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Evaluation of particulate matter concentration in Shanghai's metro system and strategy for improvement

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ABSTRACT

The air quality in Shanghai's subway system has become a big concern. At present, the system is the longest in the world, and its daily passenger volume exceeds 9×10^6 travelers every work day. In this study, we comprehensively assessed the fine particulate matter ($PM_{2.5}$) concentrations in the 14 lines of Shanghai's metro system through field measurements in the metro (subway) system and real-time data acquisition at the nearest state-run air sampling sites. We ranked and clustered the 14 lines according to the $PM_{2.5}$ concentrations and the relative concentrations in the halls and on the platform of the metro station and inside the train for each line. We identified the factors that influence the $PM_{2.5}$ concentration, and found that the external environment appears to have the strongest influence on air quality. In addition, the age of the line, type of platform (screen door versus half-height security door), air-conditioning filtration system, and other factors influenced the $PM_{2.5}$ concentration for each line. Based on our evaluation of the contamination and its causes, we propose potential solutions, such as reducing particulate matter invasion from pollution sources, updating the environmental protection hardware (i.e., filtration systems), developing a more scientific cleaning program, and optimizing the travel behavior of passengers and working conditions of merchants to improve the air quality and reduce traveler exposure to pollution in the metro system.

1. Introduction

Metro (subway) systems have quickly become the main mode of transportation in the world's cities due to their convenience, safety, high speed, and environmental benefits. Currently, metro passenger volumes in London, Paris, New York, and Tokyo account for 35%, 37%, 54%, and 86%, respectively, of their total transportation demand. In China, the average daily passenger volume of Beijing's metro in 2015 was 7.728×10^6, versus 8.395×10^6 in Shanghai. With the continuous expansion of the metro network, travelers are staying longer in this part of the transportation system. The typical one-way commute time is 48, 52, and 51 min in New York, Beijing, and Shanghai, respectively. The metro employees and merchants stay even longer in the metro system. Therefore, the air quality of metro systems has attracted increasing attention, particularly since some

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studies have found that the effects of air pollution cause more damage to human health in the metro system than in the external environment (Karlsson et al., 2005; Huang et al., 2009).

Currently, many measurements and analyses of levels of bacteria, microbes, CO_2, and iron particles have been obtained for metro systems (Chillrud et al., 2005; Nieuwenhuijsen et al., 2007; Kwon et al., 2008; Kim et al., 2011; Dybwad et al., 2012, 2014). There have also been studies of the particulate matter concentration and of traveler exposure to this pollution in the metro system. Chan et al. (1991) investigated commuters' exposure to pollutants in the Boston, Massachusetts, transport system. Johansson and Johansson (2003) monitored the PM_{10} and $PM_{2.5}$ concentrations at an underground metro station in Sweden (Mariatorget) and found that the average concentrations were 5 and 10 times, respectively, the corresponding values measured in one of the busiest streets in Stockholm. By measuring the $PM_{2.5}$ concentration in the Helsinki metro system, Aarnio et al. (2005) discovered that the $PM_{2.5}$ concentration at an underground metro station was 5 times that in the ambient environment. Salma et al. (2007) monitored $PM_{10\text{-}2.0}$ concentrations at a metropolitan underground metro station in downtown Budapest, and found that the particulate matter concentrations on the platform increased as a train entered the station and decreased as the train departed from the station due to the piston effect created by the train running through the tunnel. Li et al. (2007) compared PM_{10} concentration levels under conditions with or without an air-conditioning system inside trains of certain lines in Beijing's metro. Cheng et al. (2008) monitored PM_{10} and $PM_{2.5}$ concentrations in Taiwan's metro and found that the particulate matter concentrations in the system were positively correlated with those in the ambient environment. Park and Ha (2008) monitored the PM_{10} and $PM_{2.5}$ concentrations in Seoul's metro system and discovered that due to the lack of a mechanical ventilation system inside the metro trains, particulate matter concentrations inside the trains were significantly higher than those on the metro platforms. Kam et al. (2011) investigated the PM_{10} and $PM_{2.5}$ concentrations in an underground line and an aboveground light-rail line in the Los Angeles metro system and found that the particulate matter concentrations in the underground line were almost double the values in the light-rail line. Moreno et al. (2014) measured the particulate matter concentrations at several station platforms in the Barcelona metro system, and found that particulate matter concentrations were highly variable due to differences in station designs, the tunnel ventilation conditions, and the magnitude of the piston effect. Chan et al. (2002) and Ramos et al. (2016) studied the population exposed to particulate matter from the metro and other modes of transportation in Hong Kong and Lisbon, respectively.

In Shanghai's metro system, 14 subway lines (Lines 1–13, and Line 16) with 366 stations were operating as of December 2015. The length of the metro network now totals about 617 km, the longest network in the world, and the passenger flow totaled 3.064×10^9 people in 2015. There is also a clear daily pattern, with the day's highest passenger volumes towards the city's main employment districts in the early morning, and the highest outbound volumes in late afternoon. The passenger flow on some lines and at some hub stations is remarkable. For example, the daily passenger flow on lines 1 and 2 both exceed 1×10^6 people, and at the People's Square, Century Avenue, and Xujiahui stations, the daily passenger flow ranges from 200,000 to 400,000. In addition, the number of the staff employed in the Shanghai metro system is nearly 30,000, and large numbers of merchants have settled in the halls of these and other stations to carry out commercial activities.

Therefore, obtaining information about environmental quality in Shanghai's metro system is important to judge the risk to the health of travelers, employees, and merchants and look for ways to reduce their risk. As a result, some scholars have studied the air quality in Shanghai's metro. Ye et al. (2010) investigated the air quality at some platforms along lines 1 and 2. They found that the PM_{10} concentration at most stations exceeded the particulate matter standard defined in the Chinese Code for the Design of Metro, in which the PM_{10} level should be no more than 0.25 mg/m^3 (GB50157-2013). Yu et al. (2012) compared commuters' exposure to $PM_{1.0}$ pollution during different travel modes (e.g., metro, car, bicycle). Ma et al. (2014) measured PM_{10} and $PM_{2.5}$ concentrations at two underground platforms of Shanghai's metro Line 9. They found that the particulate matter concentrations at a platform increased with increasing depth of the station. Qiao et al. (2015) measured PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ concentrations in the tunnels of two lines of Shanghai's metro system. Lu et al. (2015) monitored $PM_{2.5}$ concentrations at three platforms of Shanghai metro Line 7 and found that the $PM_{2.5}$ concentrations were all higher than ambient levels. Wang et al. (2016) measured the $PM_{2.5}$ and $PM_{1.0}$ concentrations in Shanghai's metro Line 10 and investigated the effect of the piston wind created as the train enters a station and the effect of the train door's opening on air quality inside the train.

