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Commuter exposure to particle matter and carbon dioxide inside high-speed rail carriages

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ABSTRACT

Exposure to $PM_{2.5}$ and CO_2 inside standard high-speed Chinese rail carriages is examined. The concentrations, 0.07 mg/m^3 and 1200 ppm, are found to be significantly affected by passenger numbers, ventilation systems, and the carriage class. As passengers increase from 10 to 80 in a carriage, the concentrations increases by up to 0.04 mg/m^3 in the passenger-breathing zone, and are inversely proportional to the air exchange rate. The greatest in-carriage $PM_{2.5}$ concentration are found in the dinning carriage, with lower but similar levels found in other carriage classes. More rapid air turnover leads to slightly higher $PM_{2.5}$ removal.

1. Introduction

Commuting in China is mainly by public transportation, and the use of high-speed rail for this purpose is increasing. High PM exposure levels, however, have been reported inside subway carriages (Aarnio et al., 2005; Kam et al., 2011), but there is limited information concerning exposure inside the HSR carriages. Compared to the other transportation microenvironments, there are some characteristics of HSR carriages[1] including their enclosed nature with a fixed but low outside-air exchange rate that suggest they may pose particular problems. Here we examine $PM_{2.5}$ exposure levels, CO_2 concentrations, temperature, and humidity in HSR carriages considering different zones within them and the impact of passenger numbers, ventilation systems, and carriage classes.

2. Methodology

There are four series of HSR carriages (CRH1, CRH2, CRH3, CRH380) in-service in China. Two ventilation types were generally fitted (Fig. 1). For ventilation type *i*, the air condition unit is located on the top of the carriage, with the air supply passing through an orifice in the ceiling to enter the carriage. The recirculation air vent is located in the ceiling of the end of the carriage. For ventilation type ii, the air conditioning unit is at the bottom of the carriage, with air entering through s strip-shape vent under the luggage shelves. Recirculation air vents were located beneath the seats. Four test metro carriages (three using ventilation type *i* and one type *ii*) are studied. Ten measurement points at supply air outlet, passenger-breathing zone and recirculation air vents are used.

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[1] The term carriage is used throughout although it is appreciated that a carriage may have a number of compartments with differing uses (e.g. lavatories as well as seating).

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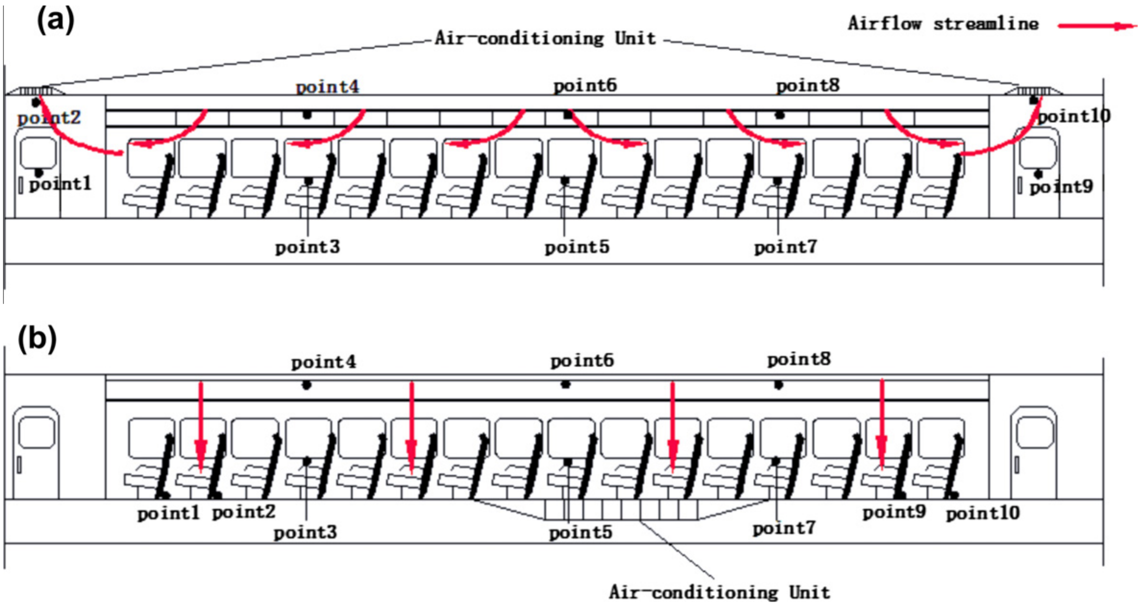

Fig. 1. Schematic of the experiment setup; (a) ventilation type *i* and (b) ventilation type *ii*.

