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Commuters' exposure to $PM_{2.5}$ and CO_2 in metro carriages of Shanghai metro system

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ABSTRACT

Air quality inside transportation carriages has become a public concern. A comprehensive measurement campaign was conducted to examine the commuters' exposure to $PM_{2.5}$ ($d_p \leqslant 2.5$ μm) and CO_2 in Shanghai metro system under different conditions. The $PM_{2.5}$ and CO_2 concentrations inside all the measured metro lines were observed at 84 ± 42 μg/m^3 and 1253.1 ± 449.1 ppm, respectively. The factors that determine the in-carriage $PM_{2.5}$ and CO_2 concentrations were quantitatively investigated. The metro in-carriage $PM_{2.5}$ concentrations were significantly affected by the ventilation systems, out-carriage $PM_{2.5}$ concentrations and the passenger numbers. The largest in-carriage $PM_{2.5}$ and CO_2 concentrations were observed at 132 μg/m^3 and 1855.0 ppm inside the carriages equipped with the oldest ventilation systems. The average $PM_{2.5}$ and CO_2 concentrations increased by 24.14% and 9.93% as the metro was driven from underground to overground. The average in-carriage $PM_{2.5}$ concentrations increased by 17.19% and CO_2 concentration decreased by 16.97% as the metro was driven from urban to the suburban area. It was found that $PM_{2.5}$ concentration is proportional to the on-board passenger number at a ratio of 0.4 μg/m^3·passenger. A mass-balance model was developed to estimate the in-carriage $PM_{2.5}$ concentration under different driving conditions.

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Introduction

In last decades, the adverse impact of particulate matter (PM) on human's health have been exclusively studied, indicating that PM is a vital cause of cardiovascular disease and atherosclerosis (Flemming et al., 2011; Langrish et al., 2012). For instance, the high CO_2 concentration has been identified as a cause of sick building syndrome symptoms, indicating the adverse health impact of high CO_2 exposure (Seppänen et al., 1999; Apte et al., 2000). In Chinese metropolitan cities (e.g. Shanghai), metro system has become the primary public transportation mode. As the largest urban metro traffic system in the world, Shanghai metro system carries 8.898 million person-times every weekday. Averagely, commuters spent 30–40 min inside the metro daily. The high $PM_{2.5}$ and CO_2 concentrations in the metro carriage are of concern to the public. Thus, it is essential to evaluate the in-carriage $PM_{2.5}$ and CO_2 exposure levels, to identify the factors that affect the in-carriage $PM_{2.5}$ and CO_2 concentrations, and to further determine the significance of each factor.

The PM and CO_2 concentrations inside various transportation cabins have been studied to some extent. In the vehicle cabins, it was found that the in-cabin particle concentrations were significantly affected by the ventilation, penetration through

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vehicle envelope and cabin air filter's filtration efficiency (Xu and Zhu, 2009; Xu et al., 2011). In the high-speed rail carriages, the predominant factors determining the $PM_{2.5}$ and CO_2 concentration were found to be the passenger numbers, ventilation systems and carriage class (Xu et al., 2013). For the subway metro system, although there were some studies measuring the PM and CO_2 concentrations, the measurements were mostly conducted at the stations or the platforms (Furuya et al., 2001; Paivi et al., 2005; Kim et al., 2010; Colombi et al., 2013; Şahin et al., 2012; Midander et al., 2012). Few studies measured the PM and CO_2 concentration inside the subway metro carriages. Only a recent study conducted in Shanghai showed that the PM_1 concentration in the metro carriage was 54% less than that at the platform (Yu et al., 2012). It was reported that the in-carriage PM_{10} concentration during rush hours was 69.40% higher than that during off-rush hours (Park et al., 2012). However, limited studies have ever been conducted to identify the factors that determine the in-carriage $PM_{2.5}$ and CO_2 concentrations. Even less studies were conducted to investigate the effects of the key factors (ventilation systems, out-carriage $PM_{2.5}$ concentrations and the passenger number) on the in-carriage $PM_{2.5}$ and CO_2 concentrations.

The aim of this study was to quantify commuters' exposure to $PM_{2.5}$ and CO_2 inside various metro carriages under different driving conditions. The controllable factors, e.g. ventilation system, the driving conditions and loading passenger number, were then examined to facilitate the measures of reducing the in-carriage $PM_{2.5}$ and CO_2 concentrations.

Methods

Sampling methodology

The measurement campaign was conducted from April to October 2013 in Shanghai Subway Metro Line 1, Line 2, Line 4, Line 9 and Line 10. Q-Traks (Model 7575X, TSI Inc., USA) and Dustraks (Model 8532, TSI Inc., USA) were used to simultaneously measure CO_2 and $PM_{2.5}$ with a 1-s interval. The $PM_{2.5}$ data from Dustrak was compared against the data from local monitoring station. The local station data was consistently observed 1.5–1.8 times larger than the Dustrak data. A correction factor of 1.6 was applied for all the data from Dustrak in this study. The particle size distributions were measured with Optical Particle Sizer (Model 3330, TSI Inc., USA). All the instruments were calibrated before measurements. For each measurement point, the $PM_{2.5}$ concentration, CO_2 concentrations and particle size distribution were recorded for 30 s. It should be noted that meteorological conditions (e.g. temperature, humidity) might affect the $PM_{2.5}$ and CO_2 concentrations. In this study, the measurement campaign was conducted under the certain meteorological conditions (11 °C < temperature < 39 °C, 30% < relative humidity < 80%) due to Shanghai's geographic location. This might cause the results in this study cannot be directly applied to other cities, of which the meteorological conditions are out of this ranges. The measurement followed the procedures below.