In each of these studies, researchers measured the particulate matter concentrations for a few metro lines or a few metro stations in a certain city. There has been no comprehensive measurement and evaluation of particulate matter concentrations throughout a city's metro system. In addition, researchers have not correlated simultaneous particulate matter concentrations at the metro station's hall and train platform, and in the train compartments. Moreover, despite big differences in metro air quality among and within cities in previous studies, the causes of this variation have not been investigated. In the present study, we attempted to fill these gaps in our knowledge through comprehensive assessments of air quality throughout the 14 lines of Shanghai's metro system. Furthermore, we attempted to clarify the influence of the ambient environment and of the metro itself on particulate matter concentrations. Most importantly, based on our measurements, we propose some measures to improve the air quality in Shanghai's metro system to reduce the population's exposure to pollution.

2. Study locations and measurements

Shanghai's metro trains are all electric, so there are no particulate matter emissions from the combustion of fuel. However, they have metal wheels and powerful brake systems, so frictional erosion of this hardware creates a significant quantity of airborne particles. The train frequency varies during the day, with a frequency of around 10 trains per hour during off-peak hours and increasing to more than 20 trains per hour during the peak (rush hour) period from 7:00 to 9:00 and 17:00 to 19:00 each day. We used two portable DustTrak aerosol monitors (model 8532; http://www.tsi.com/Products/) to measure the $PM_{2.5}$ concentration in the 14 lines of Shanghai's metro for 10 days, from 13 to 22 January 2016, during which Shanghai's first serious air pollution of the year happened. Due to limitations of the monitor's battery capacity and travel times, we could only monitor a portion of each line to ensure that all 14 lines could be tested on the same day. We sampled several stations during the peak travel period (i.e., when commuters are traveling to work or back to home) and the middle of the day, when traffic levels were lower. We measured the $PM_{2.5}$ concentration in the station's hall, on the train platform, and inside the train in every metro line. For each line, we generally obtained measurements during a journey experience four stations inside the train, and measurements in the hall and on the platform which chose the journey's beginning station and ending station. Our sampling sites were either transfer hub stations with high traffic or were located in or close to the city center, as shown in Fig. 1. The pentagrams represent the sampling stations and the thick red segments represent the sampling sections for the measure inside the train of each line. To obtain measurements in the station hall, we established a sampling site beside a ticket gate and used the same sampling site throughout the measurement campaign. For the connecting hall of a transfer hub station, we established a sampling site in one line's hall beside a ticket gate, on the upper level of the line's platform. For measurements on the station's platform/train, the sampling site was located at the center of the

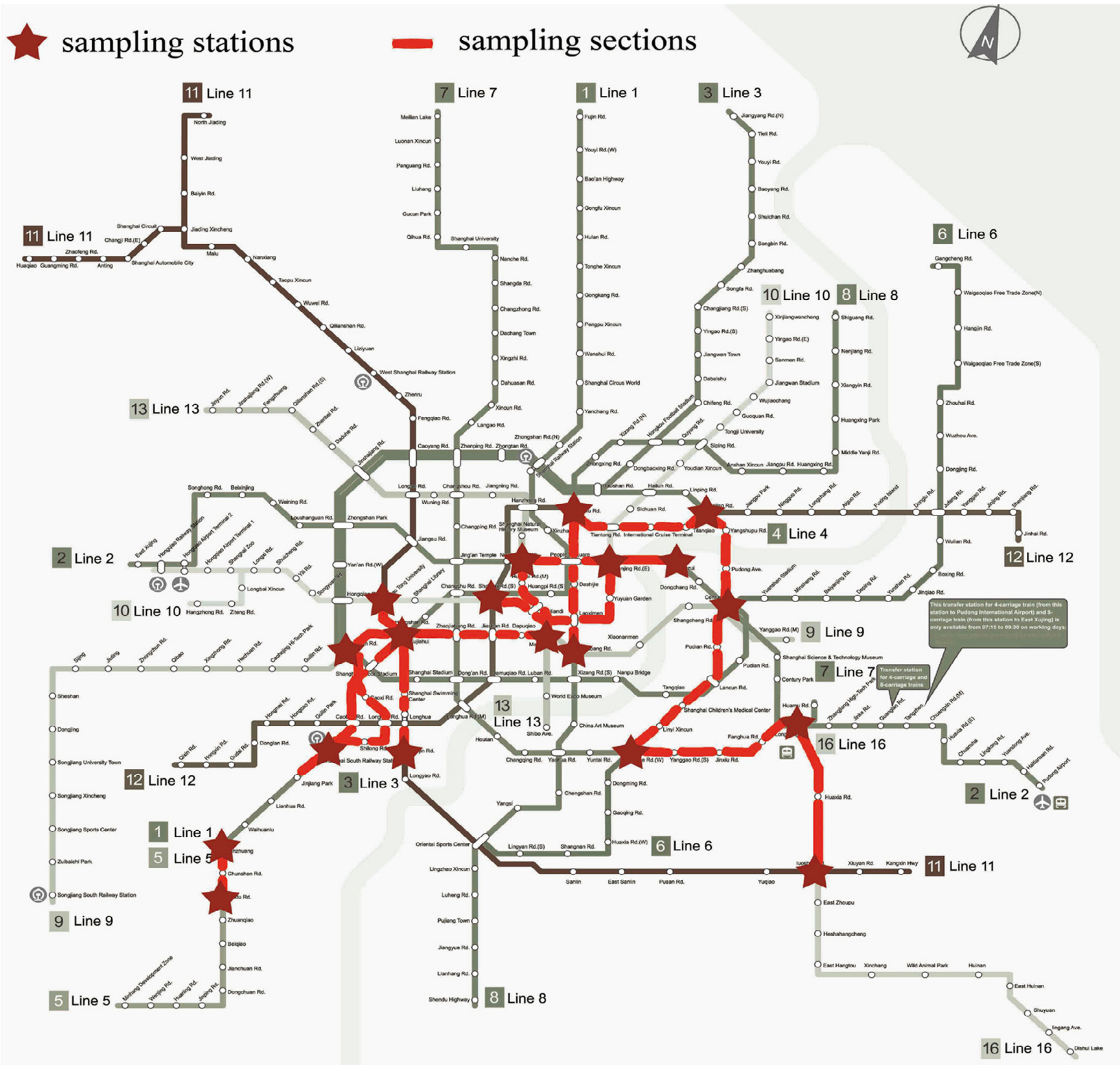

Fig. 1. The sampling sites and monitored sections in Shanghai's metro system.

Table 1
Characteristics of the monitored stations and segments in Shanghai's metro system.

