHI Research and Collaboration Fund (I01200300014). And the authors gratefully acknowledge the financial support from Key Laboratory for Comprehensive Energy Saving of Cold Regions Architecture of Ministry of Education

References

- Aarnio, P. T.-T. (2005). The concentrations and composition of and exposure to fine particles (PM_{2.5}) in the Helsinki subway system. *Atmospheric Environment*, 39(28), 5059-5066.
- Adams, H. S. (2001). Determinants of fine particle (PM_{2.5}) personal exposure levels in transport microenvironments, London, UK. *Atmospheric Environment*, 35(27), 4557-4566.
- Araji, M. T. (2017). Pilot-study on airborne pm 2.5, filtration with particle accelerated collision technology in office environments. *Sustainable Cities & Society*, 28, 101-107.
- Bachoual, R. B. (2007). Biological effects of particles from the Paris subway system. . *Chem. Res. Toxicol*, 20, 1426–1433.
- Boudia N, e. a. (2006). Manganese concentrations in the air of the Montreal (Canada) subway in relation to surface automobile traffic density. . *Science Total Environment*, 366(1), 143-147.
- Cao, S. K. (2017). An investigation of the PM_{2.5} and NO₂ concentrations and their human health impacts in the metro subway system of Suzhou, China. *Environ Sci Process Impacts*, 19, 666-675.
- Chan, L. Y. (2002). Exposure level of carbon monoxide and respirable suspended particulate in public transportation modes while commuting in urban, area of Guangzhou, China. *Atmospheric Environment*, 36(38), 5831-5840.
- Cheng, Y. H. (2012). Comparisons of PM₁₀, PM_{2.5}, Particle Number, and CO₂ Levels inside Metro Trains Traveling in Underground Tunnels and on Elevated Tracks. *Aerosol and Air Quality Research*, 12(5), 879-891.
- Colombi, C. S. (2013). Particulate matter concentrations, physical characteristics and elemental composition in the Milan underground transport system. *Atmospheric Environment*, 70, 166-178.
- Delbari¹, A. H. (2016). 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), 61-68.
- Gao, M. C. (2015). A distributed network of low-cost continuous reading sensors to measure spatiotemporal variations of PM_{2.5} in Xi'an, China. . *Environmental Pollution*, 199, 56-65.
- GB3095-2012. (2012). *Environmental air quality standard*.
- Gomez-Perales, J. C.-B.-A.-F. (2004). Commuters' exposure to PM_{2.5}, CO, and benzene in public transport in the metropolitan area of Mexico City. . *Atmospheric Environment*, 38, 1219-1229.
- Guan, B. Z. (2018). Performance investigation of outdoor air supply and indoor environment related to energy consumption in two subway stations. . *Sustainable Cities & Society*, 41, 513-524.

- Guo, L. Y. (2014). Characteristics and chemical compositions of particulate matter collected at the selected metro stations of Shanghai, China. *Science of the Total Environment*, 496, 443-452.
- Harrison, R. D. (1997). Sources and processes affecting concentration of PM_{2.5} and PM₁₀ particulate matter in Birmingham (U.K.). . *Atmospheric Environment*, 24(31), 4103-411.
- Hernandez-Castillo CR, e. a. (2014.). Whole-brain connectivity analysis and classification of spinocerebellar ataxia type 7 by functional MRI. *Cerebellum Ataxias*. .
- Hosein, K. M. (2014). Concentration and characterization of airborne particles in Tehran's subway system. . *Environment Science Pollution Research*, 21, 7319-7328.
- <https://www.datascience.com/blog/introduction-to-forecasting-with-arima-in-r-learn-data-science-tutorials>. (n.d.).
- Huang, J. D. (2012). Comparisons of personal exposure to PM_{2.5} and CO by different commuting modes in Beijing, China. *Science of the Total Environment*, 425, 52-59.
- Janssen, N. v. (2013). Exposure to PM_{2.5}, 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, 19-23.
- Kam, W. K. (2011). Particulate matter (PM) concentrations in underground and ground-level rail systems of the Los Angeles Metro. *Atmospheric Environment*, 45(8), 1506-1516.
- Kam, W. Z. (2011). Chemical Characterization and Redox Potential of Coarse and Fine Particulate Matter (PM) in Underground and Ground-Level Rail Systems of the Los Angeles Metro." . *Environmental Science & Technology*, 45(16), 6769-6776.
- Karlsson, L. L. (2006). Comparison of genotoxic and inflammatory effects of particles generated by wood combustion, a road simulator and collected from street and subway. *Toxicology Letters*, 165(3), 203-211.
- Kim, J. S.-J.-N.-H.-B. (2014). Status of PM in Seoul metropolitan subway cabins and effectiveness of subway cabin air purifier (SCAP). *Clean Techn Environ Policy*, 16, 1193-1200.
- Kim, K. Y. (2008). Spatial distribution of particulate matter (PM₁₀ and PM_{2.5}) in Seoul Metropolitan Subway stations. *Journal of Hazardous Materials*, 154(13), 440-443.
- Lepeule, J. F. (2012). Chronic Exposure to Fine Particles and Mortality: An Extended Follow-up of the Harvard Six Cities Study from 1974 to 2009. *Environmental Health Perspectives*, 120(7), 965-970.
- Ma, H. H. (2014). Passengers' Exposure to PM_{2.5}, PM₁₀, and CO₂ in Typical Underground Subway Platforms in Shanghai. *Proceedings of the 8th International Symposium on Heating, Ventilation and Air Conditioning*, 261, 237-245.