Measurement points

Fig. 1 shows the measurement points in a typical metro carriage. The measurements were conducted at the doors, the sitting area, and the air supply vents. The $PM_{2.5}$ and CO_2 concentrations at the doors were measured when the doors were open and closed when the metro train stopped. The $PM_{2.5}$ and CO_2 concentrations at sitting area and air vents were measured simultaneously during each measurement when the train was driving. It averagely took 3 min for the train driving from one station to the next. The time interval between two metro trains was 3–5 min. The measurement was conducted once a week for four consecutive weeks.

Underground/overground

The effects of driving conditions on the in-carriage $PM_{2.5}$ and CO_2 concentrations were studied on Line 4, which was the only metro carriage that drives both underground and overground. Fig. 2 shows the route of the measurement metro line. 8 consecutive stations, of which four stations were underground (Century Avenue – Pudong Avenue, Yangshupu Rd. – Dalian Rd., Dalian Rd. – Linping Rd. and Linping Rd. – Hailun Rd.) and the other four stations were overground (Zhenping Rd. – Caoyang Rd., Caoyang Rd. – Jinshajiang Rd., Jinshajiang Rd. – Zhongshan Park, Zhongshan Park – West Yan'an Rd.). The $PM_{2.5}$ and CO_2 concentrations in the sitting area were continuously measured. To better represent the underground/overground in-carriage $PM_{2.5}$ and CO_2 concentrations, data were collected one station before or after the transit station between

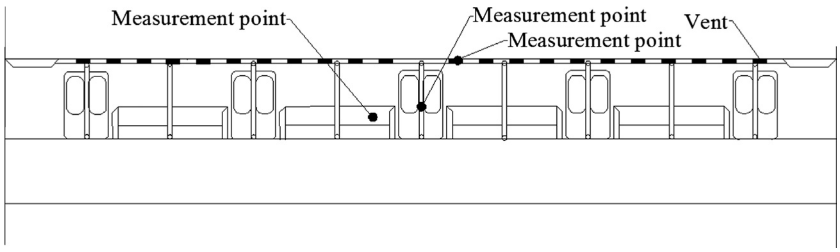

Fig. 1. Schematic diagram of the measurement points inside metro carriages.