Line No.	Opening year	Operation mode (aboveground, underground)	Door types of line's underground stations	Monitored stations	Monitored segments
1	1993	Both	Platform screen door	Xujiahui, Shanghai South Railway Station	Xujiahui-Jinjiang Park and Jinjiang Park-Xujiahui
2	2000	Both	Half-height security door	Naijing Rd. (W), Lujiazui	Naijing Rd. (W)-Lujiazui
3	2000	Entirely aboveground	None	Shanghai South Railway Station, Yishan Rd.	Shanghai South Railway Station - Yishan Rd.
4	2005	Both	Platform screen door	Century Ave, Dalian Rd.	Century Ave -Dalian Rd.
5	2003	Entirely aboveground	None	Xinzhuang, Yindu Rd.	Xinzhuang-Yindu Rd.
6	2007	Both	Platform screen door	Gaoke Rd. (W), Century Ave	Gaoke Rd. (W)-Century Ave
7	2009	Both	Platform screen door	Longyang Rd., Gaoke Rd. (W)	Longyang Rd.-Gaoke Rd. (W)
8	2007	Both	Platform screen door	Qufu Rd., Lujiabang Rd.	Qufu Rd.-Lujiabang Rd.
9	2007	Both	Platform screen door	Yindu Rd., Madang Rd.	Yindu Rd.-Madang Rd.
10	2010	Entirely underground	Platform screen door	Naijing Rd. (E), Shaanxi Rd. (S)	Naijing Rd. (E) -Shaanxi Rd. (S)
11	2009	Both	Platform screen door	Jiao Tong University, Yunjin Rd.	Jiao Tong University-Yunjin Rd.
12	2013	Entirely underground	Platform screen door	Dalian Rd., Qufu Rd.	Dalian Rd.-Qufu Rd.
13	2012	Entirely underground	Platform screen door	Madang Rd., Nanjing Rd. (W)	Madang Rd.-Nanjing Rd. (W)
16	2013	Both	Platform screen door	Luoshan Rd., Longyang Rd.	Luoshan Rd.-Longyang Rd.

platform/train. For all measurements, the sampling height was about 1.5 m, which corresponds to the breathing zone, and the instrument measured the $PM_{2.5}$ concentration for 40 min at a logging interval of 1 s for each metro line each day.

Table 1 summarizes the characteristics of the samples for each metro line and the monitored stations. The aboveground platforms of each metro line are equipped with half-height security doors, whereas the underground platforms of each line are equipped with platform screen doors, except for Line 2, which only has half-height security doors installed. For the lines that have both aboveground and underground segments, the aboveground parts are always situated at both ends of the lines. Thus, most stations and segments that we monitored were underground, except for lines 3, 5, and 16. Lines 3 and 5 run completely aboveground, and Line 16 has an underground section.

There are 10 state-run air sampling sites in the Shanghai area, and they release hourly $PM_{2.5}$ concentration data. We collected real-time data on the ambient $PM_{2.5}$ concentration (i.e., the concentration in the aboveground air) from the monitoring agency's Web site (http://www.pm25china.net), which represented the background concentration. For comparison with measurements in the metro stations, we used the data from the nearest ambient air sampling site as its background concentration. If synchronous data from the nearest ambient air sampling site was missing, we selected synchronous data from the next-nearest ambient air sampling site. For the measured metro interval, we calculated the average $PM_{2.5}$ value from the nearest ambient air sampling site with available data as the ambient air quality reference. Moreover, all of the following statistical analyses were performed using version 21 of IBM's SPSS software (http://www-01.ibm.com/software/analytics/spss/).

3. Results and discussion

3.1. Consistency of $PM_{2.5}$ concentrations between the Shanghai metro system and the ambient environment

The underground metro system communicates with the ambient atmosphere through the station entrance, air shafts, and the ventilation and air conditioning systems, whereas the aboveground metro system connects directly with the outside atmosphere. The air of the metro station halls, platforms, and train compartments exchanges to different degrees with the ambient atmosphere, and there are also air exchanges among these components. Fig. 2 shows trends in the daily average $PM_{2.5}$ concentration in each station's hall and on its platform, inside the train, and in the ambient concentration. The patterns of $PM_{2.5}$ concentrations were consistent among all sampling locations, and this suggests that the ambient air is the most important factor that influences $PM_{2.5}$ concentrations in the Shanghai metro system. Fig. 2 also shows that the $PM_{2.5}$ values in the station's hall and on the platform were nearly identical, and that both were higher than the ambient level. This is due to the semi-enclosed underground structure of the metro system. This structure interferes with free circulation of the air, so ambient air that infiltrates the metro system is recycled slowly; thus, particulate matter carried into the system from the ambient air accumulates continuously in the system. In addition, the particulate matter concentrations in the station's hall and on the platform are also influenced by factors internal to the system, such as the various metal particles eroded from the train and the track, which increase the particulate matter concentration. In addition, the piston effect created when a train enters a station and pushes air ahead of it causes dirty air from the tunnel to enter the platform and hall areas, thereby increasing their particulate matter concentrations. The particulate matter concentration was lowest inside the train because the train compartments are sealed relatively strongly against outside air until the doors open, allowing the air conditioning system to filter out more particles than would be possible in more open parts of the system such as the platform or hall.

We also performed correlation analysis to quantify the strength of the relationships among $PM_{2.5}$ concentrations at the station hall, on the platform, in train compartments, and in the ambient air (Table 2). All correlations were strong and

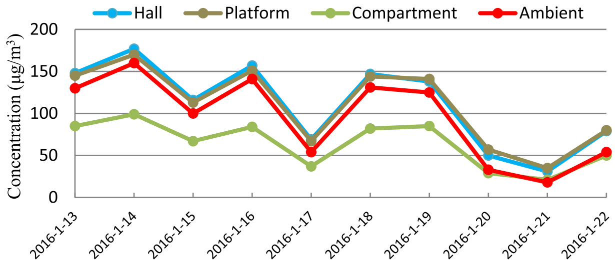

Fig. 2. Changes of the $PM_{2.5}$ concentration in the station's hall, on the platform, and in train compartments, and their relationship with ambient levels.

Table 2
Correlation analysis for synchronous PM2.5 values at four locations in the metro system.

	Pearson's correlation coefficient			
	Hall	Platform	Train compartment	Ambient
Hall	1	0.998**	0.993**	0.998**
Platform	0.998**	1	0.995**	0.996**
Train compartment	0.993**	0.995**	1	0.989**
Ambient	0.998**	0.996**	0.989**	1

** Correlation is significant at $P < 0.01$ (2-tailed).

significant. Slight differences in the strengths of the correlation may exist due to the different degrees of connectivity between the station hall, platform, train compartments, and ambient air. For the underground metro lines, particulate matter from the ambient air floats directly into the station hall through the station entrance, air shafts, and other openings, whereas the platform is generally located under the station's hall, and its air exchanges are primarily with the air in the station hall, so the influence of the ambient air on the platform is weaker than it would be in the station hall. The train compartment is affected by the air from both the hall and the platform, so the correlation would be slightly weaker.

