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Commuter exposure to particulate matters in four common transportation modes in Nanjing

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ABSTRACT

Particulate matter (PM) is one of the major air pollutants in China. Traffic-related microenvironments are the typical scenarios exposed to high PM concentrations. This paper investigates the personal exposure to PM during commuting in Nanjing in four transportation modes, i.e. subway, bicycle, bus and walking. The measurements were conducted in a heavy-traffic street during rush hours in summer and winter. The result reveals significant PM concentration differences between various commuting modes. Passengers in subway cabin are exposed to lowest PM_1 (38.3 μg/m^3) and $PM_{2.5}$ (54.4 μg/m^3) concentrations, while passengers in subway station are exposed to highest $PM_{2.5}$ (90.5 μg/m^3). Pedestrians are exposed to highest PM_1 (59.5 μg/m^3). Both outdoor and indoor-generated particles contribute a lot to the particles in subway station and 63.4% of the $PM_{2.5}$ generated in subway station are between 1 μm and 2.5 μm in size. Most particles in subway cabin are from subway station and most particles in bus cabin come from the outdoor air, while indoor sources contribute little. Spatial particle concentration variations were observed in subway station. The particle concentration at a deeper level is usually higher than the concentration at a shallower level. Substantial particles within 1–2.5 μm in size were observed at the platform and the portion within 1–2.5 μm decreased at shallower levels. The PM inhalation during subway trip is lowest while the inhalations during walking and cycling are more than 5 times higher. During a short distance subway trip, the exposure in subway station contributes most of the total particle inhalation during the entire subway trip.

1. Introduction

Urban air pollution is a public health risk that many modern cities face, particularly the cities in developing countries like China. Urban air quality can be heavily impacted by traffic-emitted pollutants such as particulate matter, black carbon, carbon monoxide, oxides of nitrogen and volatile organic compounds [1–5]. Traffic-related microenvironments such as subway station, bus cabin and roadside are usually the typical scenarios exposed to high traffic-related pollutant concentrations. According to the Exposure Factors Handbook of EPA [6], people spend average 87.4min in transit every day (approximately 6% of the time). Exposure Factors Handbook of Chinese Population (Adults) [7] revealed average 63min people spent in transit every day in China (approximately 4% of the time). People are vulnerable to high pollutant level during commuting. Black carbon (BC) is a typical traffic-related pollutant and may have short- or long-term effects on human health, e.g. cardiovascular disease, adverse respiratory effects or neurological effects [8–10]. Dons et al. [11] found it accounts for 21% of personal exposure to BC and approximately 30% of inhaled dose in transport, while Hankey and Marshall [12] estimated approximately 50% of BC concentrations were from near-traffic emissions. Apte et al. [13] measured 3.6 times higher in-vehicle BC concentrations than the ambient level in New Delhi, while Li et al. [14] observed around 50% higher BC concentrations inside vehicles. Carbon monoxide (CO) is another important traffic-emitted air pollutant, which is produced by the incomplete combustion of carbonaceous fuels [15]. Elevated CO concentrations have been found to be associated with increased mortality, exacerbate cardiovascular disease and other health problems [16–18]. Huang et al. [15], Riediker et al. [19] and de Nazelle et al. [20] observed elevated in-cabin CO concentrations than the ambient level in different cities, and higher CO concentration in car than the level in bus. Volatile organic compounds (VOCs) are important atmospheric pollutants in urban areas and different kinds of VOC will have various adverse effects on human health [21]. Kim et al. [22] analyzed 24 VOCs in vehicles and found that in-cabin VOC emissions are highly contingent on changes in engine and ventilation modes. Gong et al. [23] observed 1–2 times higher concentrations of aromatic VOCs in old subway carriages than in the new ones.

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Particulate matter (PM) has become one of the major air pollutants in most cities in China [24]. Human exposure to PM has been proved to be associated with the increases in allergic disorders, respiratory morbidity, cardiovascular disease, and premature mortality [25–32]. Fondelli et al. [33] observed that traffic-related exposure to fine particulate matter ($PM_{2.5}$, $\leq 2.5\,\mu m$ in size) contributes approximately 12% of daily $PM_{2.5}$ personal exposures, which indicates that exposure to PM during commuting contributes a considerable part to the total daily inhalation exposure, and thus is important for commuter health. Jia et al. [34] revealed that short-term exposure to PM during subway trips was associated with decreased heart rate variability. Strak et al. [35] reported increased airway inflammation and reduced lung function after short-term exposure to ultrafine particles (UFP, $\leq 0.1\,\mu m$ in size) and soot in traffic for cyclists. Exposure assessments to PM during commuting are getting increasingly more attention in recent years. Subway, bus, taxi, private car, bicycle and walking are usually the most common transportation modes during daily commuting, which were widely investigated in literature. Previous studies revealed different PM exposure levels across a variety of transportation modes. Adam et al. [36] observed much higher $PM_{2.5}$ concentration levels during subway trips than the levels during bus, car and bicycle trips in London. Fromme et al. [37] reported more than three times higher PM_{10} ($\leq 10\,\mu m$ in size) concentration levels during subway journeys than the levels during car journeys in Berlin. Yan et al. [38] found that subway commuters are more exposed to $PM_{2.5}$ than bus commuters and pedestrians in Beijing. Tan et al. [39] observed higher $PM_{2.5}$ but lower UFP concentration levels during subway trips compared to the levels during bus and taxi trips in Singapore. Tsai et al. [40] observed that the commuters using motorcycles were exposed to higher PM_{10}, $PM_{2.5}$ and PM_1 ($\leq 1\,\mu m$ in size) concentrations than the commuters using buses and subways in Taipei, while the commuters using cars were exposed to lowest PM concentrations. Goel et al. [41] suggests that pedestrians are exposed to highest $PM_{2.5}$ concentrations, while commuters in air-conditioned cars and subway are less exposed to $PM_{2.5}$ in Delhi. Gómez-Perales et al. [42], Fondelli et al. [33], McNabola et al. [43], Suárez et al. [1], Betancourt et al. [44], Onat and Stakeeva [45] and Vouitsis et al. [46] indicated that bus commuters are more exposed to PM than commuters by other transportation modes in Mexico City, Florence, Dublin, Santiago, Bogotá, Istanbul and Thessaloniki, respectively. The PM concentration levels during commuting are affected by many factors, thus the PM levels may vary greatly even by the same transportation mode. According to previous studies, the average $PM_{2.5}$ concentrations were within the range of $17\,\mu g/m^3$ to $239\,\mu g/m^3$ during subway trips [1,36,38–42,45,47–67], $2\,\mu g/m^3$ to $225\,\mu g/m^3$ during bus trips [1,15,33,36,38–44,46,50,51,54,62–64,68–70], $2\,\mu g/m^3$ to $244\,\mu g/m^3$ during car/taxi trips [1,13,15,19,33,36,39–41,43,44,46,51–54,58,61–64,69–76], $10\,\mu g/m^3$ to $207\,\mu g/m^3$ during bicycle trips [1,15,36,41,43,44,46,62–64,69,70,77], and $9\,\mu g/m^3$ to $263\,\mu g/m^3$ during walking trips [19,38,39,41,43,44,53,58,63,69,73,75,76,78–80]. Fig. 1 illustrates average $PM_{2.5}$ concentrations during subway and car/taxi trips in different cities studied in literature [1,15,19,33,38–44,46–52,54–59,61–64,69,71,72,74–76,81]. The commuter exposure to $PM_{2.5}$ during car/taxi and subway trips in different cities may have quite different features. Commuters in Delhi are basically exposed to highest PM concentration during both car/taxi and subway trips. The PM concentrations in car/taxi in Bogota, Jakarta, Dublin and Guangzhou are also relatively higher. The high PM concentrations in car/taxi may be related to the high ambient concentrations. The PM concentrations in subway in Seoul, Paris and London are quite high as well. The passengers and ventilation systems may have impacts on the PM concentrations in subway systems.

In addition, the PM inhalation doses are also associated with commuting time and inhalation rates [15,33,36,44,70,73,82–88]. Pedestrians and cyclists may experience increased physical activities compared to subway, bus and car commuters, which leads to elevated inhalation rates [64]. Therefore, pedestrians and cyclists have more potential PM inhalation doses and subsequent higher lung deposition. Yu et al. [89] noted that the PM inhalation doses by bicycle or by walking are much higher than the doses by bus, subway or taxi, although commuters by different transportation modes are exposed to close PM concentrations. Int Panis et al. [82] reported average 5.9 to 9.0 times higher inhaled PM for cyclists relative to car commuters, because of more than 4 times higher inhalation rates for cyclists since their PM exposure concentrations are very close. McNabola et al. [43] observed highest PM inhalation doses for cyclists due to higher inhalation rates, although car and bus commuters are exposed to relatively higher PM concentrations. Quiros et al. [84] reported more than 7 times higher UFP inhalation exposure for cycling and walking than driving modes. Therefore, the importance of commuting time and inhalation rates should be noted when discussing the commuter exposure to different transportation modes.

Nanjing is one of the largest cities in China, located in the Yangtze River Delta, with dense population, heavy traffic and bad air quality. Fig. 2 shows the development of annual passengers by different public transportation modes (i.e. bus, subway and taxi) in Nanjing in this decade, which reveals that subway and bus contributed almost 90% of annual total passengers by public transport in 2016 [90]. The development of subway system in Nanjing is notable within this decade. The number of annual subway passengers has been increasing steadily since 2007, with an annual increasing rate at approximate 10–30%. Lin et al. [91] reported that nowadays cycling and walking are preferred during short-distance commuting in Nanjing. However, the investigations into the commuter exposure to PM in different transportation modes in Nanjing are still scarce. Besides, few studies have investigated the spatial PM concentration distribution at different locations in subway station. Most studies investigated the PM concentrations at the platform in subway station, while the PM levels at other locations, e.g. different floors of subway station, have been rarely studied. In addition, the correlations between outdoor PM concentrations and indoor concentrations in different transport scenarios haven't been analyzed much in literature. This paper investigates personal exposure to PM during commuting in Nanjing in four common transportation modes, i.e. subway, bicycle, bus and walking. The measurements were conducted on a heavy-traffic street during traffic rush hours, and lasted for one week in summer and winter, respectively. The exposure concentrations and inhalation doses of PM_1 and $PM_{2.5}$ were analyzed. Both in-station and in-cabin concentrations were considered while travelling by subway to better understand the PM transport between subway station and cabin. The correlation of PM concentration between outdoor environment and other indoor scenarios were analyzed using statistical method. The spatial PM concentration distribution in different spaces in subway station was discussed as well.