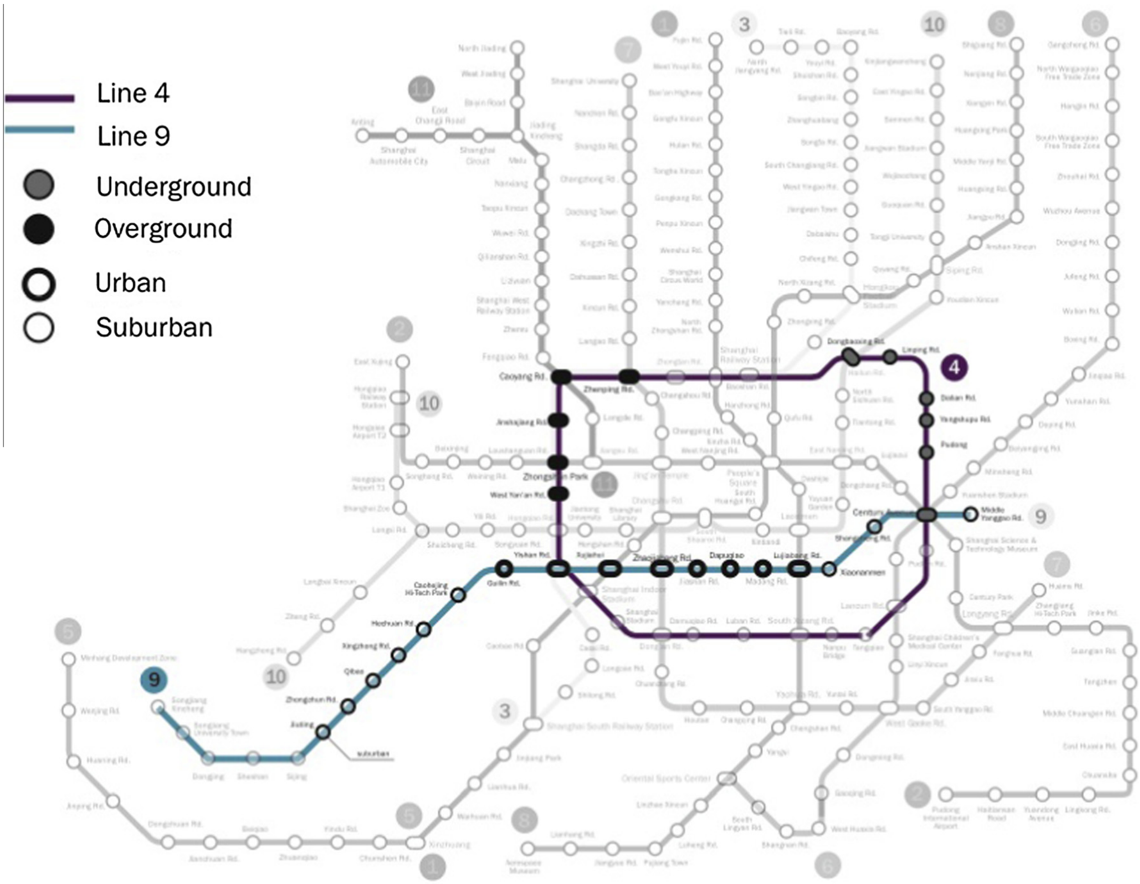

Fig. 2. The routes of Line 4 and Line 9 in Shanghai metro map.

underground and overground. To avoid the effect of passengers' boarding and leaving on the in-carriage $PM_{2.5}$ concentration, the measurements were conducted during off-rush hours. The measurement was conducted once a week for four weeks.

Urban area/suburban area

The effects of driving locations on the in-carriage $PM_{2.5}$ and CO_2 concentrations were conducted on Line 9, which drives both in urban and suburban area underground. The route was shown in Fig. 2. Sitting area was selected as the measurement point. The measurements were conducted during off-rush hours at 15 consecutive stations, including 8 suburban sections (Century Avenue-Shangcheng Rd., Shangcheng Rd.-Xiaonanmen, Xiaonanmen-Lujiabang Rd., Caohejing Hi-Tech Park-Hechuan Rd., Hechuan Rd.-Xingzhong Rd., Xingzhong Rd.-Qibao, Qibao-Zhongchun Rd., Zhongchun Rd.-Jiuting) and 7 urban stations (Lujiabang Rd.-Madang Rd., Madang Rd.-Dapuqiao, Dapuqiao-Jiashan Rd., Jiashan Rd.-Zhaojiabang Rd., Zhaojiabang Rd.-Xujiahui, Xujiahui-Yishan Rd., Yishan Rd.-Guilin Rd., Guilin Rd.-Caohejing Hi-Tech Park). The measurement was conducted once a week for four weeks.

Passenger number

The effect of passenger number on the in-carriage $PM_{2.5}$ concentration was measured on Line 1. Breathing zone was chosen as the measurement point. The maximum loading capacity of a single metro carriage is 420 passengers. The measurements were conducted during the rush hour and off-rush hour in the same metro carriage (Model AC-01, Siemens Co., Germany) at five consecutive stations (Xujiahui to Hengshan Rd., Hengshan Rd. to Changshu Rd., Changshu Rd. to South Shanxi Rd., South Shanxi Rd. to South Huangpi Rd., Huangpi Rd. to People's Square). The passenger numbers during the measurements were observed between 98 and 333. Each $PM_{2.5}$ concentration represented the mean value of the five measurements at the same passenger number in the same carriage. The measurement was conducted twice a week for four weeks.

Mathematical model of in-carriage $PM_{2.5}$ concentration

A mathematical model that incorporates the effect of ventilation and passenger number on the in-carriage $PM_{2.5}$ concentration was established. Since the model addresses $PM_{2.5}$ transport between in- and out-carriage, other potential in-carriage

$PM_{2.5}$ emission sources such as smoking was not considered in this study. Smoking was prohibited in the metro systems and it was also not observed during testing. The equation was based on the particle mass-balance principles. When the metro train stopped at the platform with the door open, the equation was shown as:

$$[Q_v(1-\eta)C_e + v_d A_d C_s + nC_p V - Q_v C_i]dt = VdC_i \tag{1}$$

where Q_v ($m^3\,s^{-1}$) is the ventilation air flow rate, C_e ($\mu g/m^3$) is the $PM_{2.5}$ concentration in the tunnel air, η is the filtration efficiency of the ventilation air filter, v_d (m/s) is the air velocity through the door into the carriage, A_d (m^2) is the area of the door, C_s ($\mu g/m^3$) is the $PM_{2.5}$ concentration in the platform air, n is the passenger number, C_p ($\mu g/m^3$ s) is the personal $PM_{2.5}$ emission rate in the carriage, V (m^3) is the volume of the metro carriage and C_i is the in-carriage $PM_{2.5}$ concentration. Eq. (1) was integrated to the following equation:

$$C_n = C_0 + \left[(1-\eta)C_e - C_0 + \frac{v_d A_d C_s + nC_p V}{Q_v}\right]\left(1 - e^{-\frac{Q_v}{V}t_1}\right) \tag{2}$$

where C_n ($\mu g/m^3$) is the in-carriage $PM_{2.5}$ concentration when the door was open, C_0 ($\mu g/m^3$) is the in-carriage $PM_{2.5}$ concentration before the door opened, and t_1 (s) is the duration that the door keeps opening.