We performed linear regression analyses for the relationships among the $PM_{2.5}$ concentration in the ambient air and those in the station hall, on the platform, and in the train compartment. Fig. 3 illustrates the results for the following linear regression equations:

$$C_{\text{Hall}} = 17.06 + 1.0C_{\text{Ambient}}$$

$$C_{\text{Platform}} = 22.66 + 0.93C_{\text{Ambient}}$$

$$C_{\text{Compartment}} = 12.78 + 0.54C_{\text{Ambient}}$$

where C represents the indicated $PM_{2.5}$ concentration.

3.2. $PM_{2.5}$ concentrations and rankings of the Shanghai metro lines

We used the mean $PM_{2.5}$ concentrations from the station halls, platforms, and train compartments to represent the $PM_{2.5}$ concentration level in each metro line and establish rankings for the most to least seriously polluted locations (Table 3). Although there was high variation in $PM_{2.5}$ concentration inside the trains (ranging from 48 to 85 μg/m^3, a difference of 37 μg/m^3), all these levels were below the minimum levels in the station hall and on the platform. $PM_{2.5}$ was highest in Line 1, and lowest in Line 12. In the station hall, variation was higher (with $PM_{2.5}$ ranging from 92 to 138 μg/m^3, a difference of 46 μg/m^3). Line 13 had the highest concentration, and Line 4 had the lowest. On the platform, the range was similar to that in the station hall (with $PM_{2.5}$ ranging from 88 to 137 μg/m^3, a difference of 49 μg/m^3). Line 2 had the highest $PM_{2.5}$ concentration, and Line 10 had the lowest. Cluster analysis (CA) is a classification approach used to divide a dataset into a number of groups and a dendrogram is often employed to visualize the results of CA. The goal of CA is to establish a set of classes so that lines in a given class are similar to each other but different from those in the other classes. We employed a hierarchical agglomeration algorithm for the clustering to create a dendrogram (Fig. 4). Squared Euclidean distance was used to calculate the between-group linkage. We applied the rescaled distance cluster combine (RDCC) approach to measure the distances (i.e., the differences) between the lines. The datasets involved in the CA were the $PM_{2.5}$ concentrations in the station halls, on the platforms, and in the train compartments. The data from all three sampling positions has been incorporated into a single dataset as a multi-index comprehensive evaluation. From Fig. 4, it can be discovered that the Shanghai metro lines can be divided into six classes. Lines 3, 5, 7, 11, and 16 are in one class, while lines 4, 8, 9, 10, and 12 are in a second class. All the rest of lines are categorized as separated classes. Combining the rankings and clustering results, we found that the air

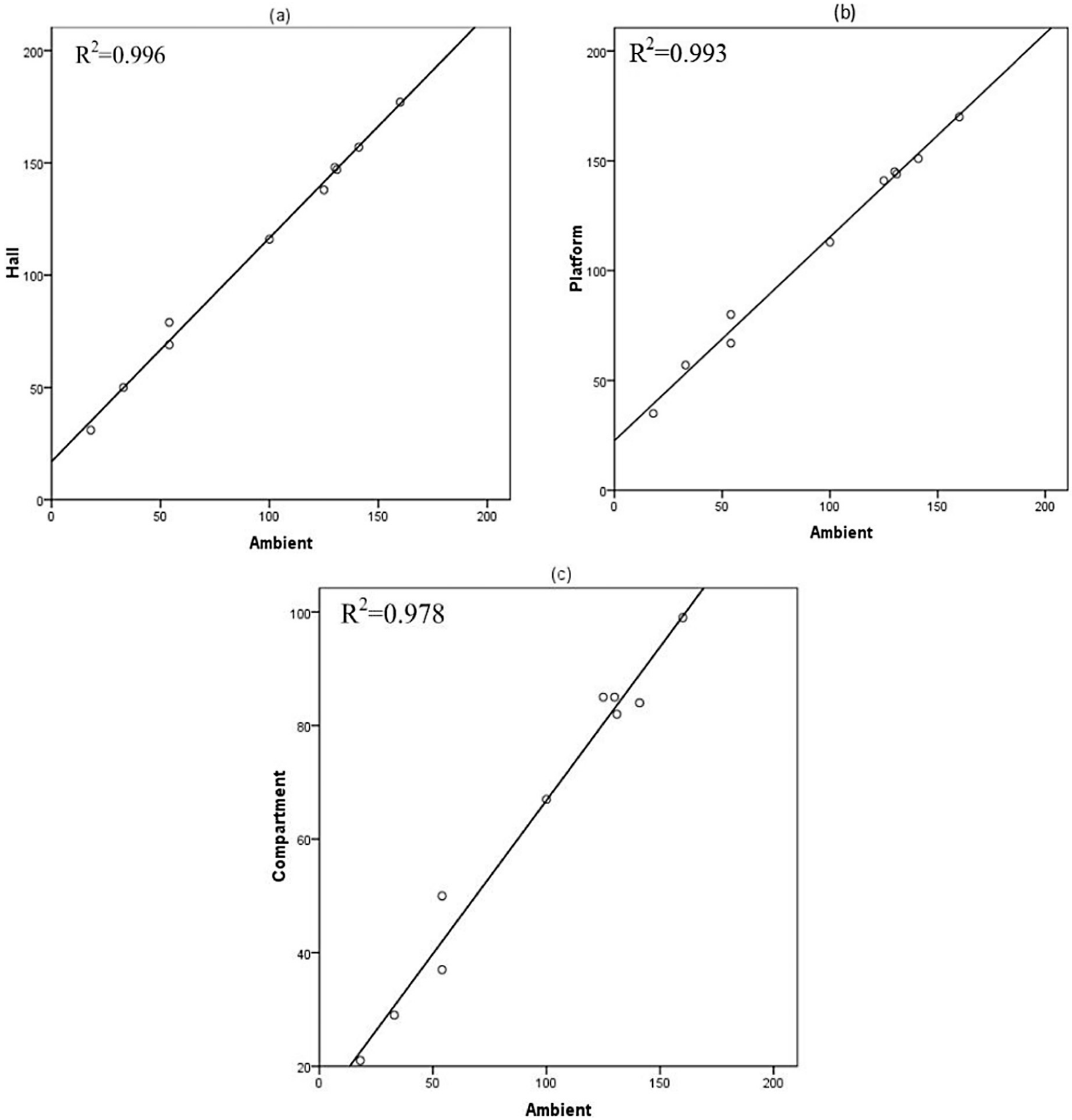

Fig. 3. Linear regression for the relationships between the ambient $PM_{2.5}$ concentration and the $PM_{2.5}$ concentration at the (a) station hall, (b) platform, and (c) train compartment sampling locations. All regressions were strong and statistically significant ($P < 0.05$).

quality was relatively good in lines 4, 8, 9, 10, and 12; was poor in lines 3, 5, 6, 7, 11, and 16; and was worst in lines 1, 2, and 13.