2. Methodology

2.1. Field measurement

The study of commuter exposure to PM was conducted on a 2 km route of Zhongshan Road between Gulou and Xinjiekou, located in the centre of Nanjing city, with heavy traffic and dense crowds. The exposure concentrations of PM_1 and $PM_{2.5}$ in four common transportation modes, i.e. subway, bicycle, bus and walking, were sampled with a logging interval of 1 s. The measurements were performed during morning, noon and evening traffic rush hours (approximately 8:00–10:00, 12:00–14:00 and 17:00–19:00, respectively) for one week in summer (May 7 to 13, 2017) and winter (Dec 11 to 18, 2017) on non-rainy days, respectively. The carbon dioxide (CO_2) concentrations in subway cabin and bus cabin during the experimental periods in winter were sampled with a logging interval of 10 s, whereas the CO_2 concentrations during bicycle and walking trips were not recorded. The concentrations of CO2 were monitored to indicate the commuter number inside subway and bus cabins. The measurements were not performed simultaneously for different commuting modes due to the lack of enough instruments, but by one volunteer in sequence taking a

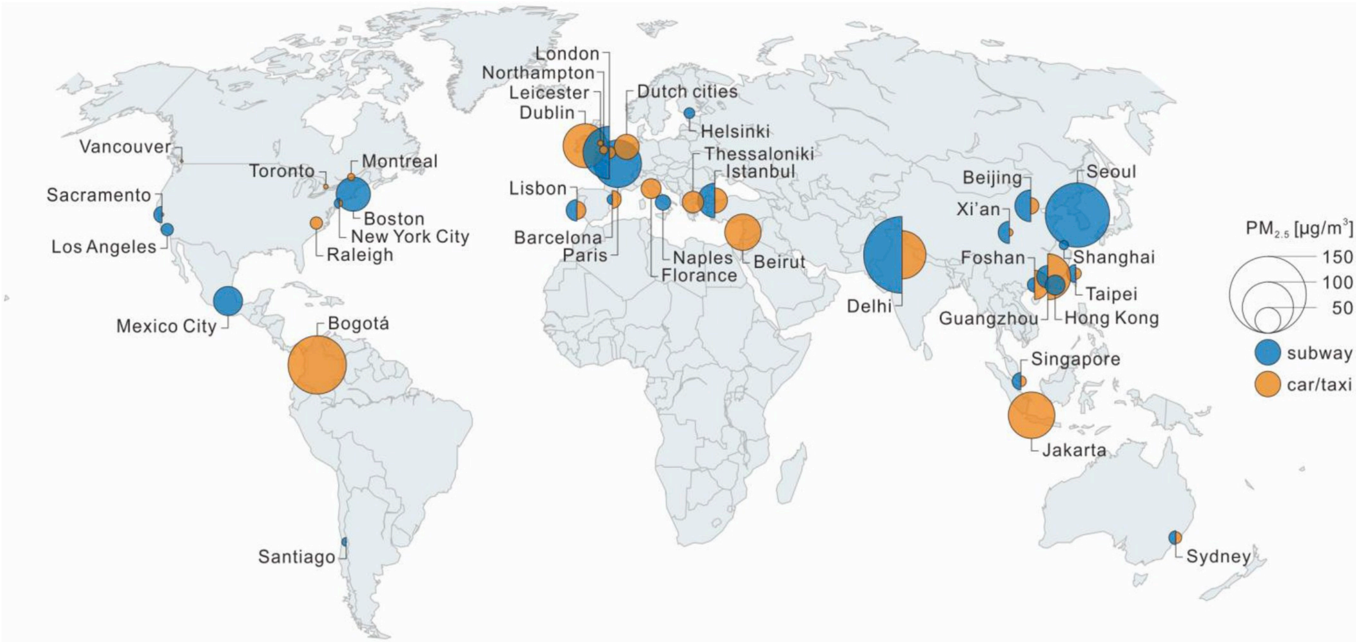

Fig. 1. $PM_{2.5}$ concentrations during subway and car/taxi trips in different cities [1,15,19,33,38–44,46–52,54–59,61–64,69,71,72,74–76,81].

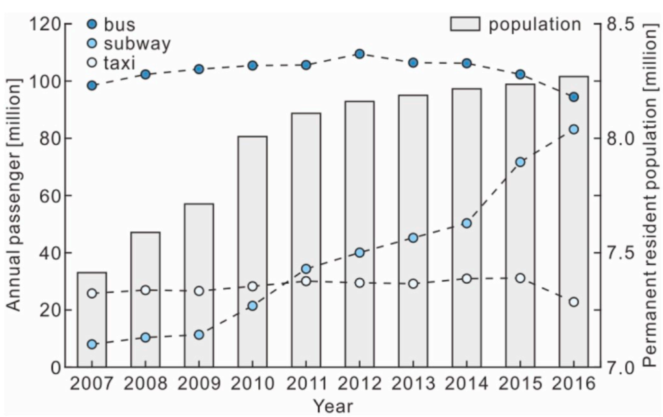

Fig. 2. Development of permanent resident population and annual passengers by different public transportation modes (i.e. bus, subway and taxi) in Nanjing from 2007 to 2016 [90].

subway, riding a bicycle, taking a bus and walking along the route between Gulou and Xinjiekou (Fig. 3). For subway or bus mode, the commuting journey was divided into the in-cabin part and the in-station part, which represented the journey inside the cabin (from entering to exiting the cabin), and the rest journey staying at the station, respectively. The PM concentrations in subway station were recorded during winter while not recorded during summer. The PM concentrations in bus station were not monitored during both summer and winter.

Nanjing Metro Line 1 is the only subway line connecting Gulou and Xinjiekou, with one stopover station. The ventilation and air condition (VAC) systems in subway station and cabin kept running during the experiment periods, while the windows in subway cabin were stationary and well-sealed. In this research, all the subway stations and trains were located underground. There are two bus lines running between Gulou and Xinjiekou, i.e. Nanjing Bus Line 16 and Line 33, with three stopover bus stops, respectively. The bus cabins of two lines are basically same and both have VAC system and openable windows. Both bus lines were studied in this study, but the operation conditions of the VAC system and windows in bus cabin were not recorded. Therefore, either mechanical or natural ventilation or both were possible during the experiment period. OFO sharing bicycles were used during the bicycle journeys in this study. Cycling was performed along the east side of the target road while walking along the west side.

Two portable and battery-operated TSI DustTrak II Aerosol Monitors (Model 8532, TSI Inc., USA) were utilized to measure the mass concentrations of PM_1 and $PM_{2.5}$. This instrument acquires real-time aerosol mass concentrations by light scattering technology in the range of 0.001 mg/m^3 to 150 mg/m^3, and the resolution is the greater of 0.1% of the reading or 0.001 mg/m^3. The CO_2 concentrations were measured by a real-time CO_2 monitor (Model WEZY-1, TJHY Inc., China) with an accuracy of 75 ppm or 10% of reading and measurement range of 0–5000 ppm. Two PM monitors were placed inside a backpack and the CO_2 monitor was fixed outside the backpack. The sampling inlets of the PM monitors were extended by external rubber tubes to pump the ambient air into the monitors. The monitor inlets were placed as far as possible from the volunteer's body to avoid the potential influence from the volunteer. The backpack was carried on the back of a 25-year-old male volunteer to keep the monitors at an approximate breathing height (Fig. S1). All the monitoring instruments were calibrated within one year by the manufacturers. The PM concentrations were not recorded during the transfer between different transportation modes. Table 1 shows the monitoring schedule during commuting in this study.

2.2. Data analysis

The PM concentration was sampled every 1 s and the CO_2 concentration was sampled every 10 s. For data analysis, the average exposure concentration (C_{avg}) of each transportation during each commuting trip is calculated as the mean data of the time sequence along the journey, which can be calculated by

$$C_{avg} = \frac{\int_{t1}^{t2} C(t)\cdot dt}{t2 - t1} \quad (1)$$

where C_{avg} is the average exposure concentration of each trip (μg/m^3), $t2$ and $t1$ are the start and end moment of each trip (s), and $C(t)$ is the exposure concentration at moment t (μg/m^3). The PM concentrations were originally read in mg/m^3 by the monitors, but here the concentrations were converted to μg/m^3 for better analysis. Pearson

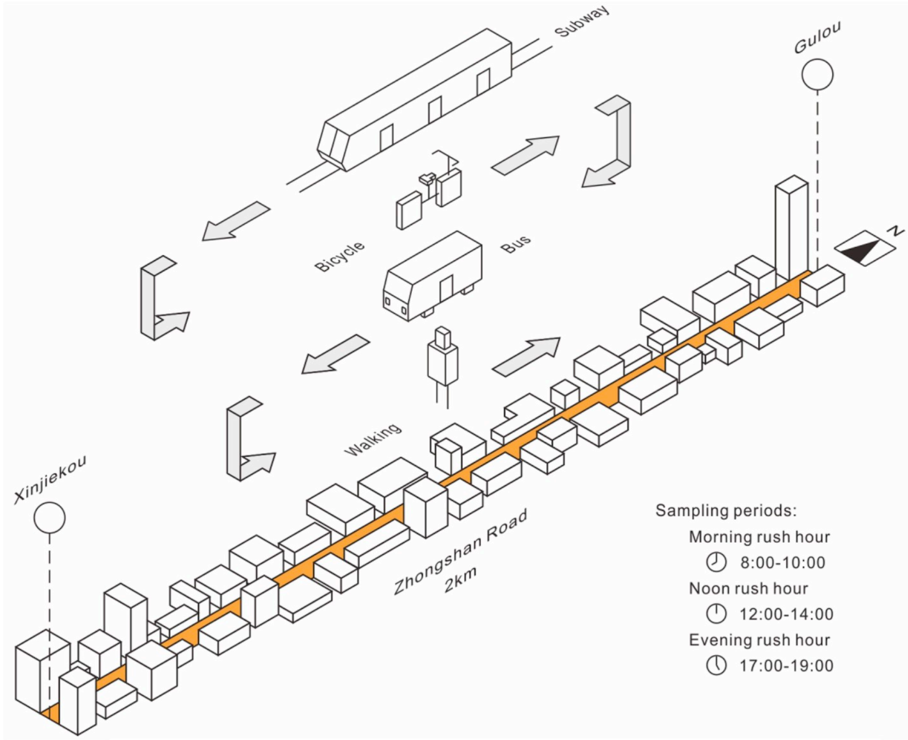

Fig. 3. Schematic illustration of the route and measuring procedure.