When the metro train was running, no out-carriage air entered the carriage through the door. Thus, Eq. (1) was modified to:

$$[Q_v(1-\eta)C_e + nC_p V - Q_v C_i]dt = VdC_i \tag{3}$$

Eq. (3) was integrated to the following equation:

$$C_n' = C_0' + \left[(1-\eta)C_e - C_0' + \frac{nC_p V}{Q_V}\right]\left(1 - e^{-\frac{Q_v}{V}t_2}\right) \tag{4}$$

where C_n' is the in-carriage $PM_{2.5}$ concentration when the metro train was running in the tunnel, C_0' is the in-carriage $PM_{2.5}$ concentration when the metro train just left the station, and t_2 (s) is the duration when the metro train is running. It should be noted that, the metro carriage envelope was more air-tightened than the vehicles. The air leakage played a negligible role on air exchange between in-carriage and outside.

Results

Fig. 3 shows the average $PM_{2.5}$ and CO_2 concentrations of five measured metro lines. The average $PM_{2.5}$ and CO_2 concentrations inside all the five measured metro lines were 84 ± 42 $\mu g/m^3$ and 1253.1 ± 449.1 ppm. The $PM_{2.5}$ concentration was higher than the Chinese National Standard at 75 $\mu g/m^3$, the 24-h US National Standard at 35 $\mu g/m^3$ and WHO standard at 10 $\mu g/m^3$, indicating poor air quality in the metro carriages.

As shown in Fig. 3, the $PM_{2.5}$ and CO_2 concentrations of Line 1 and Line 2 were much higher than the other three. This is because the metro trains of Line 1 (Model DC-01, Siemens Co., Germany; Model AC-01, Siemens Co., Germany) and Line 2 (Model AC-02, Adtranz Co. and Siemens Co., USA and Germany) are the oldest trains in Shanghai metro system, which began in operation from 1993 and 2000, respectively. Fig. 4 shows the particle size distributions measured inside different metro lines. Similar to Fig. 3, the particle concentrations at all sizes inside the metro carriage of Line 1 and Line 2 were larger than those in the other three lines. Due to the long-time usage, ventilation systems in the metro trains are not only aged but also functioned improperly. The ventilation air filter used in Line 1 and 2 are coarse stainless steel wire mesh or aluminum mesh that cannot effectively keep $PM_{2.5}$ entering the carriage. On the other hand, the metro train of Line 4 (Model AC-05, Siemens Co. and CSR Inc., Germany and China), Line 9 (Model AC-04, CNR Inc., China) and Line 10 (Alstom Model AC-13, Alstom Inc.,

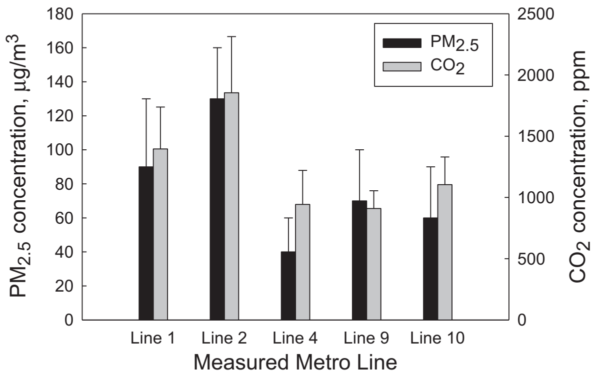

Fig. 3. Average in-carriage $PM_{2.5}$ and CO_2 concentrations at five measured metro lines.

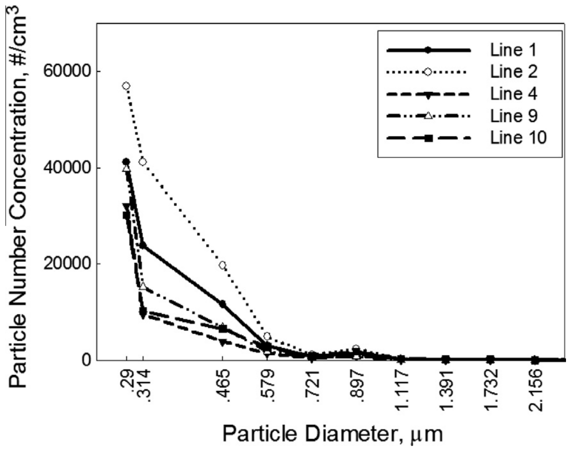

Fig. 4. Particle size distributions measured in different metro carriages.

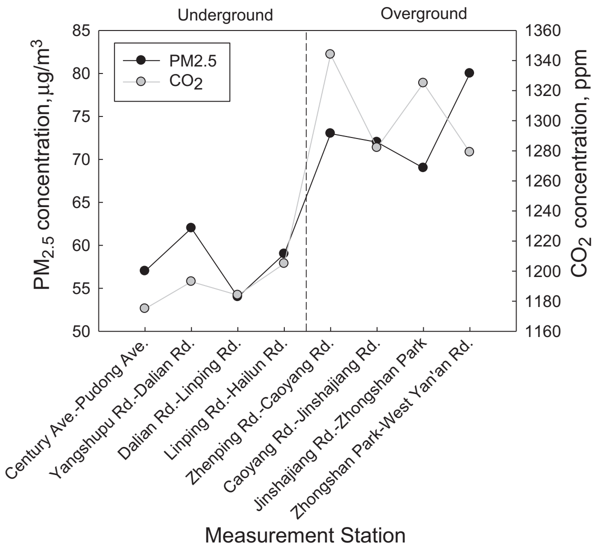

Fig. 5. Average in-carriage $PM_{2.5}$ and CO_2 concentrations in underground and overground. The Metro Line 4 was used in the measurement.