Measurements were conducted Shanghai–Nanjing round trips in July and August when the air conditioning is turned on. The route consists of four stations and takes approximately 70 min with 20 ± 2 min between two stations. During each 20 ± 2 period, 2 min are taken as measurement point. $PM_{2.5}$ concentrations are measured using Dustrak (TSI Model 8530) with a one-second interval. The CO_2 concentration, temperature, and relative humidity (RH) are measured using the Q-Trak (TSI Model 7565), again at a 1 s interval. The standard passenger carriage holds a maxmium of 80 people, and their numbers were recorded. To determine the effect of ventilation on the $PM_{2.5}$ concentrations, low, medium, and high supply air rates ventilation airflow rates were used measurement. A range of 15 ± 5% of outside air is extracted in the ventilation system, and the air exchange rate (AER) inside a carriage at each ventilation airflow rate is estimated using

$$\mathrm{AER} = Q_0/V \tag{1}$$

where Q_0 (m^3/h) is the outside airflow rate, and V (m^3) is the volume of the metro carriage (256 m^3). Because it is difficult to measure Q_0 precisely from the orifice in the ceiling, this is estimated by solving an equation based on particle mass-balance principles;

$$nQ_FC_F + Q_0C_0 - Q_0C_i = V\frac{dC_i}{dt} \tag{2}$$

where n (−) is the number of passengers, QF (m^3/h) is the human respiration rate, CF (ppm) is the CO_2 concentration of human respiration, C_0(ppm) is the outside CO_2 concentration, C_i (ppm) is the in-carriage CO_2 concentration, t(s) is the time. Under steady state, the in-carriage CO_2 concentration does not change. Eq. (2) can be modified to allow calculation of Q_0 as;

$$Q_0 = nQ_FC_F/(C_i - C_0) \tag{3}$$

3. Results

Fig. 2 shows the results for $PM_{2.5}$ concentrations, CO_2, temperature and humidity at the ten measurement points carriages equipped with ventilation type *i*. Twelve passengers were loaded in the carriage during the exercise and a low ventilation airflow with an AER of 2.7 h^{-1} used. The $PM_{2.5}$ concentration in the passenger-breathing zone points 3, 5, 7 close to the recirculation air vent points 1, 2, 9, 10 are 20% higher than those at the air inlet points 4, 6, 8, suggesting that the existence of the passengers and their activities are $PM_{2.5}$ sources, and that the HSR ventilation systems is reducing the in-carriage concentration by 20%. Similarly, CO_2 concentrations in the passenger-breathing zone are higher than by the air outlets inside the carriage. The differences in concentrations between the passenger breathing zone and ventilation supply air inlets is about 15%; lower than the difference in $PM_{2.5}$ concentrations between measurement points. This is probably because CO_2 is only diluted by external air in the ventilation system without any other loss, while $PM_{2.5}$ is not only being diluted by outside air but also being removed by an air filter installed in the ventilation system.

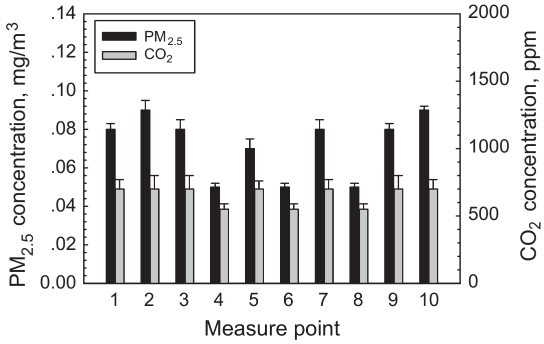

Fig. 2. $PM_{2.5}$ and CO_2 at points inside the test metro carriages. *Note*: The test carriage uses ventilation type *i* with low ventilation airflow rates.

3.1. Passenger numbers

As the very existence of passengers influence in-carriage $PM_{2.5}$ and CO_2 concentrations, and so measurements are conducted involving various numbers of passengers in the same carriages with an AER of 5.2 h^{-1} (Fig. 3). Both $PM_{2.5}$ and CO_2 increase in response to increasing passengers. To quantify the effect of passenger numbers on these emissions, the correlation between $PM_{2.5}$, CO_2 and passengers using simple linear regressed as shown in Fig. 4.