Table 1
Monitoring schedule during commuting in this study.

Season	Transportation mode	Route[a]	Ventilation	PM	CO_2
Summer (May 7–13, 2017)	Subway (cabin)	G-X	Mechanical	✓	
	Subway (station)	G-X	Mechanical		
	Bicycle	X-G	/	✓	
	Bus (cabin)	G-X	Mechanical/ Natural[b]	✓	
	Bus (station)	G-X	/		
	Walking	X-G	/	✓	
Winter (Dec 11–18, 2017)	Subway (cabin)	G-X	Mechanical	✓	✓
	Subway (station)	G-X	Mechanical	✓	
	Bicycle	X-G	/	✓	
	Bus (cabin)	G-X	Mechanical/ Natural[b]	✓	✓
	Bus (station)	G-X	/		
	Walking	X-G	/	✓	

[a] G stands for Gulou and X stands for Xinjiekou.
[b] Either mechanical or natural ventilation or both were possible during the experiment period. Because the operation conditions of the VAC system and windows in bus cabin were not recorded.

correlation analysis is applied to analyze the correlation between two groups of data, e.g. the PM concentrations inside and outside a transportation microenvironment. The impact of transportation modes, commuting seasons and periods on PM exposure concentrations were analyzed by one-way ANOVA (analysis of variance) for multiple variables and *t*-test for double variables. The statistical significance of the relationship between data could be evaluated by the index *p*-value.

The parameter cabin/station ratio of PM can indicate the overall relationship of PM concentrations between subway/bus cabin and station. Table 2 shows the mean $PM_{2.5}$ concentrations (arithmetic mean, AM) in subway cabin and station in different cities. The in-cabin $PM_{2.5}$ concentrations in various cities are mainly within the range of 25 μg/m^3 to 125 μg/m^3; while the in-station $PM_{2.5}$ concentrations are mainly between 35 μg/m^3 and 135 μg/m^3. Usually, the $PM_{2.5}$ concentrations in subway station are higher than the concentrations inside subway cabin and outdoors. The $PM_{2.5}$ cabin/station ratios for most cities are between 0.43 and 0.97. However, in Singapore, the in-station $PM_{2.5}$ concentrations are lower than the in-cabin concentrations and the $PM_{2.5}$ cabin/station ratio reaches 1.31. Besides, the $PM_{2.5}$ concentrations in subway station and cabin are usually higher than the outdoor concentrations.

Li et al. [92] introduced the infiltration factor (F_{inf}) to evaluate the contribution of ambient PM concentrations to microenvironmental PM concentration in a subway system, which can represent the equilibrium fraction of ambient particles that penetrate indoors and remain suspended under steady state conditions [93]. The PM concentrations can be calculated by

$$C_i = F_{inf} \cdot C_a + C_{na} \tag{2}$$

where C_i is microenvironmental PM concentration (μg/m^3), C_a is ambient PM concentration (μg/m^3), C_{na} is non-ambient concentration from indoor generated PM (μg/m^3), e.g. emission and/or resuspension, and F_{inf} is the infiltration factor (−). According to Li et al. [92], linear regression can be used to estimate the infiltration factor F_{inf} (the slope) and non-ambient concentration C_{na} (the intercept).

The PM inhalation doses are determined by the PM exposure concentrations, commuting time and inhalation rates [15,33,36,44,70,73,82–88], and can be calculated by

$$D = \int_{t1}^{t2} C(t) \cdot IR(t) \cdot dt \tag{3}$$

where D is the inhalation dose (μg), $C(t)$ is the exposure concentration at the moment t (μg/m^3), $t1$ and $t2$ are the start and end time of exposure respectively (min), and $IR(t)$ is the inhalation rate at the moment t (L/min). In this paper, the equation was simplified to $D = C_{avg} \cdot IR_{avg} \cdot (t2\text{-}t1)$, where C_{avg} is the average exposure concentration (μg/m^3), and IR_{avg} is the average inhalation rate during commuting (L/min). Inhalation rate is a breathing parameter associated with physical activity level. Previous investigations showed heterogeneous inhalation rate across studies, which may be because of the differences on fitness status of the commuter, road, weather and terrain [64]. Table 3 shows the

Table 2
$PM_{2.5}$ average concentrations during subway journeys.

City	$PM_{2.5}$ (AM) [μg/m^3]			Cabin/Station $PM_{2.5}$ Ratio [−]	Reference
	Cabin	Station	Outdoor		
London	170.0	350.0		0.49	Seaton et al., 2005 [66]
Taipei	31.5[a]	35.0[a]	29.6	0.90	Cheng et al., 2008 [67]
Seoul	125.5	129.0[b]	102.1	0.97	Kim et al., 2008 [55]
Los Angeles	24.2[a]	56.7[a]	19.9	0.43	Kam et al., 2011 [56]
Istanbul	72.9[a]	131.3[a]		0.56	Onat and Stakeeva, 2012 [45]
Naples	29.0	52.3	5.2	0.56	Cartenì et al., 2015 [48]
Singapore	34.0	26.0[b]	27.0	1.31	Tan et al., 2017 [39]

[a] Data adapted only from underground subways.
[b] Data adapted only from subway platform.

Table 3
Average inhalation rate IR_{avg} during commuting by different transportation modes in literature and this study.

IR_{avg} [L/min]					Reference
Subway	Car/Taxi	Bus	Walking	Bicycle	
	12.3			28.7	van Wijnen et al., 1995 [88]
			26.7	50.0	McNabola et al., 2007 [97]
	11.8	12.7		23.5	Zuurbier et al., 2009 [94]
	12.4			52.7	Int Panis et al., 2010[a] [82]
4.8	4.8	4.8	12.0	27.0	Yu et al., 2012[b] [89]
14.6	12.4	14.6	44.5	52.7	Dons et al., 2012[c] [11]
	11.0	11.0		26.0	Huang et al., 2012[d] [15]
12.0	12.0	12.0		36.0	Dirks et al., 2012[e] [95]
	19.9	20.1	34.1	41.0	de Nazelle et al., 2012[f] [69]
	7.8	7.8	23.4	34.8	Quiros et al., 2013[g] [84]
12.9		13.7	22.5	30.5	Nyhan et al., 2014[a] [87]
	19.9	20.1		41.0	Vouitsis et al., 2014[h] [46]
7.8	7.8	7.8	10.5	11.7	Li et al., 2015[i] [96]
13.9	13.9	13.9		55.9	Ramos et al., 2016[j] [64]
	5.1	13.0	29.2	29.2[l]	Betancourt et al., 2017[k] [44]
8.4[n]		8.4	22.5	33.8	This study[m]

[a] Arithmetic mean of male and female data.
[b] Arithmetic mean of inhalation rates for age groups between 16 and 60 years from the Exposure Factors Handbook of EPA [6].
[c] Data adopted from Allan and Richardson [98] and Int Panis et al. [82].
[d] Data adopted from the Exposure Factors Handbook of EPA [6].
[e] Data adopted from Zuurbier et al. [94], Int Panis et al. [82] and Bernmark et al. [99].
[f] Inhalation rates calculated using a random population distribution and algorithms developed by EPA [100,101].
[g] Data adopted from Hinds [102].
[h] Data adopted from de Nazelle et al. [69].
[i] Arithmetic mean of inhalation rates for age groups between 20 and 45 years from Wang et al. [103].
[j] Arithmetic mean of inhalation rates for age groups between 21 and 60 years from the Exposure Factors Handbook of EPA [6].
[k] Arithmetic mean of inhalation rates for age groups between 21 and 31 years from the Exposure Factors Handbook of EPA [6].
[l] This value may be underestimated [44].
[m] Data adopted from the Exposure Factors Handbook of Chinese Population (Adults) [7].
[n] This value may be underestimated, because both walking and standing were usually behaved in subway station in this study.

inhalation rates during commuting by different transportation modes in literature, of which some studies measured the inhalation rates or used activity intensity to derive the inhalation rates [43,82,87,88,94], whereas the others used published parameters [11,15,44,46,69,84,89,95,96]. The inhalation rates while commuting by subway are from 4.8 to 14.6 L/min, by car/taxi from 4.8 to 19.9 L/min, by bus from 4.8 to 20.1 L/min, by walking from 10.5 to 44.5 L/min, and by bicycle from 11.7 to 55.9 L/min. Cycling is usually the transportation mode with highest activity intensity compared to the other modes, resulting in highest inhalation rate for commuters, typically 2 or 3 or even more times higher than the inhalation rates for commuters by subway, car/taxi or bus. Walking is usually the transportation mode with second highest inhalation rate for commuters. The inhalation rates during subway, car/taxi or bus journeys generally vary insignificantly as the commuters usually conduct light intensity physical activity, i.e. seated or standing in the cabin.

