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Influencing Factors of Particulate Matter Concentration in the Metro Carriage and the Corresponding Inhalation Intake Estimation: A Field Measurement in Chengdu

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Abstract: Urbanization promotes the development of the subway system, and the particulate matter (PM) concentrations inside have received increasing attention. This study first measured the dynamic $PM_{2.5}$ and PM_{10} concentrations in a metro carriage in Chengdu and explored the dominant influencing factors. The personal inhalation intakes of different routes were evaluated. The results showed that the in-carriage $PM_{2.5}$ and PM_{10} concentrations ranged from 11 to 74 μg/m^3 (mean: 36.7 μg/m^3) and 13 to 89 μg/m^3 (mean: 40.1 μg/m^3), respectively. When the train passed from the overground to underground, the in-carriage $PM_{2.5}$ and PM_{10} concentrations increased by 30.4% and 32.9%, respectively. No specific linear relationship between passenger number and in-carriage PM concentrations was found. In-carriage PM concentrations decreased after the carriage doors were opened on the platforms. $PM_{2.5}$ inhalation intakes ranged from 1.08 to 9.52, with a mean of 4.24 μg. For the passengers with the same age and sex, the average inhaled $PM_{2.5}$ intake in the metro carriage on the route with more underground platforms was higher. This study not only revealed the PM characteristics in the Chengdu metro system for the first time, but also provided guidelines for reducing the in-carriage PM concentrations to build a healthier travel environment.

Keywords: metro carriage; particulate matter; driving condition; passenger number; carriage door; inhalation intake

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1. Introduction

Rapid urban population growth brings with it severe ground traffic congestion, which increases citizens' commuting time and causes environmental pollution [1–3]. The development of the metro system can effectively alleviate this issue in many countries, especially in China [2,4–6]. By the end of 2020, the metro system existed in 45 cities in China, resulting in a total operating mileage of 6280.8 km and an annual passenger number of 17.6 billion [7]. Obviously, the metro system, an essential travel tool, has been an inseparable part of urban daily life of citizens. Compared with a normal indoor environment, the metro system has many specific characteristics, including relative closure, limited ventilation, and special sources of heavy metals, making it a unique microenvironment [8]. Exposure to such an environment when traveling is drawing increasing attention.

As a dominant air pollutant species, particulate matter (PM) can cause diverse respiratory and cardiovascular diseases [9–13]. Revealing the characteristics of PM in the metro system has been a hot issue. Prior studies have shown that, with few exceptions, PM concentrations in metro systems were much higher than those measured in ambient air [14–16]. The sources of PM in metro systems were related to brake emissions, wheel-rail abrasion products, and the outdoor contribution to the platform ambient air [17]. However, passengers spend more time in the metro carriages than on the platforms when they take the subway [18,19]. Gao et. al. demonstrated that platform and air outside the carriage are two sources of $PM_{2.5}$ in metro carriages. During operation and braking, $PM_{2.5}$ on the platform produced by the friction between the wheel and the track entered the metro carriage. Meanwhile, $PM_{2.5}$ in the ambient air outside the carriage could enter the inside through the ventilation system [20]. Thus, it is more important to explore the PM characteristics in the metro carriage and its impact on human health.

Investigations of PM concentrations in the metro carriage have been conducted in the US [21,22], Korea [23,24], Spain [25], Turkey [26], Italy [27], and China [28,29]. Some but not all of these have tried to explore the dominant influencing factors. Wang et al. [30] found that the change in the driving condition could cause in-carriage $PM_{2.5}$ concentration variations. Nevertheless, he did not mention the in-carriage passenger as a variable that might influence the in-carriage $PM_{2.5}$ levels. Thus, when studying the influence of the driving conditions, the impact of the passenger should be excluded. Zheng et al. [29] reported that the in-carriage $PM_{2.5}$ concentration had no relationship with the passenger number in Hong Kong, but the experiments were conducted in two different metro lines. The difference in ambient PM concentrations around the two trains and the varied ventilation efficiencies of the two metro air conditioning systems might lead to additional influences on the in-carriage $PM_{2.5}$ concentration. When exploring the influence of the factor, an experiment should be carried out in the same carriage of the same type of train on the same route in the same position so as to eliminate the aforementioned differences and to more accurately reflect the relationship between passenger number and $PM_{2.5}$ concentration. On the other hand, a positive relationship between passenger number and in-carriage $PM_{2.5}$ concentration was found by Xu et al. [31]. The opposite results mean that the correlation between the in-carriage $PM_{2.5}$ concentration and the passenger number is still unclear. In addition, the research about the influence of train door operation (door opening and closing) on in-carriage PM concentrations was quite limited. Consequently, the impacts of these factors on in-carriage PM concentrations should be further investigated.