3.2. Ventilation

Ventilation airflow rates with respect to AERs of 2.7, 5.2, and12 h^{-1} can be selected in the HSR. To investigate the effect of these alternatives on the $PM_{2.5}$ and CO_2, a carriage with 62–65 passengers is used (Fig. 5). We find the $PM_{2.5}$ and CO_2 concentrations significantly decreased as the AER increased. It was noted that the CO_2 decreasing rate is much larger than the $PM_{2.5}$ decreasing rate. It is because the outside CO_2 concentrations are 2–5 times lower than in-carriage concentrations that CO_2 dilution faster inside the carriages. On the other hand, the $PM_{2.5}$ concentration difference between in-carriage and outside is much less. Thus, larger outside AER diluted in-carriage CO_2 more effectively than $PM_{2.5}$.

3.3. $PM_{2.5}$ concentrations

HSR trains comprise 1st and 2nd class carriages, dinning carriages, and lavatories. Unlike other carriages, an exhaust fan, rather than air conditioning is installed in lavatories. To investigate the $PM_{2.5}$ concentrations in various carriage types, measurements are conducted in each category using, with the exception of lavatories, similar passenger numbers; the AERs for the carriages being 5–5.4 h^{-1}. Fig. 6 shows the results. For a lavatory, the measurement was conducted only at passenger breathing zones and exhaust vents because of the lack ventilated supply air. The $PM_{2.5}$ concentrations in 1st and 2nd class carriages are similar, although the price of a ticket for the former is twice that for the latter. At all measurement points, the

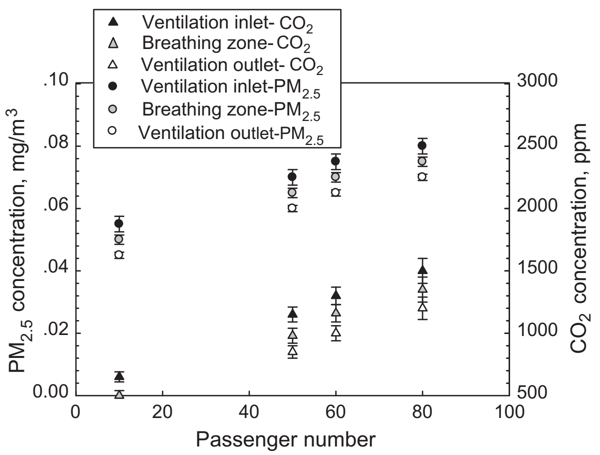

Fig. 3. $PM_{2.5}$ and CO_2 as a function of passenger numbers in a carriage. *Note*: Middle ventilation airflow rates are used.

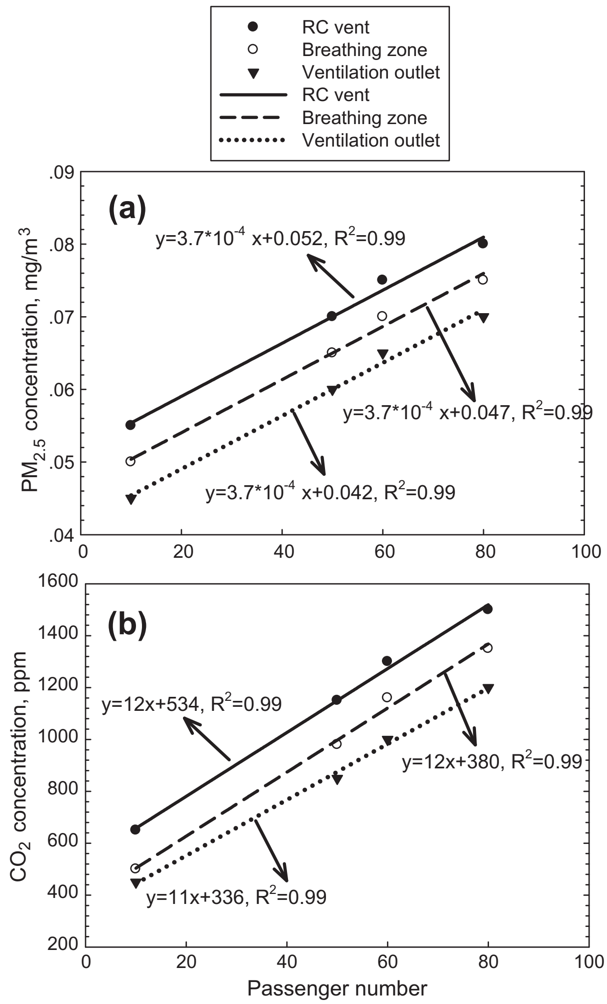

Fig. 4. Correlations between in-carriage (upper) $PM_{2.5}$ and (lower) CO_2 and passenger numbers inside the same metro carriage.