France) were equipped with fibrous air filter with much higher filtration efficiency, which led to a lower in-carriage $PM_{2.5}$ concentration.

It can be seen that the largest particle concentration occurred at dp $\leqslant$ 0.3 μm in all the five measured lines. This is because the larger particles deposited faster than the smaller particles on the metro carriage inner surface that was consistent with the previous measurement in the experimental chamber (Lai 2006).

Besides ventilation system, the effect of driving condition on the in-carriage $PM_{2.5}$ concentration was also investigated. Fig. 5 shows the average $PM_{2.5}$ and CO_2 concentrations when the metro was driven underground and overground (Metro Line 4). The passenger numbers during the measurements were similar. It was found that, as driving from underground to overground, the in-carriage $PM_{2.5}$ concentration increased by 24.14%. That is because overground out-carriage $PM_{2.5}$ concentrations (133 μg/m^3) were higher than the underground concentrations (110 μg/m^3). More out-carriage $PM_{2.5}$ entered the carriage through the ventilation system.

Fig. 6 shows the average in-carriage $PM_{2.5}$ and CO_2 concentrations at urban and suburban area (Line 9). The in-carriage $PM_{2.5}$ concentration in the suburban area was 10–20% higher than that in the urban area. This is because, in the suburban area along Line 9, the emissions of several factories led to a much higher $PM_{2.5}$ concentration (Wang et al., 2013). The measured data showed that the average overground $PM_{2.5}$ concentration in the suburban area (302 μg/m^3) was 14.83% higher than that in the urban area (263 μg/m^3). However, the in-carriage CO_2 concentration driving in the suburban area was 10–20% lower than that in the urban area. More than 2.7 million vehicles in the Shanghai urban area led to a very high CO_2 concentration.

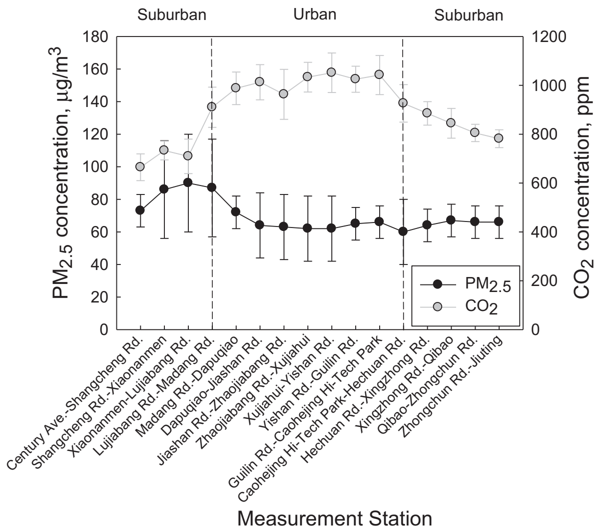

Fig. 6. Average in-carriage $PM_{2.5}$ and CO_2 concentrations in urban area and suburban area. The Metro Line 9 was used in the measurement.

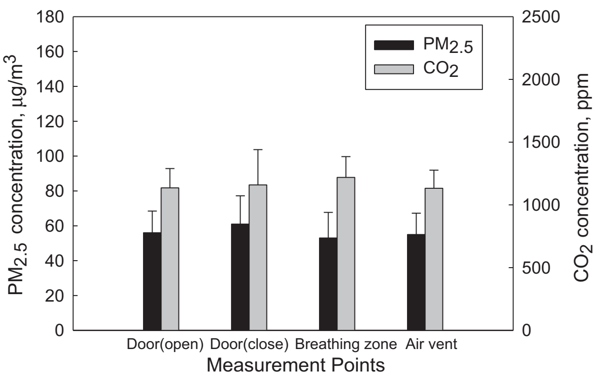

Fig. 7. Average $PM_{2.5}$ and CO_2 concentrations in the metro carriage at various measurement points.

Fig. 7 shows the average $PM_{2.5}$ and CO_2 concentrations at the measurement points. It can be found that the $PM_{2.5}$ concentrations measured at the door both close and open were slightly higher than the concentrations measured at the breathing zone and air vents. This is because the out-carriage $PM_{2.5}$ concentration at the platform was high (244 µg/m^3). When the train stopped at the platform, the in-carriage $PM_{2.5}$ concentration at the door increased significantly as the out-carriage air entered the carriage through the doors. On the other hand, the out-carriage $PM_{2.5}$ concentration in the tunnel was measured at 141 µg/m^3 that was much lower than that in the platform air. This led to a lower $PM_{2.5}$ concentration at air vent since the out-carriage $PM_{2.5}$ entered the carriage through the ventilation system with air filters. The CO_2 concentration at the breathing zone was found as the highest due to the exhalation of passengers.