In this study, the inhalation rates are adopted from the Exposure Factors Handbook of Chinese Population (Adults) [7] since no measurement on inhalation rate was performed. The inhalation rates while seated or standing (e.g. in subway or bus cabin, or waiting at station), walking, and riding a bicycle, were 8.4, 22.5, 33.8 L/min, respectively. In this paper, the IR_{avg} value in subway station is equal to the value in subway cabin, i.e. 8.4 L/min, but this value is probably underestimated, because both walking and standing are usually behaved in subway station during the measurements. The inhalation rates adopted here are generally in accordance with the values in previous studies.

3. Results and discussions

3.1. Average exposure concentration

3.1.1. Average exposure concentration during different commuting modes

Totally 133 sets of available PM exposure concentrations (both PM_1 and $PM_{2.5}$) were measured, including 30 sets sampled in subway cabin during subway trips, 16 sets sampled in subway station during subway trips, 29 sets sampled during bicycle trips, 30 sets sampled in bus cabin during bus trips and 28 sets sampled during walking trips (the mean data of each set is shown in Table S1). Totally 30 sets of available CO_2 concentrations were measured, of which 16 sets in subway cabin and 14 sets in bus cabin. The boxplots of mean PM_1 and $PM_{2.5}$ exposure concentrations during different transportation modes (C_{avg}) are illustrated in Fig. 4(A). In each box, the mid-line indicates the median value, the top and bottom of the boxes indicate the upper and lower quartiles (the 75th and 25th percentiles), and the top and bottom of the whiskers indicate the lowest datum still within 1.5 interquartile range of the lower quartile, and the highest datum still within 1.5 interquartile range of the upper quartile, respectively. The data not included between the whiskers are plotted as outliers with dot markers (see Fig. S2 for boxplot introduction). The PM concentrations during bicycle, bus and walking trips vary within a relatively wider range compared to the PM concentrations measured in subway cabin and station. The PM concentrations in subway cabin are generally lower than the PM concentrations in other transportation modes. Table 4 shows the arithmetic mean (AM) and standard deviation (SD) of average PM_1 and $PM_{2.5}$ concentrations during each sampling period of different transportation modes. The result shows that subway cabin is exposed to lowest PM_1 (38.3 μg/m^3) and $PM_{2.5}$ (54.4 μg/m^3) concentrations compared to the other commuting modes, while subway station is exposed to high PM concentrations, particularly $PM_{2.5}$ concentration. Subway station is

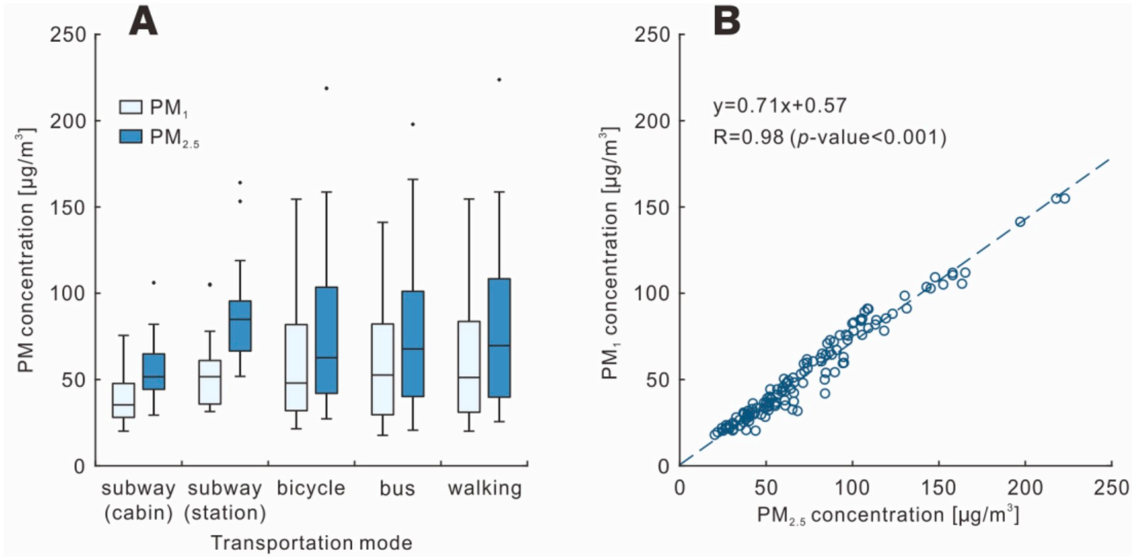

Fig. 4. (A) Boxplots of average PM exposure concentrations during different transportation modes (C_{avg}) and (B) the distribution of measured average PM_1 and $PM_{2.5}$ concentrations (C_{avg}).

Table 4
PM concentrations and $PM_1/PM_{2.5}$ ratios in different transportation modes.

Mode	PM concentration (AM ± SD) [μg/m³]		$PM_1/PM_{2.5}$ [-]	Sample size
	PM_1	$PM_{2.5}$		
Subway (cabin)	38.3 ± 13.9	54.4 ± 16.4	0.703	30
Subway (station)	54.8 ± 23.6	90.5 ± 31.5	0.606	16
Bicycle	58.7 ± 33.0	79.0 ± 45.7	0.744	29
Bus	56.0 ± 31.3	74.7 ± 43.9	0.750	30
Walking	59.5 ± 33.2	80.3 ± 46.6	0.741	28

exposed to highest $PM_{2.5}$ concentration (90.5 μg/m^3) among different transportation scenarios, while walking is exposed to highest PM_1 concentration (59.5 μg/m^3). The mean PM concentration difference among various commuting modes is statistically significant according to one-way ANOVA (p-value = 0.029 for PM_1 and p-value = 0.025 for $PM_{2.5}$).

Fig. 4(B) shows the distribution of average PM_1 and $PM_{2.5}$ concentrations during each sampling period of different transportation modes (C_{avg}). Correlations observed between average PM_1 and $PM_{2.5}$ concentrations during commuting are strong (i.e. Pearson correlation coefficient R = 0.98) and statistically significant (p-value < 0.001) through Pearson correlation analysis. The overall (i.e. all transportation modes) mean $PM_1/PM_{2.5}$ ratio is 0.718 and the $PM_1/PM_{2.5}$ ratios of four commuting modes are generally between 0.6 and 0.8, implying that PM_1 is a significant portion of $PM_{2.5}$ during commuting, which is consistent with previous studies. Guo et al. [104] found that the $PM_1/PM_{2.5}$ ratios of three subway lines in Shanghai were between 0.7 and 0.8. Rivas et al. [105] measured the PM concentrations of car, subway and bus in London, and found the $PM_1/PM_{2.5}$ ratios were generally in the range of 0.7–0.9. Kwon et al. [106] indicated that the $PM_1/PM_{2.5}$ ratios in Seoul subway stations were within the range of 0.7–0.9. In this study, the mean $PM_1/PM_{2.5}$ ratio measured in subway station is 0.606, relatively lower than the ratios measured in the other commuting microenvironments, and also lower than the results in literature [106]. Therefore, particles with size between 1 μm and 2.5 μm may count a significant portion of the PM generated in subway station in this study. A portion of these in-station generated PM may then enter subway cabin so that the $PM_1/PM_{2.5}$ ratios in subway cabin are also lower than the ratios of the other three commuting modes.

3.1.1.1. Subway. The air quality during the subway commuting has been of particular public concern [107]. In this research, the subway trip can be divided into two parts, i.e. in subway cabin and in station. The mean concentrations of PM_1 and $PM_{2.5}$ in subway cabin are 38.3 and 54.4 μg/m^3, respectively, while the mean concentrations in subway station are 54.8 and 90.5 μg/m^3, respectively. The mean PM concentrations in subway cabin are significantly lower than in subway station (p-value = 0.018 for PM_1 and p-value < 0.001 for $PM_{2.5}$).

According to Pearson correlation analysis, the correlation coefficient of PM_1 concentrations between cabin and station is R = 0.94 (p-value < 0.001) and the one of $PM_{2.5}$ concentrations is R = 0.89 (p-value < 0.001), which both indicate significantly strong correlation between the PM concentrations in subway cabin and station. Fig. 5(A) shows the distribution of mean PM concentrations in cabin and station (C_{avg}). The correlation coefficient of PM_1 between station and outdoors is R = 0.92 (p-value < 0.001), while the correlation of $PM_{2.5}$ is R = 0.87 (p-value < 0.001). In this study, the PM concentrations during the bicycle trips were treated as outdoor ambient concentrations since the bicycle trips were totally exposed to outdoor environment. A significantly strong correlation between PM concentrations in subway station and outdoors was observed according to the Pearson correlation analysis, which is consistent with previous studies [108,109]. However, relatively moderate correlation was observed between the PM concentrations in cabin and outdoors, i.e. R = 0.79 (p-value < 0.001) for PM_1, and R = 0.66 (p-value = 0.007) for $PM_{2.5}$. Therefore, the PM concentrations in subway cabin has stronger correlation with the PM concentrations in subway station while relatively weaker correlation with outdoor concentrations.