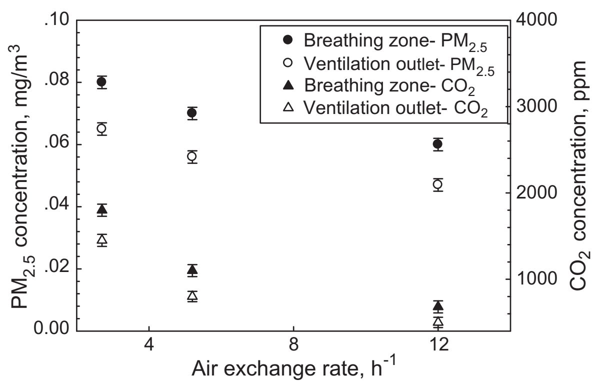

Fig. 5. $PM_{2.5}$ and CO_2 at various AERs inside the HSR carriages. *Note*: The measurement points are at passenger breathing zone.

highest $PM_{2.5}$ concentrations (0.18 ± 0.02 mg/m^3) are in dinning carriages with 12 dinners; when six passengers had fried noodle and six had fried rice. Similar to the other carriages, $PM_{2.5}$ concentrations at ventilation outlets in dinning carriages were 20–30% less than at passenger-breathing zones; suggesting that the efficiency of $PM_{2.5}$ removal in the different classes of carriage classes is about same. The $PM_{2.5}$ concentration in the lavatory is similar to that at recirculation air vents in 1st and 2nd class carriages, probably because its exhaust fan takes air from the passenger carriages into it.

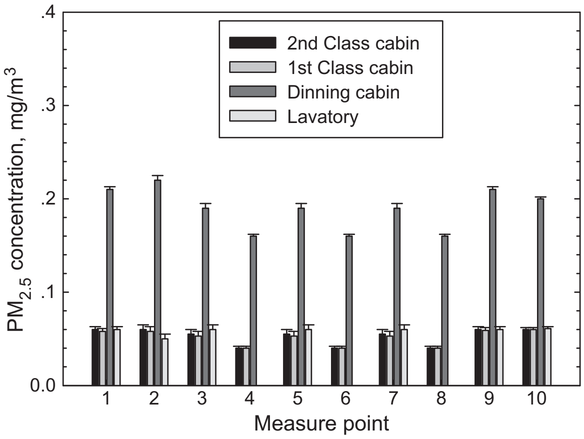

Fig. 6. $PM_{2.5}$ concentrations at measurement points in different carriage types.

Table 1
Summary of $PM_{2.5}$ and CO_2 under different ventilation conditions.

Measurement location		$PM_{2.5}$ and CO_2 concentration (mg/m^3, ppm)	
		Ventilation type *i*	Ventilation type *ii*
Passenger carriage	Supply air outlets	0.04 ± 0.002 450 ± 40	0.045 ± 0.002 430 ± 30
	Passenger breathing zone	0.05 ± 0.002 500 ± 40	0.05 ± 0.002 480 ± 40
	Recirculation vents	0.06 ± 0.002 600 ± 50	0.055 ± 0.002 500 ± 40
Dinning carriage	Supply air outlets	0.16 ± 0.01 450 ± 50	0.14 ± 0.01 430 ± 40
	Passenger breathing zone	0.19 ± 0.01 500 ± 50	0.18 ± 0.01 520 ± 40
	Recirculation vents	0.20 ± 0.01 610 ± 50	0.18 ± 0.01 530 ± 50

3.4. Airflow distribution

Measurements of $PM_{2.5}$ and CO_2 are conducted inside the passenger and dinning carriages for both ventilation types using 12–15 passengers (Table 1). The $PM_{2.5}$ and CO_2 concentration at passenger breathing zone and recirculation vents associated with ventilation type ii are slightly lower than those for type *I*. This is probably because ventilation type *ii* exchanges air more efficiently, with its the recirculation vents beneath seats leading to the in-carriage air residence time being shorter leading to more AER and greater $PM_{2.5}$ removal. The AERs at passenger breathing zones for both ventilation types are calculated as 5.1 and 5.6 h^{-1}, and similar to passenger carriages, the AER inside the dinning carriage under ventilation type ii exceeds that for ventilation type *i*.

4. Conclusions

Examination of the atmosphere inside 300 km/h HSR carriages were finds that passengers and their activities are sources of $PM_{2.5}$. Linear relationship between this concentration and passenger number were developed and with 80 passengers in a carriage there is a 0.04 mg/m^3 rise in the $PM_{2.5}$ concentration. The system of ventilation has a significant effect on in-carriage $PM_{2.5}$ removal, with a 25% concentration reduction occurring as the AER increases from 2.7 to 12 h^{-1}. Cabin class does not affect the in-carriage air quality significantly, compared to the passenger carriages, there about a 300% higher $PM_{2.5}$ concentration in the dinning carriage during meal time.

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