The impact of passengers on the in-carriage $PM_{2.5}$ concentration was also studied. Fig. 8(a)–(e) shows the correlation between average $PM_{2.5}$ concentration and passenger number in the same metro carriage at different stations. More passengers led to more PM entrance during boarding. Also, more passengers and luggage movements caused more PM resuspension from the carriage floor. As the passenger number increases in the carriage, the $PM_{2.5}$ concentration increases by 0.4 µg/m^3 s^{-1} per passenger in the metro carriage, that was similar to a former study on the commuters' exposure inside the high-speed rail carriages (Xu et al., 2013). Therefore, the passengers can be identified as the in-carriage $PM_{2.5}$ source.

To verify the model estimation of the in-carriage $PM_{2.5}$ concentration, Eq. (2) $C_n = C_0 + \left[(1-\eta)C_e - C_0 + \frac{v_d A_d C_s + nC_p V}{Q_v}\right]\left(1 - e^{-\frac{Q_v}{V}t_1}\right)$ was used to calculate the in-carriage $PM_{2.5}$ concentration (C_n) when the metro train stopped at platform. The input parameters of C_0, η, C_e, v_d, A_d, C_s, n, V, Q_v and t_1 were obtained from the measurements conducted in the metro carriage at the station of Line 10. C_p = 0.4 µg/m^3 s^{-1} was used. The model results were compared against the measured C_n, as shown in Fig. 9(a), (c), (e). Eq. (4) $C'_n = C'_0 + \left[(1-\eta)C_e - C'_0 + \frac{nC_p V}{Q_V}\right]\left(1 - e^{-\frac{Q_v}{V}t_2}\right)$ was used to estimate the in-carriage $PM_{2.5}$ concentra-