According to Eq. (2) and the fitting curve in Fig. 5, the infiltration factor F_{inf} of $PM_{2.5}$ from outdoors to subway station is 0.59 and the F_{inf} from station to cabin is 0.51. The non-ambient $PM_{2.5}$ concentration C_{na} in subway station is 41 μg/m^3, while the C_{na} inside cabin is 9 μg/m^3. It reveals that most of the $PM_{2.5}$ inside subway cabin is infiltrated from subway station while only a few of the in-cabin $PM_{2.5}$ is generated by the sources inside cabin. By contrast, the outdoor $PM_{2.5}$ contributes the majority of the $PM_{2.5}$ in subway station, but the in-station source may also contribute a lot to the $PM_{2.5}$ in subway station. The F_{inf} of PM_1 are relatively higher than the one of $PM_{2.5}$. The F_{inf} of PM_1 from outdoors to station is 0.64 and the F_{inf} from station to cabin is 0.59. The non-ambient PM_1 concentration C_{na} in subway station is 15 μg/m^3, while the C_{na} inside cabin is 5.7 μg/m^3. Compared to $PM_{2.5}$, indoor generated

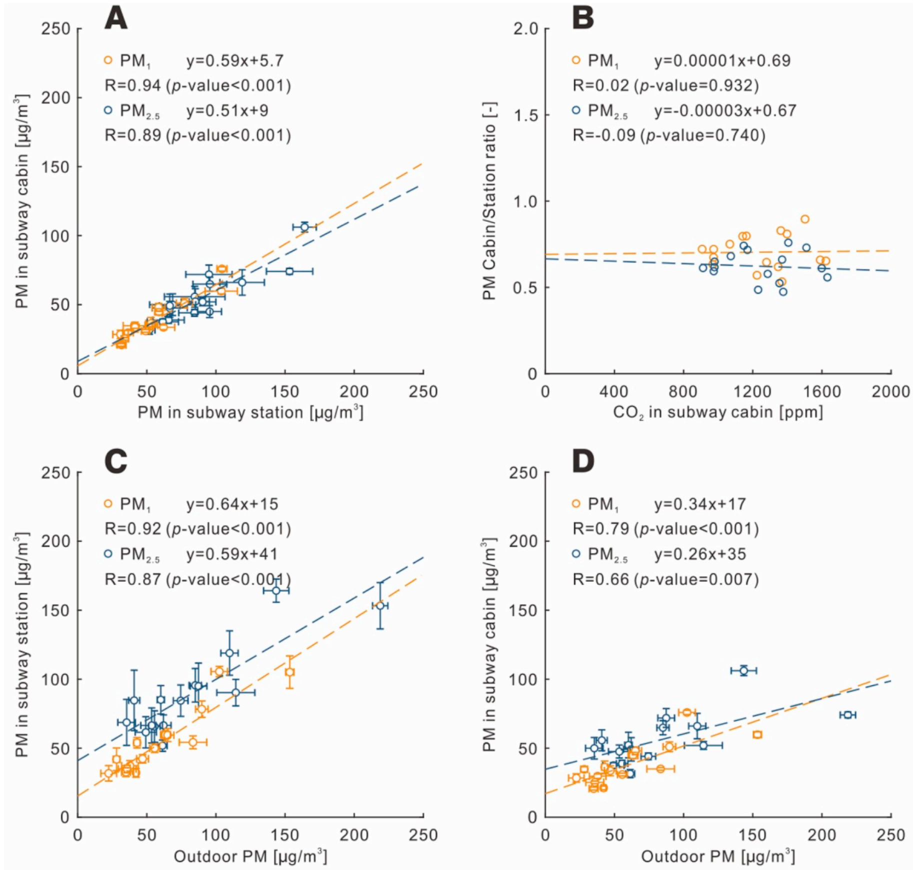

Fig. 5. (A) Mean PM concentrations in subway cabin and station; (B) the relationship between PM cabin/station ratios and in-cabin CO_2 concentrations; (C) Mean PM concentrations in subway station and outdoors; (D) Mean PM concentrations in subway cabin and outdoors.

PM_1 contributes relatively less to the PM_1 concentrations in subway station and cabin, which means most indoor PM_1 in station and cabin comes from ambient environments, i.e. outdoors and station, respectively. The result consists with the analysis of the $PM_1/PM_{2.5}$ ratios in subway station and cabin. A great quantity of $PM_{2.5}$ (41 μg/m^3) are generated inside subway station, of which particles with size between 1 μm and 2.5 μm count the major portion (63.4%) since the in-station generated PM_1 concentration is 15 μg/m^3, which indicates a $PM_1/PM_{2.5}$ ratio of 0.37 for in-station generated $PM_{2.5}$. This results in a lower $PM_1/PM_{2.5}$ ratio in subway station, also a low $PM_1/PM_{2.5}$ ratio in cabin owing to the transfer from station to cabin. Some studies suggested that most PM generated in subway station are from mechanical abrasion between rails, wheels and brakes of the subway train, which are usually within the coarse fraction (2.5–10 μm in size) [49,105,110–113]. The movement of passengers which promotes the mixing and suspension of PM is another potential source of the particles in subway station [49].

The passengers and ventilation systems in station and cabin may also affect the PM concentrations in subway station and cabin. The number of passengers in subway cabin was not recorded during the experiments, but the CO_2 concentrations in subway cabin were monitored. However, CO_2 cannot be a good indicator of occupancy without good air-tightness and constant ventilation rate since the cabin door will open at each station. According to Pearson correlation analysis, the correlation between PM cabin/station ratios and CO_2 concentrations in cabin doesn't show any significance (p-value = 0.932 for PM_1 and p-value = 0.740 for $PM_{2.5}$), which is consistent with our understanding. Therefore, in this study, the effects of passengers and ventilation systems on PM concentration cannot be decided.

The in-cabin mean $PM_{2.5}$ concentration measured in this study is 54.4 μg/m^3, while the in-station concentration is 90.5 μg/m^3 and the outdoor level is 79.0 μg/m^3 (the mean $PM_{2.5}$ concentration in bicycle is adopted as the outdoor level). The ventilation system may be an important cause for the large $PM_{2.5}$ concentration difference in cabin and station. Compared to the in-cabin and in-station $PM_{2.5}$ concentrations measured in other cities in Table 2, the concentrations measured in this study are generally in accordance with the data in different cities. The concentrations in station are higher than the concentrations in cabin and outdoors. The $PM_{2.5}$ cabin/station ratio is 0.60, close to the ratios in Istanbul and Naples. But the PM concentration in cabin in this study is lower than the outdoor concentration, which is different from the results in the other studies.

The PM concentrations in subway station were found having spatial variations. Xinjiekou Subway Station is the largest and busiest subway station in Nanjing and has three underground levels (basement levels) with a total area of 37176 m^2. Basement 1 (B1) level of the station is the commercial area with an underground mall also a circulation area. Basement 2 (B2) level is the circulation area and the platform for Subway Line 2 as well. Passengers of Line 1 should check-in or check-out at this level. Basement 3 (B3) level is the platform for Line 1, which is the studied line in this paper. This is a typical layout for subway stations in China, particularly for large stations. Smaller stations usually have two levels (could be underground or aboveground), one for circulation and another for platform. Fig. 6(A) shows a typical case of real-time $PM_{2.5}$ concentration distribution in Xinjiekou Subway Station during the noon commuting test on December 12. Since the volunteer walking through the station during the experiment, the time sequence of PM concentration can indicate the spatial PM concentration distribution in station. The bold curve indicates the in-station part (PM concentration inside Xinjiekou station). According to our record, during a typical in-station commuting in Xinjiekou station, the passengers of Line 1 will spend approximately 20% of the in-station commuting time at the platform (B3 level), 39% in the circulation area (B2 level) and

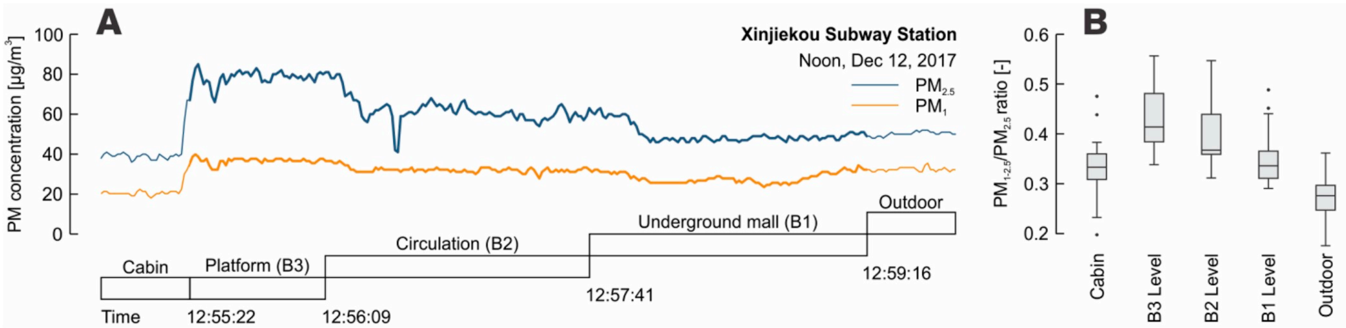

Fig. 6. (A) Real-time $PM_{2.5}$ concentration in Xinjiekou Subway Station during noon period on December 12, 2017. (B) $PM_{1\text{-}2.5}/PM_{2.5}$ ratios in each station level, subway cabin and outdoor environment for all test periods during the entire experiment.

41% in the mall (B1 level). Assume that the volunteer walked in a constant speed, then the real-time PM concentration measured in station can be divided into three parts to indicate the PM concentration at each station level (Fig. 6(A)). The PM concentration in subway cabin was quite steady and kept at a relatively low concentration level. However, the PM concentration at platform is much higher than the concentration in cabin. The PM concentration gradually decreased with the commuter walking through the station. In the area closer to the ground, the particle concentration will decrease to a level closed to the outdoor concentration.