This analysis supports the regression results in Fig. 3, which suggested that the ambient environment exerts a strong impact on the $PM_{2.5}$ concentrations in the metro system. To exclude the influence of the ambient environment on the $PM_{2.5}$ levels in different lines, we calculated the relative concentration in each line. The relative concentration is obtained by subtracting the ambient $PM_{2.5}$ concentration from the measured $PM_{2.5}$ at a given position (Table 4). In this table, negative values indicate that the measured value was lower than the value at the nearest ambient air sampling site. The relative concentrations can reflect the self-purification capacity of the metro, which refers to its ability to reduce pollution levels without external interference, and includes the filtering capacities of the ventilation and air conditioning systems, the ability of the platform screen doors to form an air-tight barrier, and other characteristics of each station. Table 4 shows that the relative $PM_{2.5}$ concentrations differed greatly among the stations for measurements in the station halls, on the platforms, and in the train compartments, thereby revealing differences in the pollution purification capacity of the lines. In the station halls,

Table 3
The rankings of the lines based on the mean $PM_{2.5}$ concentration values in the station halls, on the platforms, and in the train compartments.

Ranking	Hall		Platform		Train compartment	
	Line	Mean $PM_{2.5}$ ($\mu g/m^3$)	Line	Mean $PM_{2.5}$ ($\mu g/m^3$)	Line	Mean $PM_{2.5}$ ($\mu g/m^3$)
1	13	138	2	137	1	85
2	5	121	13	126	5	72
3	6	119	1	117	11	72
4	16	119	5	117	16	72
5	2	116	6	116	2	69
6	7	116	16	116	13	69
7	1	111	7	115	3	66
8	3	110	3	111	7	66
9	11	110	11	110	4	56
10	9	104	9	104	9	56
11	8	103	8	100	8	55
12	10	101	12	100	6	54
13	12	96	4	90	10	54
14	4	92	10	88	12	48

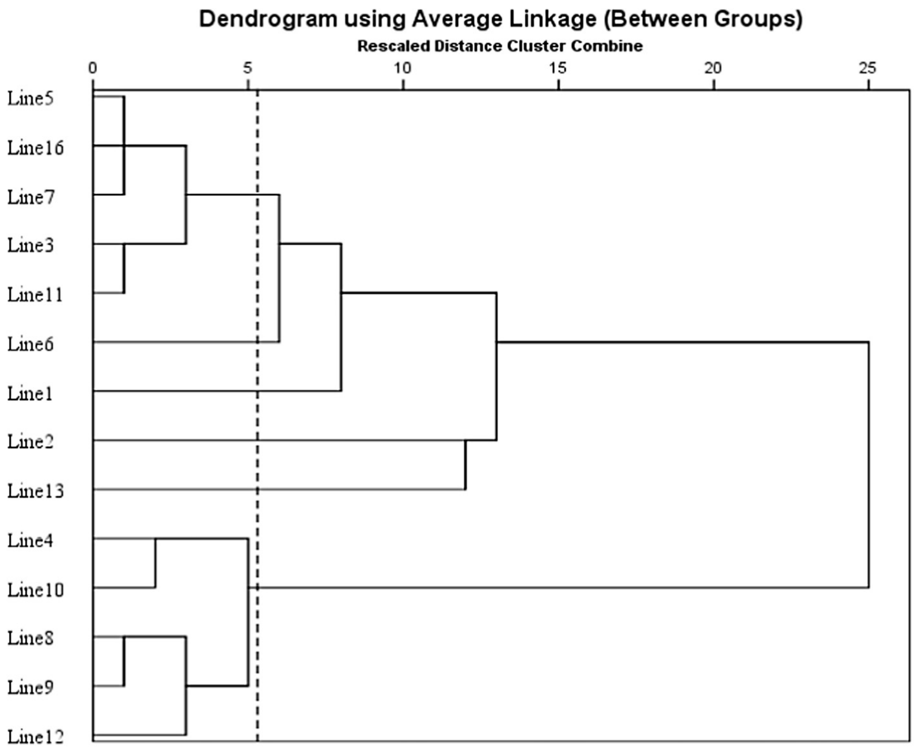

Fig. 4. Dendrogram for the $PM_{2.5}$ concentrations in the lines of Shanghai's metro system.

the relative $PM_{2.5}$ concentration ranged from −8 to +45 $\mu g/m^3$ (a difference of 53 $\mu g/m^3$); the value was worst in Line 13, and best in Line 4. On the platforms, the relative $PM_{2.5}$ concentration ranged from −10 to +48 $\mu g/m^3$ (a difference of 58 $\mu g/m^3$); it was worst in Line 2 and best in Line 4. Inside the trains, the relative $PM_{2.5}$ concentration ranged from −46 to −15 $\mu g/m^3$, a difference of 31 $\mu g/m^3$; it was worst in Line 1, and best in Line 6. The same clustering analysis as of the Fig. 4 is utilized for Fig. 5, in which the datasets were the relative $PM_{2.5}$ concentrations in the station halls, on the platforms, and in the train compartments. In Fig. 5, we can find that the Shanghai metro lines were divided into six classes as well. The first class contains Lines 3, 5, 6, 7, 8, and 11. Lines 9, 10, and 12 are in a second class, while Lines 1 and 16 in the third class. All the other lines are categorized as separated classes. Combining the rankings and clustering results, the best air quality was found in lines 4, 9, 10, and 12. In contrast, the air quality was poor in lines 3, 5, 6, 7, 8, and 11, and worst in lines 1, 2, 13, and 16.

Based on the measured and relative concentrations of $PM_{2.5}$ in each metro line, the worst air conditions in the station halls, on the platforms, and in the train compartments were in lines 13, 2, and 1, whereas the cleanest air was in Line 4.

Table 4
The rankings of the mean relative $PM_{2.5}$ concentrations (measured – ambient air) in the station halls, on the platforms, and in the train compartments.