Although the long-term health effects of exposure to pollutants during travel have not been specifically determined, it is often assumed in a health impact assessment that the impacts of changes in inhaled pollutants during regular (commuter) travel, as a percentage of daily inhaled pollutants, are similar to the impacts of changes in the proportion of long-term exposure levels [32,33]. Exposure to high concentrations of in-carriage PM with more heavy metal elements, organic compounds, and transition metal elements might cause more severe adverse health effects [34]. Hence, it is important to evaluate the inhalation intake of PM in the metro carriage. The inhalation intakes of PM in some forms of public transport such as bike, taxi, and bus have been investigated [35–38], but few studies have assessed the inhalation intake of in-carriage PM [39–41]. Shen and Gao [40] calculated a volunteer's inhalation intake of PM in the metro carriage, but they did not estimate the results in terms of the conditions of different sexes, ages, and routes. Lacking these variables in the evaluation is not conducive to understanding the impact of PM on passengers' health for such a popular mode of transportation.

Chengdu, the economic and cultural center of Southwest China, has a population density of 1460 persons/km^2 [42]. The Chengdu metro system has been rapidly developed in the most recent 10 years. By September 2021, the mileage of the Chengdu metro line ranked third in China. However, investigations into PM in the Chengdu metro System are still scarce. In this study, we first measured the $PM_{2.5}$ and PM_{10} levels in the metro carriage in Chengdu to: (1) explore the impacts of some influencing factors, including driving routes (overground route/underground route), passenger number, and the opening and closing of the metro carriage door; (2) quantify the in-carriage personal inhalation intakes of PM in the Chengdu metro system, and finally (3) provide recommendations to reduce the in-carriage PM concentrations and inhalation intake.

2. Methodology

2.1. Measurement Site Description

To conduct the measurement, a metro line in Chengdu was selected; the line began operation in December 2019 with a total length of 49.02 km. It comprises 42 platforms (5 of them were overground platforms and the others were underground platforms). The train, equipped with an aluminum alloy body, is 185 m long and 3 m wide, and consists of 8 marshaling A-type carriages. There are 5 doors and 4 benches on each side of a single standard carriage. The maximum speed achieved is 80 km/h.

Our measurement campaign was conducted in a typical middle carriage of the trains on the chosen metro line (the fifth carriage) from 19 April to 25 June 2021 (longitude 104°066′–104°105′ E, latitude 30°75′–30°83′ N). The experiment involved five overground platforms (P1, P2, P3, P4, and P5) and five underground platforms (P6, P7, P8, P9, and P10) (Figure 1). The route sections between the two consecutive platforms were named from R1 to R9.

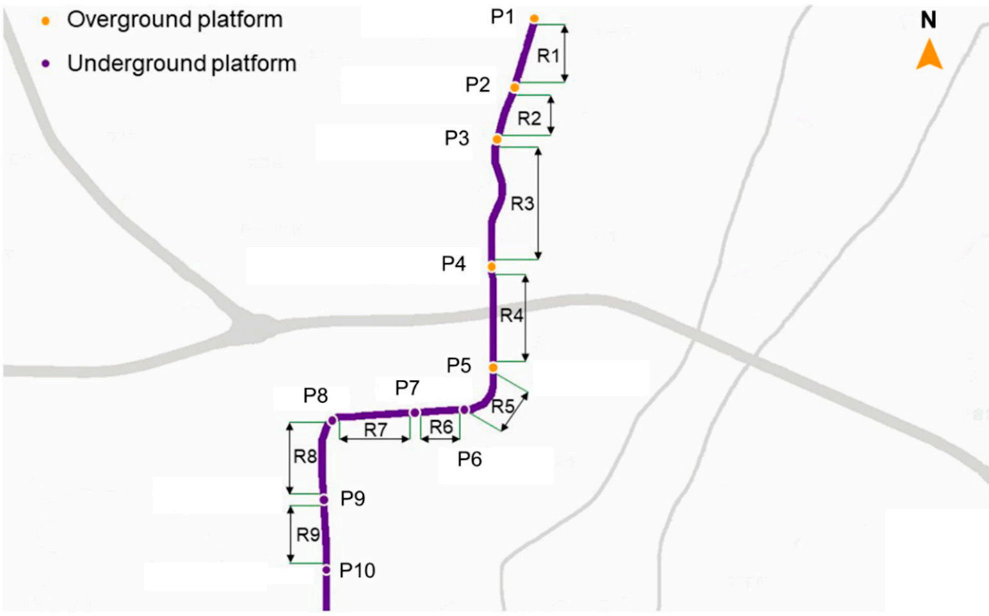

Figure 1. The map of measured routes. P1–P10 represent the 10 platforms measured.