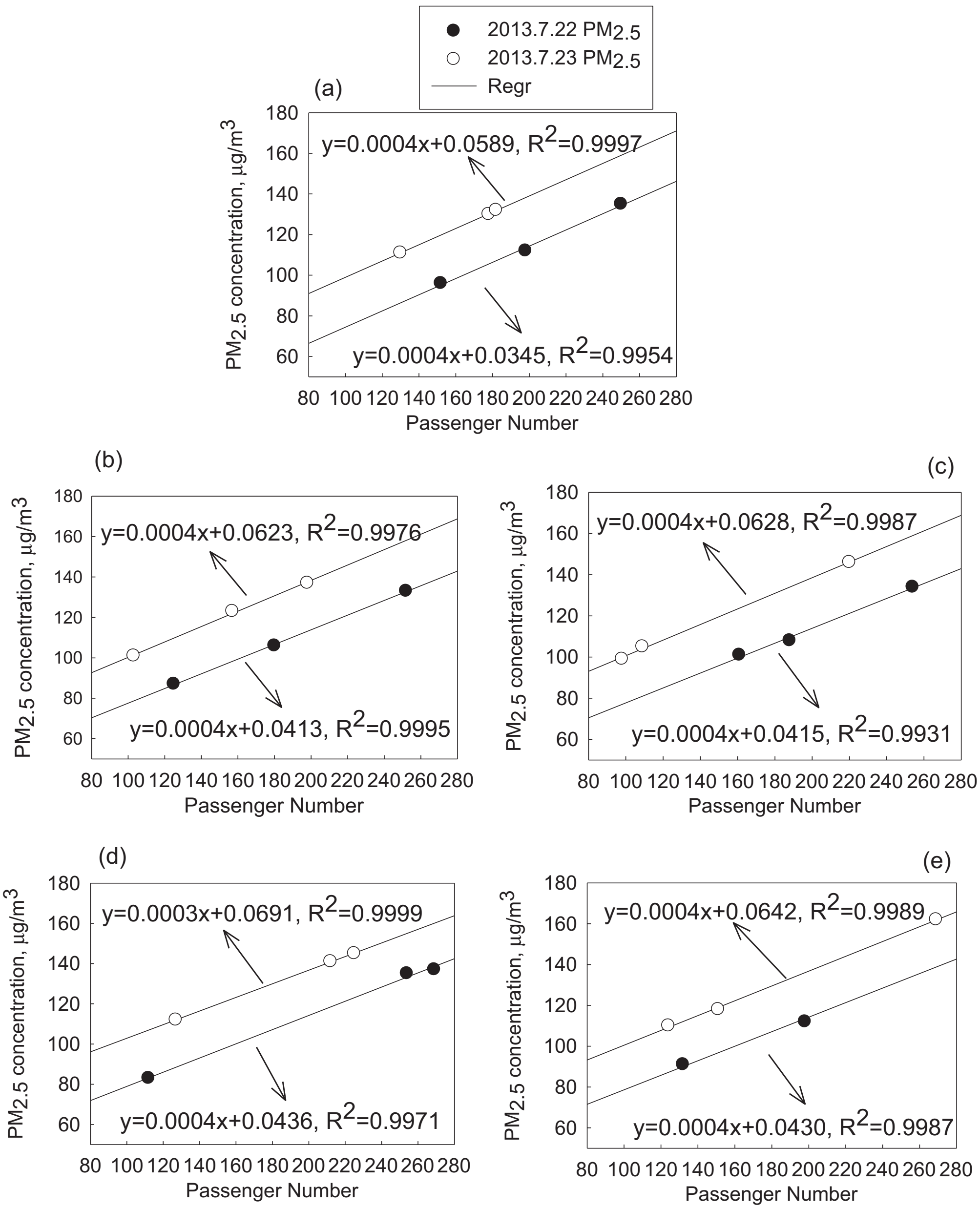

Fig. 8. Correlations between the average $PM_{2.5}$ concentration and passenger number in the same metro carriage between different stations: (a). Xujiahui to Hengshan Rd., (b). Hengshan Rd. to Changshu Rd., (c). Changshu Rd. to South Shanxi Rd., (d). South Shanxi Rd. to South Huangpi Rd., (e). South Huangpi Rd. to People's Square.

tion (C_n) when the metro train was running in the tunnel. The input parameters of C'_0, η, C_e, n, V, Q_v and t_2 were obtained from the measurements conducted in the running metro carriage of Line 10. $C_p = 0.4\ \mu g/m^3\ s^{-1}$ was used. The modeled results were compared against the measured C'_n, as shown in Fig. 9(b), (d), (f). The modeled and measured results illustrated a similar trend with little differences (<10%).

Conclusion

In summary, the in-carriage $PM_{2.5}$ and CO_2 concentrations were investigated under various conditions. The aged ventilation system and the out-carriage air with higher $PM_{2.5}$ concentrations can be considered as the primary drivers for higher in-carriage $PM_{2.5}$ and CO_2 concentrations. Also, more passengers led to the increase of in-carriage $PM_{2.5}$ concentration at a ratio of 0.4 $\mu g/m^3$·passenger. The established mathematical model that incorporated all the factors that affect the in-carriage $PM_{2.5}$ and CO_2 concentrations can be used to estimate the in-carriage $PM_{2.5}$ concentration under different conditions. With