Table 5 shows the mean PM_1 and $PM_{2.5}$ concentrations in each basement level, subway cabin and outdoor environment. The platform is generally exposed to the highest PM_1 and $PM_{2.5}$ concentration, while the cabin is exposed to the lowest concentration. The ventilation system is probably the most critical factor in making such a large concentration difference between the cabin and platform. Unfortunately, the air change rate in the cabin or platform was not measured during the experiment and the ventilation setting of VAC system is not available. The VAC systems in cabin and station were kept running during the experiment. According to the design criteria in China, the minimum required ventilation rate for each person in subway cabin is 10 m^3/h [114] and for each person in station is 12.6 m^3/h [115]. For the studied subway cabin, the maximum passenger number for each cabin section is 310, and there're totally 6 sections for the entire cabin. According to the subway vehicle design criteria [114], for this type of subway cabin, the interior volume of each cabin section is approximately 138.6 m^3 (i.e. 22 m in length, 3 m in width and 2.1 m in height for each section). Then the design air change rate for the entire subway cabin is calculated as 22.4 h^{-1}. For the platform in station (B3 level), we assume that the maximum commuter number at the platform equals the maximum total passenger number in the cabin (including two subway trains with opposite route). The volume of the platform is around 5544 m^3, with 132 m in length (roughly equals to the subway train length), 14 m in width and 3 m in height. Thus, the design air change rate for the platform is derived as 8.5 h^{-1}. The difference of air change rate between subway cabin and station probably result in the high concentration difference.

Besides, it can be found that the particle concentration at a deeper level is usually higher than the level at a shallower level and the PM concentration at shallowest level (B1) is usually close to the outdoor PM concentration. The PM concentrations at the shallowest level (B1) have the highest correlation ($R = 0.94$, $p\text{-value} < 0.001$ for PM_1 and $R = 0.92$, $p\text{-value} < 0.001$ for $PM_{2.5}$) with the outdoor PM concentrations compared to the concentrations at deeper levels (B2 and B3) with the outdoor concentration. Hwang et al. [116] indicated the different ventilation systems among different basement levels may result in the PM concentration variation. However, in this study, neither the air change rate measurement or the ventilation setting of the VAC system

Table 5
Mean PM_1 and $PM_{2.5}$ concentration in different scenarios in Xinjiekou Subway Station and the correlation between real-time PM concentration and commuting time.

Date	Period	In-cabin		B3 Level		B2 Level		B1 Level		Outdoor[b]	
		PM_1[a]	$PM_{2.5}$[a]	PM_1	$PM_{2.5}$	PM_1	$PM_{2.5}$	PM_1	$PM_{2.5}$	PM_1	$PM_{2.5}$
Dec 11	Morning	50.7	66.1	82.4	135.6	79.5	120.0	72.1	101.7	90.5	109.8
	Noon	44.4	64.8	62.2	102.1	59.1	92.8	55.6	79.1	64.1	85.0
	Evening	34.7	52.0	54.9	100.1	52.8	92.9	49.5	75.3	84.1	114.3
Dec 12	Morning	34.4	55.7	49.1	104.5	41.3	82.6	31.2	56.9	28.6	40.8
	Noon	20.4	38.8	36.5	78.4	32.2	61.6	28.0	50.1	35.4	55.5
	Evening	29.4	47.6	42.5	85.2	36.1	65.2	32.4	52.4	38.3	53.5
Dec 13	Morning	28.1	50.0	39.8	89.7	33.0	72.8	25.0	48.9	22.9	35.4
	Noon	24.9	37.5	34.0	63.1	32.7	53.6	30.8	44.5	36.3	49.2
	Evening	20.9	31.5	28.4	48.4	31.9	49.4	35.3	53.3	42.7	61.3
Dec 14	Morning	30.6	44.1	49.1	84.9	49.2	77.8	48.7	71.0	56.3	74.5
Dec 16	Morning	59.5	74.1	102.5	154.9	106.0	153.9	114.2	161.8	154.5	218.8
	Noon	75.6	106.1	103.9	170.8	105.8	167.6	106.3	160.1	103.3	143.6
Dec 18	Morning	47.7	71.9	62.6	100.4	56.7	89.5	54.3	81.4	65.7	87.4
	Noon	36.0	52.3	56.2	87.5	54.5	82.7	48.5	72.4	43.5	60.1
	Evening	33.3	49.2	42.8	67.0	42.3	66.6	38.1	58.6	47.5	62.1

[a] Unit for PM_1 and $PM_{2.5}$ concentration is $\mu g/m^3$.
[b] Herein the PM concentrations measured during cycling trips were adopted as outdoor PM concentrations.

at each level is available. Another potential cause of the elevated PM concentration at the subway platform is the particle generation source at the platform. According to Fig. 6(A), a substantial number of $PM_{2.5}$ were generated at the platform, most of which are within the size between 1 μm and 2.5 μm. According to the previous studies, mechanical abrasion between rails, wheels and brakes of the subway train, usually contribute a great portion to the particles generated at the platform [49,105,110–113]. Although the abrasion-generated particles are usually within the coarse fraction (2.5–10 μm in size), the concentration elevation of the particles within the size of 1–2.5 μm ($PM_{1-2.5}$) was also observed in literature [49]. Therefore, the mechanical abrasion is believed to be the main source leading to the elevated $PM_{1-2.5}$ at the platform. Fig. 6(B) shows the portion of the particles within the size of 1–2.5 μm to the total $PM_{2.5}$ ($PM_{1-2.5}/PM_{2.5}$) in each station level, subway cabin and outdoor environment for all test periods during the entire experiment. The portion of the particles within 1–2.5 μm at the platform (B3) is highest and the shallower basement level has a lower $PM_{1-2.5}/PM_{2.5}$ ratio, with a significant difference observed (p-value < 0.001). Since the subway train only stopped by the platform, the mechanical-abrasion-generated particle source usually only exists at the platform (B3 level). It is consistent with the result observed in Fig. 6(B). Besides, the movement of passengers which promotes the mixing and suspension of PM is probably another important source of the generated particles in the station [49]. The platform usually has a higher passenger density, which will probably result in more particle generation by the passenger movement.

3.1.1.2. Bus. During the bus journeys, the PM concentrations were recorded only inside bus cabin, while the concentrations in bus station were not recorded. The mean concentrations of PM_1 and $PM_{2.5}$ in bus cabin are 56.0 and 74.4 μg/m^3, respectively. Fig. 7(A) shows the distribution of mean PM concentrations in bus cabin and outdoors. In-cabin concentrations show significantly strong correlation with outdoor concentrations for both PM_1 (R = 0.95, p-value < 0.001) and $PM_{2.5}$ (R = 0.95, p-value < 0.001). The infiltration factor F_{inf} of both PM_1 and $PM_{2.5}$ from outdoors to cabin is 0.91, while the non-ambient concentration C_{na} is 1.7 μg/m^3 for PM_1 and 1.4 μg/m^3 for $PM_{2.5}$. Therefore, most of the PM inside cabin comes from outdoor environment while the in-cabin PM source contributes a small portion.

The passenger numbers and the CO_2 concentrations inside bus cabin were recorded during the experiment periods in winter. As shown in Fig. 7(B), the correlation between the PM cabin/outdoor ratios and the passenger numbers is significant. The cabin/outdoor ratios for PM_1 have a moderate correlation with the passenger numbers (R = 0.58, p-value = 0.031), while the ratios for $PM_{2.5}$ have relatively stronger correlation (R = 0.71, p-value = 0.004). The correlation between CO_2 concentrations and passenger numbers in cabin is not very strong, which means that CO_2 concentrations in bus cabin cannot be a good indicator for passengers. Fig. 7(D) reveals the PM cabin/outdoor ratios have an insignificant correlation with the in-cabin CO_2 concentrations, which is in accordance with the result observed during subway trips.

3.1.1.3. Bicycle and walking. Commuters are totally exposed to outdoor ambient PM during cycling and walking. As shown in Fig. 8, the PM concentrations measured during cycling are highly consistent and have significantly strong correlation with the concentrations during walking (R = 0.97, p-value < 0.001 for PM_1; R = 0.98, p-value < 0.001 for $PM_{2.5}$). According to t-test analysis, the PM concentrations during walking and cycling don't show any significant difference (p-value = 0.969 for PM_1 and p-value = 0.955 for $PM_{2.5}$). Fig. 8 indicates the mean $PM_{2.5}$ concentrations measured during walking and cycling are generally consistent with the data from the monitoring stations in Nanjing during the sampling period (i.e. 8:00–10:00am, 12:00–14:00pm, 17:00–19:00pm, respectively). The data monitored by stations have strong correlation with the concentrations measured during cycling (R = 0.96, p-value < 0.001) and walking (R = 0.94, p-value < 0.001). However, the station-monitored $PM_{2.5}$ concentrations are significantly lower than the measured concentrations during cycling (p-value = 0.003) and walking (p-value = 0.003) according to t-test analysis. It's probably because the field measurements were conducted in a heavy-traffic road located in the city center, while the data from the monitoring stations represent the average $PM_{2.5}$ levels of the whole Nanjing City, including urban and rural areas. The PM concentrations in the heavy-traffic road may be higher than the average ambient levels of Nanjing owing to the possible elevated particle emission sources, e.g. vehicle emissions.

Apart from the vehicle emissions, cyclists and pedestrians are potential to be directly exposed to some other local particle emissions along the commuting route, like outdoor barbeque, smoking and/or building dust, which probably result in elevated PM concentrations in some specific areas at specific time. Fig. 9 shows the time sequence of real-time $PM_{2.5}$ concentrations during three typical experiment periods. Short-term elevated $PM_{2.5}$ concentrations were observed during cycling and walking, particularly during walking. Though elevated exposure happened within a short period, it may still have potential short-term effects on pedestrian health and affect the perception to air quality [117]. The $PM_{2.5}$ concentration distribution in subway station shows obvious variation with time, which indicates spatial variation of $PM_{2.5}$ concentration in different areas of subway station, and it's consistent with the result discussed in subsection 3.1.1.1.