Ranking	Hall		Platform		Train compartment	
	Line	Mean relative $PM_{2.5}$ (μg/m^3)	Line	Mean relative $PM_{2.5}$ (μg/m^3)	Line	Mean relative $PM_{2.5}$ (μg/m^3)
1	13	45	2	48	1	−15
2	2	27	13	34	16	−17
3	16	27	16	25	2	−21
4	7	23	7	22	13	−22
5	5	20	1	20	7	−26
6	6	18	5	16	5	−28
7	1	14	3	15	11	−28
8	8	14	6	15	3	−30
9	3	14	11	11	8	−34
10	11	12	8	11	10	−36
11	10	10	12	7	9	−40
12	9	7	9	7	4	−43
13	12	3	10	−3	12	−44
14	4	−8	4	−10	6	−46

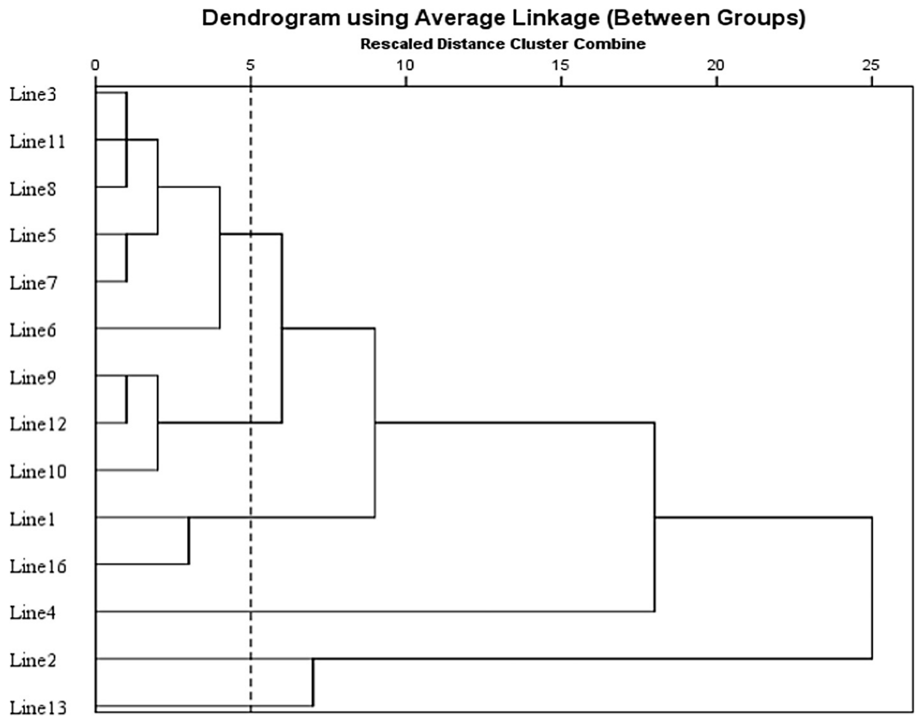

Fig. 5. Dendrogram for the relative $PM_{2.5}$ concentrations (measured – ambient air) in the Shanghai metro system.

One possible reason for these differences is that dust that collects in the stations and tunnels is an important contributor to the $PM_{2.5}$ concentration. Most of the recently opened lines have less particulate matter, with a lower relative concentration than older lines that have been operated for more than 10 years, which is long enough for large amounts of dust to collect in the tunnels and the ceiling above the stations, as in the case of lines 1 and 2. The piston effect is another important cause of $PM_{2.5}$ pollution on the station platforms. Dirty air from the tunnels is pushed onto the platform by the arriving trains. Line 2 retains half-height security doors rather than the platform screen doors installed on the platforms of all other lines, which create a more effective barrier to transport of particulate matter. The half-height security doors allow a direct connection between the platforms and the tunnels, making it possible for the piston wind to push the pollutants onto the platform. In contrast, platform screen doors create a barrier that mitigates the piston effect to some extent. The worst air quality was found on the platform of Line 2, where the average $PM_{2.5}$ concentration was at least 25 μg/m^3 higher than in the other normal lines (Table 4). The $PM_{2.5}$ concentration on the platforms can also affect the $PM_{2.5}$ concentration inside the trains, because the concentration on the platforms is generally higher than that inside the trains. Thus, when the train doors open, dirty air from the platforms enters the train compartments, increasing their pollution level. The bigger the difference between the air quality on the platforms and inside the train and the longer the train doors are open, the greater the increase in the $PM_{2.5}$ concentration inside the train. For all measurements, Line 13 appears anomalous, since the Nanjing Rd. (W) station chosen for our measurements was opened at the end of 2015, and is located in the station hall that always shows smoggy conditions. It appears that the air conditioning and ventilation systems are not yet fully operational, thus the $PM_{2.5}$ concentrations in the station hall and on the platform were high. The ventilation system of Line 4 has the best throughput in the Shanghai metro system, and has played a significant role in giving this station the cleanest air. In addition, the relatively high $PM_{2.5}$ concentration in Line 16 is similar to that in Line 5 because of the similar positions of the sampling sites. Both lines operate in suburban areas with high passenger numbers. However, the relative $PM_{2.5}$ concentration of Line 16 is higher than that of Line 5 (Table 4), because there is a big gap between the ambient background data respectively corresponding to these two sampling lines.

3.3. Potential improvements in the $PM_{2.5}$ concentration

During our measurements, we found that the $PM_{2.5}$ concentration measured within a given line varied greatly between measuring times. Table 5 summarizes the daily maximum and minimum $PM_{2.5}$ concentrations for each line. For each line, the highest and lowest concentrations differed by one order of magnitude in all lines and at all stations for the hall and platform positions, and differed by more than 100% inside the trains. Fig. 6 illustrates the differences between the daily maximum and minimum $PM_{2.5}$ concentrations (hereafter, the "range"), as this reflects the potential improvement of the air quality. The ranges for both the station halls and the platforms were greater than 120 $\mu g/m^3$, which is much higher than the range within the train compartments (50–105 $\mu g/m^3$). Since an air-conditioning filtering system was installed inside the trains, this system filters out much of the particulate matter and can therefore reduce the range of $PM_{2.5}$ concentrations to some extent. Fig. 6 also shows that the range of the concentrations in the ambient environment, indicating that the potential improvement for the metro system is affected both by the ambient environment and by the internal conditions within the metro system. For instance, in Line 7, the ranges for the station hall and platform are both bigger than that of the ambient air, suggesting that improvement of the system's self-purification capacity, such as strengthening the ventilation and air purification systems could reduce the $PM_{2.5}$ pollution levels.

3.4. The effects of aboveground and underground operation on the $PM_{2.5}$ concentration inside the trains

Lines 3 and 5 are the only lines that run completely aboveground, whereas lines 10, 12, and 13 run entirely underground. To distinguish the effect of these different patterns on the air quality within the train compartments, we compared the $PM_{2.5}$

Table 5
The daily maximum and minimum $PM_{2.5}$ concentrations for each line's stations, platforms, and train compartments.