- Midander, K. K. (2012). Characterisation of nano- and micron-sized airborne and collected subway particles, a multi-analytical approach. *Science of the Total Environment*, 427, 390-400.
- Moreno, T. N. (2014). Subway platform air quality: Assessing the influences of tunnel ventilation, train piston effect and station design. *Science of the Total Environment*, 427, 390-400.
- Mugica-Alvarez, V. J.-L.-R.-S.-M. (2012). Concentrations and properties of airborne particles in the Mexico City subway system. . *Atmospheric Environment*, 49, 284-293.
- Pun, V. C. (2017). Long-Term PM_{2.5} Exposure and Respiratory, Cancer, and Cardiovascular Mortality in Older US Adults. *American Journal of Epidemiology*, 186(8), 961-969.
- Qiao, T. G. (2015). Preliminary investigation of PM₁, PM_{2.5}, PM₁₀ and its metal elemental composition in tunnels at a subway station in Shanghai, China. . *Transportation Research Part D*, 41, 136-146.
- Ruzmyn, M. V. (2015). Black Carbon and Particulate Matter (PM_{2.5}) Concentrations in New York City's Subway Stations. . *Environment Science Technology*, 48, 14738-14745.
- Şahin, U. O. (2012). PM₁₀ concentrations and the size distribution of Cu and Fe-containing particles in Istanbul's subway system. *Transportation Research Part D Transport & Environment*, 17(1), 48-53.
- Seung Chul, L. H. (2014). 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, 87-98.
- shengquan he, L. J. (2018). Commuter health risk and the protective effect of three typical metro environmental control systems in Beijing,China. *Transportation Research Part D*, 633-645.
- Son, J. L. (2012). Characterization of fine particulate matter and associations between particulate chemical constituents and mortality in Seoul, Korea. *Environ Health Perspect*, 120, 872-874.
- Song, P. S. (2019). Analysis and interpretation of the particulate (PM_{2.5} and PM₁₀) concentration at the subway stations in Beijing, China. *Sustainable Cities and Society*, 366-377.
- Tokarek, S. B. (2006). An exemple of particle concentration reduction in parisian subway stations by electrostatic precipitation. . *Environmental Technology*, 27(11), 1279-1287.
- Wang, B. L. (2016). Concentrations, properties, and health risk of PM_{2.5} in the Tianjin City subway system. *Environ Sci Pollut Res*, 23, 22647-22657.
- Wang, Y. L. (2017). "Subway simulation of CO₂ concentration during close mode operation". . *Sustainable Cities & Society*, 28, 201-208.
- Yang, L. Z. (2018). Case study of train-induced airflow inside underground subway stations with simplified field test methods. . *Sustainable Cities & Society*, 37, 275-287.

Figures

(a) open system

(b) Closed system

(c) Screen door system

Figure 1

Different environmental control systems (the red circles indicate how the closed system allows air to pass between the tunnel and the platform, while the screen door system keeps the two areas sealed off from one another)

Figure 2

Monitored subway lines in Beijing: line 6 (green); line 8 (yellow); and Yizhuang (red)

(a) Line 6

(b) Line 8

Figure 3

Schematic of Lines 6 and 8 at NLGX station

Figure 4

Schematic of the measurement points on the platforms (screen door system, with similar points being used in all stations)

Figure 5

TSI 8532 monitoring device

Figure 6

Platform measurement results for closed systems and screen door systems: top - PM2.5 concentrations; bottom - PM10 concentrations

(a) Good outside conditions (PM2.5 was 18 µg/m³)

(b) Heavy pollution outside (PM2.5 was 549 µg/m³)

Figure 7

PM2.5 concentration in the carriages for a screen door system

(a) Good outside conditions (PM2.5 was 77 µg/m³)

(b) Heavy pollution outside (PM2.5 was 630 µg/m³)

Figure 8

PM2.5 concentration in the carriages for an open system

Figure 9

PM2.5 concentrations in the various work areas