3.1.2. Impact of different commuting seasons and periods

Table 6 shows the PM concentrations during different commuting seasons in each transportation mode. Generally, the PM concentrations in winter are larger than the concentrations in summer. However, there is no significant difference of PM concentrations between summer and winter according to the one-way ANOVA. However, significant difference of in-vehicle particle concentrations between summer and winter was found in previous studies [118]. In this study, the obtained data may not be enough to analyze the seasonal difference for each transportation. More works are needed in future investigation. The PM concentrations during different commuting periods in each mode are shown in Table 7. No statistically significant difference was observed between the PM concentrations of different periods according to the analysis of one-way ANOVA.

3.2. PM intake during commuting

The PM intake doses are determined by the PM exposure concentrations, commuting time and inhalation rates. Fig. 10 shows the measured commuting time during different transportation trips. Commuters usually spend average 3.9min in subway cabin and 6.0min in subway station, i.e. 9.9min during the whole subway trip, and 11.8min during bicycle trip, 10.3min during bus trip, 21.6min during walking. Walking is the transportation that will cost the most time while subway cost least. However, commuters will always spend more time in station during such a short distance subway journey in this study. The subway train usually follows the schedule more punctually, while the other transportations, particularly bus, highly depend on the traffic conditions, as the commuting time during bus trip varies from around 7min to more than 20min.

Previous studies revealed that the inhalation rates and commuting time may be more conclusive to determine the inhalation doses for different transportation modes along the same route. Pedestrians and cyclists generally experience elevated inhalation doses than the commuters by buses, cars or subways owing to considerably longer commuting time and higher inhalation rates during the trips as shown in Table 3 [36,41,44,65,70,73,82,84,86–89]. This study adopted the inhalation rates from the Exposure Factors Handbook of Chinese Population (Adults) [7]. The inhalation rates while seated or standing (e.g. in subway or bus cabin, or waiting at station), walking, and riding a bicycle, were 8.4, 22.5, 33.8 L/min, respectively.

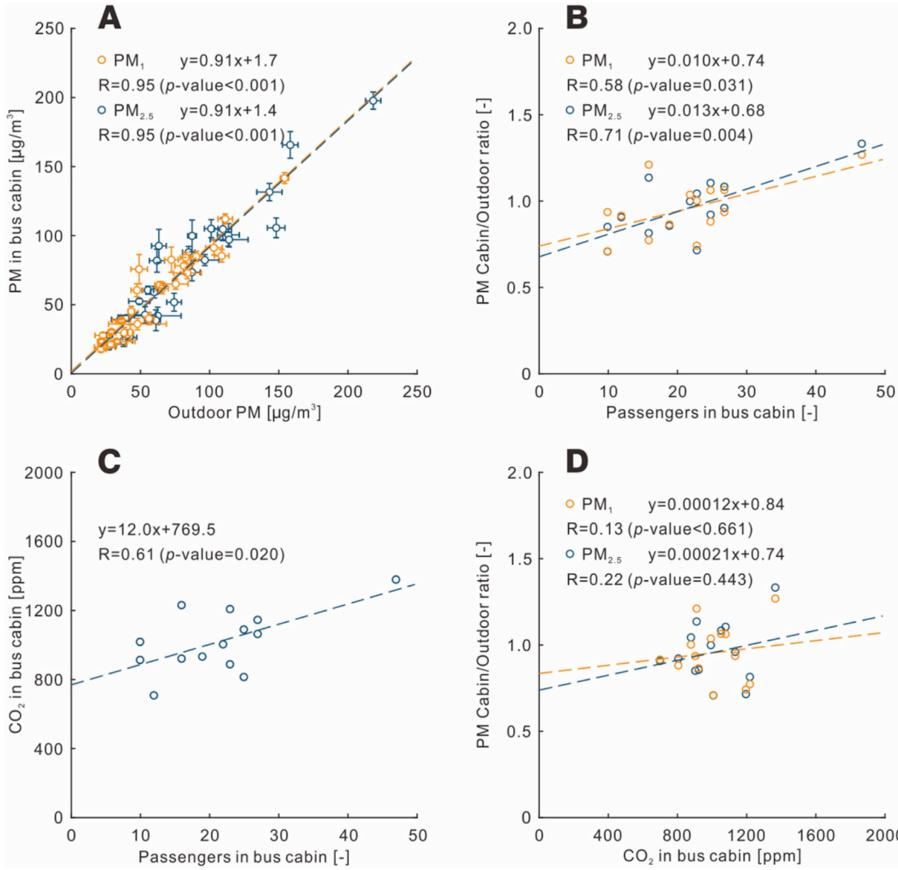

Fig. 7. (A) Mean PM concentrations in bus cabin and outdoors; (B) the relationship between PM cabin/outdoor ratios and passenger numbers; (C) the relationship between in-cabin CO_2 concentrations and passenger numbers; (D) the relationship between PM cabin/outdoor ratios and in-cabin CO_2 concentrations.

The PM inhalation doses during different commuting trips are shown in Table 8. Inhalation dose during subway trip is lowest and inhalation during bus trip is a little higher, while inhalations during cycling and walking are much higher than the inhalations during subway and bus trips. The PM concentrations in bus station were not recorded. The result in this study was estimated using assumed exposure values. The PM concentration in bus station is assumed to be equal to ambient PM concentration, i.e. PM concentration during bicycle trip, since the bus station is completely exposed to outdoor environment. The average time waiting in bus station is assumed to be equal to the average time spent in subway station. However, the PM concentration in bus station may be actually higher than the ambient PM level [119]. Therefore, commuters in bus station are probably exposed to higher PM concentration than the level estimated in this paper, which suggests that the inhalation dose during the total bus trip may be underestimated.

For subway journeys, compared to inside cabin, commuters are always exposed to higher PM concentrations and spend more time in station. Thus, the inhalation in station is much higher than the inhalation in cabin, which means during such a short distance subway trip as in this study (2 km), exposure in subway station may contribute most of the PM inhalation during the total subway trips. It should be mentioned that the inhalation rate in station is likely underestimated in this study, thus the actual PM doses inhaled in subway station may be

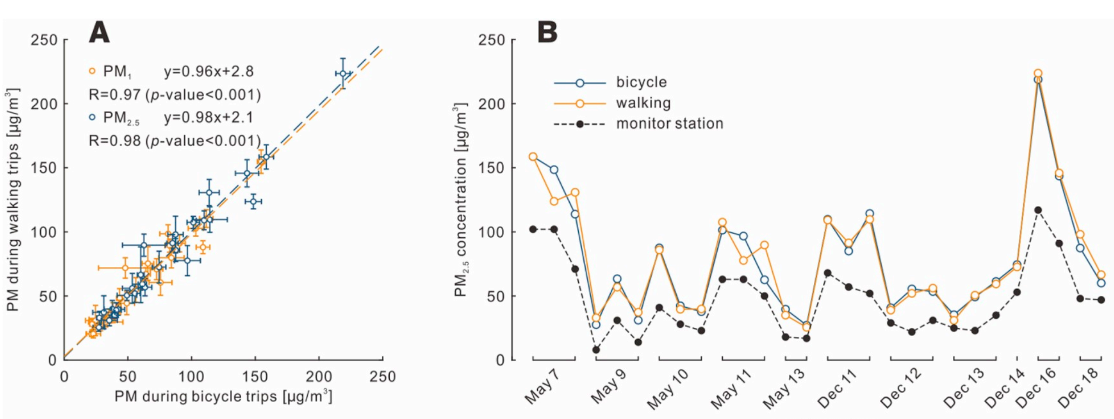

Fig. 8. (A) Mean PM concentrations during walking and cycling; (B) Mean $PM_{2.5}$ concentrations sampled during experiment and monitored by the stations in Nanjing.

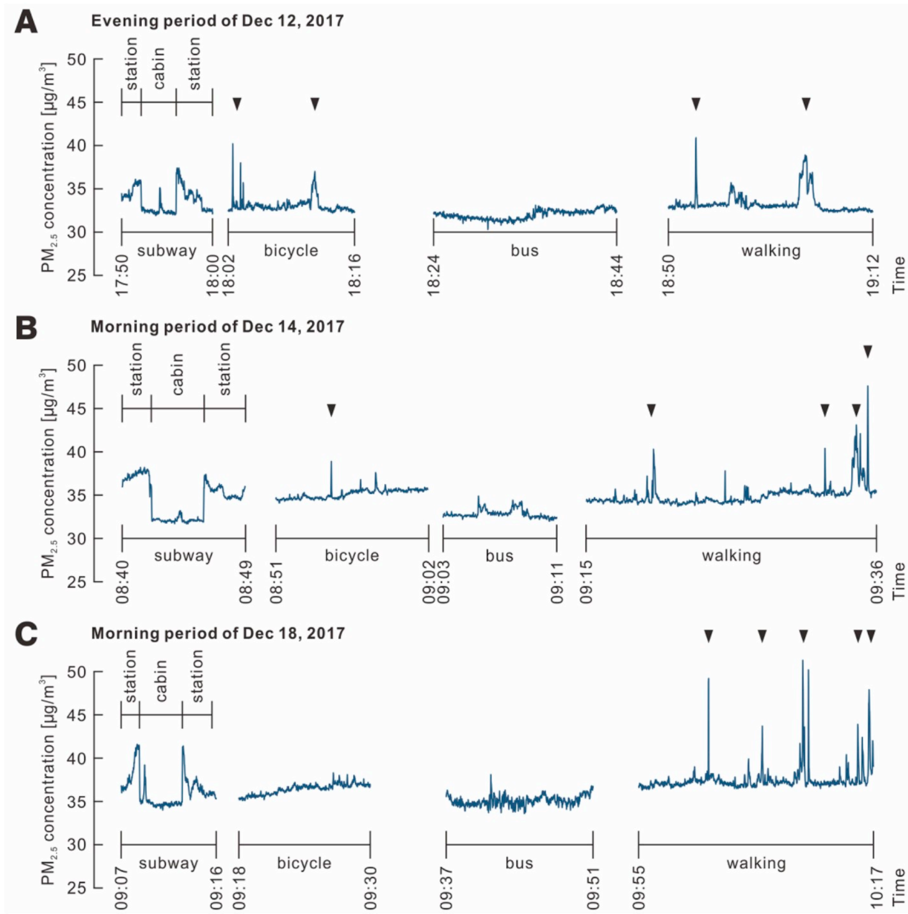

Fig. 9. Time sequence of real-time $PM_{2.5}$ concentrations during (A) evening period of Dec 12, (B) morning period of Dec 14 and (C) morning period of Dec 18, 2017.

even higher. Note that the studied route is a short distance (only 2 km). If commuters take longer subway journeys, the PM inhalation in cabin will increase with the commuting distance, while the inhalation in station usually changes slightly since commuters only entering and exiting the station one time if they don't make a transfer. Assume that the commuting time is homogeneous along the trip distance, then the PM inhalation in subway station may exceed the inhalation in station when the commuting distance is longer than 4.3 km (for PM_1) or 5.1 km (for $PM_{2.5}$). It indicates that for longer distance commuting ($> \sim 5$ km), exposure in subway cabin may contribute more to the total PM inhalation during subway trips. Therefore, for longer commuting distance, subway is believed to be a transportation mode with much less PM inhalation relative to bus, bicycle and walking. However, commuter inhalation during subway transferring is likely quite high according to the inhalation in subway station. Thus, commuters are recommended to avoid too many transfers during subway commuting.