		$PM_{2.5}$ ($\mu g/m^3$) in line													
		1	2	3	4	5	6	7	8	9	10	11	12	13	16
Hall	Max.	168	185	169	159	207	192	192	169	164	180	192	169	223	197
	Min.	37	43	23	26	41	33	25	25	25	19	30	22	52	21
Platform	Max.	175	195	170	152	203	177	192	162	159	160	178	162	207	192
	Min.	45	76	22	25	33	35	30	38	25	22	32	29	45	21
Train compartment	Max.	124	97	116	100	123	81	109	81	78	85	108	78	119	121
	Min.	37	44	16	14	20	17	18	18	15	17	20	15	16	16

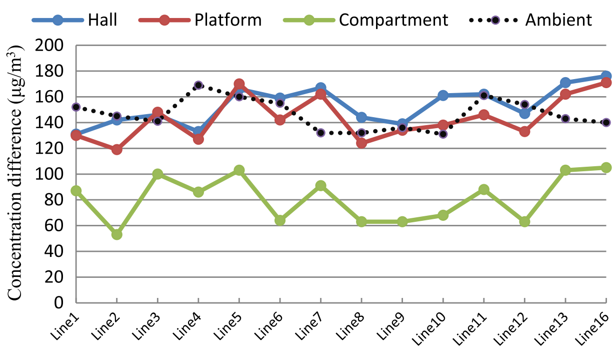

Fig. 6. The differences between the daily maximum and minimum $PM_{2.5}$ concentrations in the station hall, on the platform, in train compartments, and in the ambient air.

Table 6
Paired-sample *t*-test results for the difference in $PM_{2.5}$ concentrations and relative concentrations inside the train compartments.

	Mean	Std. deviation	Std. error Mean	95% confidence interval of the difference		*t*	*P* (2-tailed)
				Lower	Upper		
$PM_{2.5}$ concentration difference (aboveground–underground)	−12.400	15.123	4.782	−23.218	−1.582	−2.593	0.029
$PM_{2.5}$ relative concentration difference (aboveground–underground)	−5.400	17.859	5.647	−18.175	7.375	−0.956	0.364

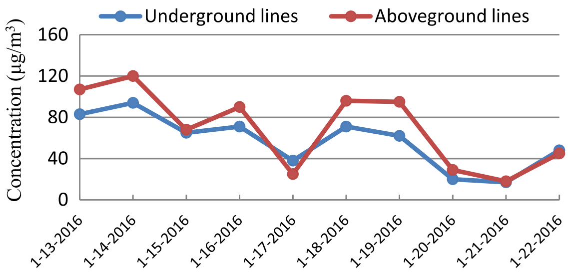

Fig. 7. Comparison of $PM_{2.5}$ concentrations inside the trains that ran entirely underground and aboveground in Shanghai's metro system.

concentrations and relative concentrations between these two aboveground and underground groups of lines (Table 6). The actual concentrations in train compartments were significantly difference ($P < 0.05$) between these two patterns, but there was no significant difference for the relative concentrations ($P > 0.05$). This shows that the compartments of train that run entirely above the ground are in direct contact with and are therefore likely to be affected more strongly by the ambient environment. In contrast, the compartments of train run completely underground exchange with the ambient air weaker than that run entirely aboveground, therefore the concentrations in train compartments of underground lines more stable. However, excluding the impact of ambient air on the metro system, the $PM_{2.5}$ relative concentrations inside the trains between these two groups were pretty much the same. Fig. 7 compares the $PM_{2.5}$ concentrations within trains running entirely underground and completely above the ground. The air quality of the compartments of trains that run entirely underground was much better than that of the trains that run entirely above the ground, except on January 17. This conclusion contradicts the previous study by Kam et al. (2011), who found better air quality in the aboveground system of Los Angeles than in the underground system. There are two possible explanations. First, the air conditions in Los Angeles are better than those in Shanghai. Second, the air quality on the underground platforms in Los Angeles was worse than that within train compartments because there were no platform screen doors, allowing dirty air to easily enter the train compartments.

3.5. The influence of traffic volume on $PM_{2.5}$ concentrations

The evening rush hour for the Shanghai metro system is between 17:00 and 19:00. During the study period, we obtained data both during the evening rush hour and during the off-peak period for lines 2, 4, 8, 10, 12, and 13 (Fig. 8). In Fig. 8, we have used the relative concentration because it eliminates the effect of the ambient air during different measuring periods. For most of the lines, the $PM_{2.5}$ concentration during the evening peak periods was higher than during off-peak periods at all locations, except for the station halls and platforms in Line 13. As we noted earlier, the air quality in the Nanjing Rd. (W) station was abnormal during the study period, and this may explain why Line 13 does not follow the general pattern. Based on this analysis, we found that an increasing volume of passengers will increase the $PM_{2.5}$ concentration in the metro system in the station halls, on the platforms, and in the train compartments. The large flow of passengers will carry $PM_{2.5}$ into the metro system, and will stir up dust that has been deposited on the floor. In addition, the subway managers schedule more trains to run during the rush hour, and this would increase the frequency of the piston effect, thereby pushing more particulate matter from the tunnels into the platform area.

4. Proposed measures to reduce exposure to particulate matter pollution

Based on the measured $PM_{2.5}$ concentrations, their distribution characteristics, and the probable sources of these particles in the Shanghai metro system, we have proposed several strategies to reduce the travelers' exposure to $PM_{2.5}$ pollution and the resulting damage to their health. These measures should be implemented as soon as possible.

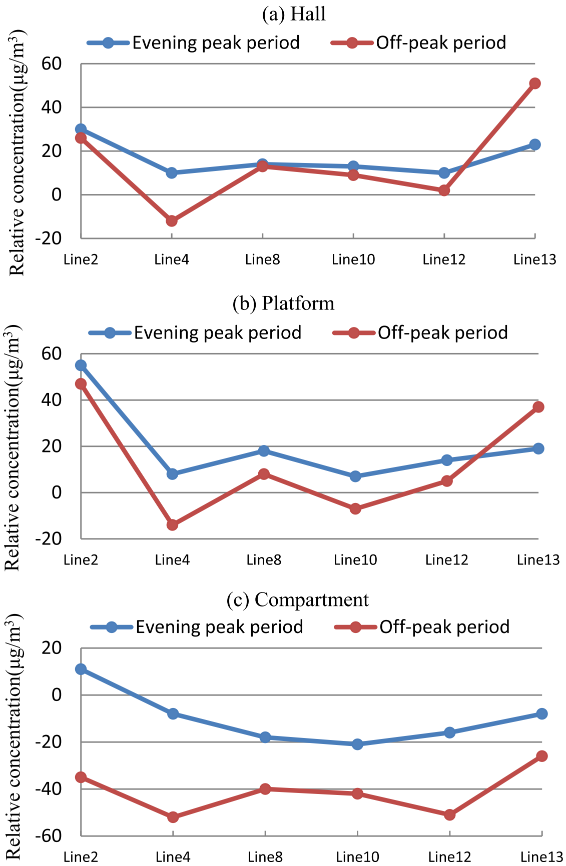

Fig. 8. The relative $PM_{2.5}$ concentrations at six stations for which we recorded data during both the evening peak period (rush hour) and off-peak periods. Values were measured (a) in the station halls, (b) on the platforms, and (c) in the train compartments.