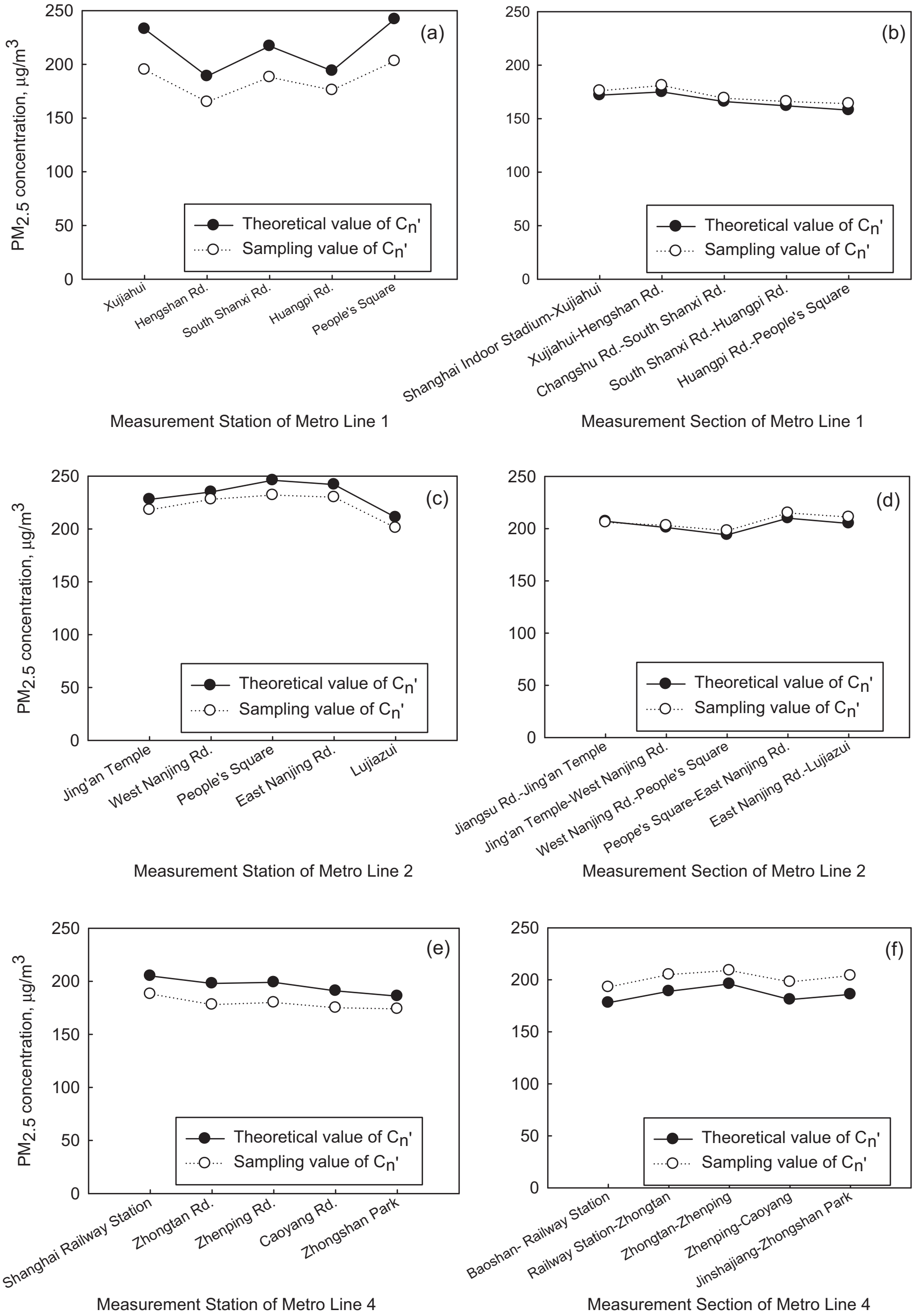

Fig. 9. Comparison between the modeled and the measured in-carriage $PM_{2.5}$ concentrations when the metro was stopping at the stations: (a), (c), (e) and running between stations: (b), (d), (f). The Metro Line 1, 2, 4 were used in the measurements.

this information, $PM_{2.5}$ concentration can be determined and measures can be further determined to reduce the in-carriage particle concentrations.

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References

Apte, M.G., Fisk, W.J., Daisy, J.M., 2000. Associations between indoor CO_2 concentrations and sick building syndrome symptoms in U.S. office buildings: an analysis of the 1994–1996 BASE study data. Indoor Air 10, 246–257.

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

Flemming, R.C., Nicholas, L.M., David, N., 2011. Cardiovascular Effects of Inhaled Ultrafine and Nanosized Particles. John Wiley & Sons Inc, New York.

Furuya, K., Kudo, Y., Okinagua, K., Yamuki, M., Takahashi, K., Araki, Y., Hisamatsu, Y., 2001. Seasonal variation and their characterization of suspended particulate matter in the air of subway stations. J. Trace Microprobe Tech. 19, 469–485.

Kim, Y., Kim, J., Kim, I., Kim, J., Yoo, C., 2010. Multivariate monitoring and local interpretation of indoor air quality in Seoul's metro system. Environ. Eng. Sci. 27, 721–731.

Lai, A.C.K., 2006. Particle deposition and decay in a chamber and the implications to exposure assessment. Water Air Soil Pollut. 175, 323–334.

Langrish, J.P., Bosson, J., Unosson, J., Muala, A., Newby, D.E., Mills, N.L., Blomberg, A., Sandström, T., 2012. Cardiovascular effects of particulate air pollution exposure: time course and underlying mechanisms. J. Int. Med. 272, 224–239.

Midander, K., Elihn, K., Wallén, A., Belove, L., Karlsson, A., Wallinder, I., 2012. Characterisation of nano- and micro-sized airborne and collected subway particles, a multi-analytical approach. Sci. Total Environ. 427, 390–400.

Paivi, A., Tarja, Y.T., Anu, K., Timo, M., Anne, H., Kaarle, H., Mika, R.I., Risto, H., Tarja, K., Matti, J., 2005. The concentrations and composition of and exposure to fine particles (PM2.5) in the Helsinki subway system. Atmos. Environ. 39, 5059–5066.

Park, D., Oh, M., Yoon, Y., Park, E., Lee, K., 2012. Source identification of PM10 population in subway passenger cabins using positive matrix factorization. Atmos. Environ. 49, 180–185.

Şahin, Ü.A., Onat, B., Stakeeva, B., Ceran, T., Karim, P., 2012. PM10 concentrations and the size distribution of Cu and Fe-containing particles in Istanbul's subway system. Transp. Res. Part D 17, 48–53.

Seppänen, O.A., Fisk, W.J., Mendell, M.J., 1999. Association of ventilation rates and CO_2 concentrations with health and other responses in commercial and institutional buildings. Indoor Air 9, 226–252.

Wang, J., Hu, Z., Chen, Y., Chen, Z., Xu, S., 2013. Contamination characteristics and possible sources of PM10 and PM2.5 in different functional areas of Shanghai, China. Atmos. Environ. 68, 221–229.

Xu, B., Liu, S., Liu, J., Zhu, Y., 2011. Effects of vehicle cabin filter efficiency on ultrafine particle concentration ratios measured in-cabin and on-roadway. Aerosol Sci. Technol. 45, 215–224.

Xu, B., Zhu, Y., 2009. Quantitative analysis of the parameters affecting in-cabin to on-roadway (I/O) ultrafine particle concentration ratios. Aerosol Sci. Technol. 43, 400–410.

Xu, B., Cui, P., Xu, H., Chen, H., Lin, Y., 2013. Commuter exposure to particle matter and carbon dioxide inside high-speed rail carriages. Transp. Res. Part D 20, 1–6.

Yu, Q., Xiao, S., Shen, J., Li, X., Ma, W., Chen, L., 2012. Commuters' exposure to PM1 by common travel modes in Shanghai. Atmos. Environ. 59, 39–46.