The PM inhalations during cycling and walking are generally more than 5 times higher than the level during subway journey. By contrast, pedestrians may inhale more PM than cyclists due to the long commuting time, even though the value of IR_{avg} for pedestrians is lower and the PM concentrations during walking and cycling are very close. Therefore, it's not recommended to spend too much time cycling or walking during commuting.

4. Conclusions

This paper investigates personal exposure to PM_1 and $PM_{2.5}$ during commuting in Nanjing in four common transportation modes, i.e.

Table 6
PM concentrations of different commuting seasons in each transportation mode.

Mode	Period	PM_1 [μg/m^3]		$PM_{2.5}$ [μg/m^3]		Sample size
		AM ± SD	*p*-value	AM ± SD	*p*-value	
Subway (cabin)	Summer	38.9 ± 13.6	0.817	53.3 ± 14.8	0.733	14
	Winter	37.7 ± 14.7		55.4 ± 18.2		16
Bicycle	Summer	56.4 ± 32.0	0.719	74.2 ± 44.4	0.595	14
	Winter	60.9 ± 35.0		83.4 ± 47.9		15
Bus	Summer	53.7 ± 32.2	0.709	68.8 ± 44.9	0.502	14
	Winter	58.1 ± 31.5		79.8 ± 43.7		16
Walking	Summer	56.9 ± 30.8	0.693	74.4 ± 42.9	0.516	14
	Winter	62.0 ± 36.4		86.1 ± 50.9		14

Table 7
PM concentrations of different commuting periods in each transportation mode.

Mode	Period	PM_1 [μg/m^3]		$PM_{2.5}$ [μg/m^3]		Sample size
		AM ± SD	*p*-value	AM ± SD	*p*-value	
Subway (cabin)	Morning	41.2 ± 14.4	0.324	59.7 ± 14.1	0.152	11
	Noon	40.5 ± 17.4		56.5 ± 21.8		10
	Evening	32.4 ± 7.1		45.8 ± 8.4		9
Subway (station)	Morning	60.8 ± 26.8	0.579	100.8 ± 30.6	0.381	6
	Noon	57.0 ± 29.4		94.4 ± 41.4		5
	Evening	45.5 ± 12.6		74.1 ± 18.2		5
Bicycle	Morning	66.9 ± 41.8	0.535	89.2 ± 58.2	0.590	11
	Noon	57.0 ± 30.3		77.2 ± 41.3		10
	Evening	49.6 ± 22.1		67.1 ± 31.2		8
Bus	Morning	64.2 ± 39.9	0.517	85.6 ± 56.4	0.550	11
	Noon	54.2 ± 25.5		72.5 ± 34.8		10
	Evening	48.0 ± 25.9		63.8 ± 36.7		9
Walking	Morning	67.8 ± 42.2	0.576	90.4 ± 60.0	0.668	11
	Noon	52.9 ± 26.5		73.0 ± 37.8		10
	Evening	55.8 ± 27.0		74.7 ± 36.0		7

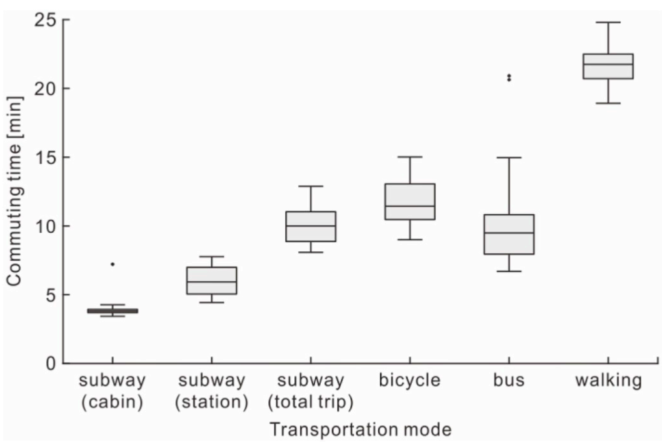

Fig. 10. Commuting time of different transportation modes.

subway, bicycle, bus and walking. The PM concentrations were measured during traffic rush hours for a week in summer and winter, respectively. The result shows that the mean PM concentrations in various commuting modes have significant difference. Subway cabin is exposed to lowest PM_1 (38.3 μg/m^3) and $PM_{2.5}$ (54.4 μg/m^3) concentrations compared to the other commuting modes. Subway station is exposed to highest $PM_{2.5}$ concentration (90.5 μg/m^3), while walking is exposed to highest PM_1 concentration (59.5 μg/m^3). The $PM_1/PM_{2.5}$ ratios of four commuting modes are generally between 0.6 and 0.8. For subway commuting, the mean PM concentrations in subway cabin are significantly lower than in subway station. The PM concentrations in subway cabin has stronger correlation with the PM concentrations in subway station while relatively weaker correlation with outdoor concentrations. Most of the PM inside subway cabin is infiltrated from subway station while only a few of the in-cabin PM is generated by the sources inside cabin. The outdoor PM contributes a great portion of the PM in subway station. But the in-station source may also contribute a lot to the PM in subway station, of which particles with size between 1 μm and 2.5 μm count the major portion (63.4%). This results in a lower $PM_1/PM_{2.5}$ ratio in subway station also a low $PM_1/PM_{2.5}$ ratio in cabin owing to the transfer from station to cabin. The PM concentrations in subway station were found having spatial variations. The particle concentration at a deeper level is usually higher than the level at a shallower level. A substantial number of particles within 1 μm–2.5 μm in size were observed at the platform and the particle portion within 1–2.5 μm decreased at shallower levels. The ventilation systems and indoor particle sources such as mechanical abrasion and passenger movement may cause the PM concentration difference between different station levels. The platform (B3 level) is generally exposed to the highest $PM_{2.5}$ concentration, while the cabin is exposed to the lowest concentration.

For bus commuting, in-cabin concentrations show significantly

Table 8
PM_1 and $PM_{2.5}$ inhalation doses of different commuting modes.

Mode	PM concentration [μg/m^3]		Commuting time [min]	Inhalation rate [L/min]	Inhalation dose [μg]	
	PM_1	$PM_{2.5}$			PM_1	$PM_{2.5}$
Subway (cabin)	38.3	54.4	3.9	8.4	1.3	1.8
Subway (station)	54.8	90.5	6.0	8.4[a]	2.8	4.6
Subway (total trip)	/	/	/	/	**4.0**	**6.3**
Bicycle	58.7	79.0	11.8	33.8	**23.4**	**31.5**
Bus (cabin)	56.0	74.7	10.2	8.4	4.8	6.4
Bus (station)[b]	58.7[c]	79.0[c]	6.0[d]	8.4	3.0	4.0
Bus (total trip)	/	/	/	/	**7.8**	**10.4**
Walking	59.5	80.3	21.6	22.5	**28.9**	**39.0**

[a] The value herein may be underestimated.
[b] The PM exposure was not measured during the test period. The result shown here is estimated.
[c] The PM concentration in bus station is assumed to be equal to the PM concentration during bicycle trips.
[d] The average time waiting in bus station is assumed to be equal to the average time spent in subway station.

strong correlation with outdoor concentrations for both PM_1 and $PM_{2.5}$. Therefore, most of the PM inside cabin comes from outdoor environment while the in-cabin PM source contributes a small portion. The PM cabin/outdoor ratios have an insignificant correlation with the in-cabin CO_2 concentrations for both subway and bus commuting. The PM concentrations during cycling are highly in consistence and have significantly strong correlation with the concentrations during walking and they don't show any significant difference. The $PM_{2.5}$ concentrations measured during walking and cycling have strong correlation with the concentrations sampled by the monitoring stations. However, the station-monitored $PM_{2.5}$ concentrations are significantly lower than the measured concentrations during cycling and walking. It's probably because the field measurements were conducted in a heavy-traffic road located in the city center, where the PM concentrations may be higher than the average ambient levels of Nanjing. Cyclists and pedestrians are potential to be directly exposed to some other local particle emissions along the commuting route, which probably result in elevated PM concentrations in some specific areas and time.

No significant impact of commuting seasons and periods on PM exposure concentrations was found in this study. The PM inhalation doses are determined by the PM exposure concentrations, commuting time and inhalation rates. The PM inhalation dose during subway trip is lowest while the commuters during cycling and walking may inhale more than 5 times higher PM doses. During a short distance subway trip as in this study, exposure in subway station may contribute most of the PM inhalation during the entire subway trip owing to the high PM concentrations and longer commuting time in station.

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Appendix A. Supplementary data

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