4.1. Develop a $PM_{2.5}$ concentration standard for the Shanghai metro system

The current Chinese Code for the Design of Metro provides a PM_{10} concentration standard of 0.25 mg/m^3. This corresponds to an air quality index (AQI) of 150 based on China's air pollution index calculation standard, which represents the boundary between light pollution and moderate pollution. However, there is currently no standard for $PM_{2.5}$, and the standard for PM_{10} is probably too weak for $PM_{2.5}$, which is believed to be more dangerous. Shanghai should therefore develop standards for metro $PM_{2.5}$ concentrations that reflect the city's actual situation. To support implementation of this standard, the $PM_{2.5}$ concentrations in the station halls, on the platforms, and inside the trains and tunnel should be monitored automatically in real-time. When the $PM_{2.5}$ concentration exceeds the standard, measures should be taken immediately to improve the air quality.

4.2. Reduce the influence of ambient air on the system's $PM_{2.5}$ pollution

Our results suggest that the most important factor that influences the $PM_{2.5}$ concentration in Shanghai's metro is the ambient environment. Therefore, efforts should be made to reduce the input of $PM_{2.5}$ from the ambient air, especially on days when there is serious contamination of the ambient air. Specific measures should include regular replacement and cleaning of the metro system's ventilation equipment. Second, if a pollution source is identified near the metro's air intake vents, an isolation device should be installed to prevent intake of these contaminants; where possible, the pollution should also be reduced at the source. Third, all of the metro's fresh air intakes should have air purification and disinfection devices installed to eliminate as much of the ambient pollutants as possible. Last but not least, the metro's entrances should be equipped with air curtains, which can be lowered on days with heavy pollution to reduce the access of outside particles to the metro system; conversely, the curtains can be lifted in good weather to improve air circulation.

4.3. Reconstruct the metro system to reduce the creation and diffusion of $PM_{2.5}$ pollution and formulate a scientifically designed cleaning plan to remove what cannot be eliminated

The $PM_{2.5}$ concentration in Line 2's platform was higher than that at other platforms because the line's half-height security doors do a poor job of blocking particle transport from the tunnel. Therefore, these doors should be replaced with platform screen doors. Furthermore, to prevent the piston effect from blowing tunnel "dirty" air into the platform, each line should monitor the dust situation in its tunnels daily and implement a scientifically designed tunnel cleaning plan to mitigate the problem. Advanced equipment can be used to improve the efficiency and effectiveness of the cleaning. For example, tunnel-cleaning vehicles can remove the dust that has been deposited on the inner walls of the tunnels and could use vacuums to recover dust deposited on the floor of the tunnel. In addition, the efficient filtering function of the trains' air conditioning system significantly decreased the $PM_{2.5}$ concentration inside the trains compared with the station halls and platforms. This equipment should be regularly cleaned to maintain its filtering capability, and managers should explore the possibility of installing similar systems in the system's air intakes. Without reducing passenger comfort, the temperature, humidity, and wind speed of the air conditioning system should also be adjusted to reduce the frequency of conditions that lead to accumulation of particles. For older lines and high traffic lines, cleaning should be conducted more frequently and the scope of the cleaning should be expanded.

4.4. Optimize passenger behavior and adjust metro employee and merchant work plans to reduce $PM_{2.5}$ exposure

Our results show that the $PM_{2.5}$ concentration at each line's station halls and platforms is significantly higher than that inside the train, so passengers should minimize the time they spend in the halls and platforms. If possible, passengers should also avoid traveling during the peak periods and prioritize taking lines with lower pollution levels, such as lines 4, 9, and 10. For the metro staff, a job-rotation program should be implemented to avoid long-term exposure to the work areas with the highest $PM_{2.5}$ levels. When it's necessary to work in areas with high $PM_{2.5}$, workers should minimize their activity intensity to reduce inhalation of the particles or wear respirators in particularly hazardous work areas, such as when cleaning the dirtiest parts of the tunnels. Metro merchants are seriously exposed to the station hall's particulate pollution. Thus, shops should try to create good ventilation conditions, such as a shop with a door that closes fully and that is protected by an air conditioner with strong filtration capacity, to reduce the level of particulate contamination in their working environment.

5. Conclusions

In this paper, we comprehensively measured the $PM_{2.5}$ concentration in the Shanghai metro's 14 lines. The main research results are as follows: First, for all stations and lines, the variation of $PM_{2.5}$ concentrations in the station halls, on the platforms, and inside the train showed high consistency with that in the ambient air; this suggests that the ambient air is the most important factor that affects air quality in Shanghai's metro system. $PM_{2.5}$ concentration in the station's hall and on the platform are higher than that in the ambient air, but the $PM_{2.5}$ concentration inside the trains is lower than ambient levels due to the use of effective filtration systems. Because Shanghai's ambient $PM_{2.5}$ concentration is high, the concentration inside the trains that run entirely above the ground was higher than that in trains that run completely underground. Second, we ranked stations based on their $PM_{2.5}$ concentrations and relative $PM_{2.5}$ concentrations based on cluster analysis of each line's station hall, platform, and train compartments. We found that the air quality was worst in lines 1 and 2, and best in Line 4. This appears to result from local factors such as the age of the line and the type of platform screen doors used. Third, for each metro line, the daily average concentration varied widely during our 10-day measurement campaign. This resulted both from variations in the ambient $PM_{2.5}$ concentration and from characteristics of the metro system itself, such as differences in the ventilation, air conditioning, and level of passenger traffic.

Based on these results, we proposed several measures to minimize traveler and worker exposure to $PM_{2.5}$. First, a safety standard for the $PM_{2.5}$ concentration should be established to provide a target level for management. Based on that standard, air purification and filtering systems should be installed in the metro's air intakes and air curtains should be installed at metro entrances to reduce the intrusion of $PM_{2.5}$ from the ambient air. An automatic real-time monitoring system for $PM_{2.5}$ should be installed, and when levels increase beyond the safe level, scientifically designed cleaning programs should be implemented to lower these levels. Finally, passengers and workers should minimize their time in the station's halls and on the platform. For metro employees and merchants who must spend much time in areas with high $PM_{2.5}$ concentrations, their job should be rotated periodically to areas with lower concentrations, better air purification facilities should be provided, and protective equipment (e.g., masks and respirators) should be used in the most hazardous areas.

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