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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