2.2. Monitoring Instruments and Experiment Design

$PM_{2.5}$ and PM_{10} were measured simultaneously using two laser dust samplers (DustTrak 8530, TSI Inc., Shoreview, MI, USA), with a measurement range of 0.001–400 mg/m^3 and an accuracy of 0.001 mg/m^3. A carbon dioxide recorder (HOBO MX1102, Onset Computer Corp., Bourne, MA, USA) was used to measure the CO_2 concentrations, with measurement ranges of 0–5000 ppm. The recording intervals of the DustTraks and HOBO were set at 1 s and 10 s, respectively. The two DustTraks were conducted with zero calibration using a high-efficiency particulate air (HEPA) filter and flow adjustment using a calibrated rotameter, and the particulate-battering hammer inside was cleaned with ethanol before each measurement. Furthermore, the $PM_{2.5}$ and PM_{10} of the local air quality monitoring station data were found to be 1.03–1.26 (mean: 1.15) times larger than the real-time DustTrak data. In addition, the real-time PM data were corrected according to the gravimetric method using the 37 mm Teflon filter in the DustTrak under some conditions, and the correction coefficients were close to the results from the monitoring station. Therefore, as shown in Equation (1), a reasonable correction coefficient of 1.15 was applied for the dynamic data correction in this study. Before each experiment, we placed the HOBO in an unmanned environment to measure the atmospheric carbon dioxide concentrations. The measured concentration was compared with the recommended atmospheric value (400 ppm) by the manufacturer, and similar results could reflect the measurement accuracy of the sensor. This operation procedure is the standard calibration procedure in the instruction manual.

$$C_{calibration} = A \times C_{measurement}, \tag{1}$$

where $C_{calibration}$ and $C_{measurement}$ are the calibrated and measured PM concentrations (μg/m^3), respectively. A is the correction coefficient.

Three sub-campaigns were undertaken: (1) the underground/overground campaign, which explored the effects of driving routes on the in-carriage $PM_{2.5}$ and PM_{10}; (2) the passenger number campaign, to reveal the effect of passenger number on the in-carriage $PM_{2.5}$ and PM_{10}, and (3) the door opening/closing campaign, for exploring the effect of the door opening process on in-carriage PM concentrations.

2.3. Monitoring Process

In each campaign, two anti-static tubes were connected to the two DustTraks, respectively (Figure 2a,b). The air inlets of the tubes were fixed at a height of 1.5 m from the ground, in the breathing zone of the sitting passengers. The details of the campaigns were introduced below.

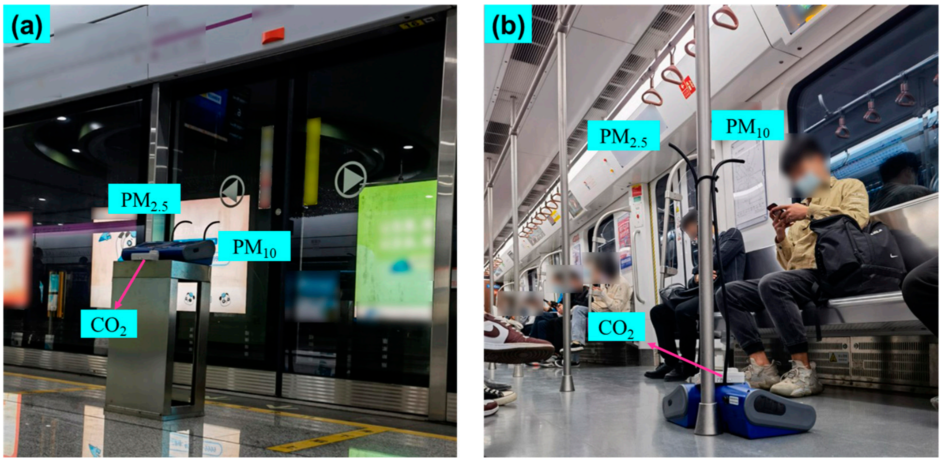

Figure 2. Field measurement conditions. (**a**) Metro platform. (**b**) Metro carriage.

When exploring the PM difference between the underground route and the overground route, the operator entered the fifth carriage on platform P1 or P10, which is the start or the end of the measurement route. All the instruments were turned on and then put at the corresponding position (Mp_a in Figure 3). To minimize the effect of passengers on the experiment, the measurement campaign was carried out from 22:00 to 23:00, during which time there were almost no passengers in the metro carriage. A measurement lasting about 20 min was conducted on six days, including weekdays (Tuesday, Wednesday, Thursday, and Friday) and weekends (Saturday and Sunday). Therefore, there were six measurements in this sub-campaign.

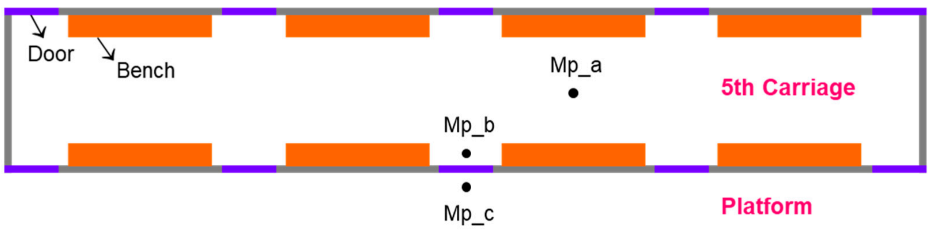

Figure 3. Measurement points in all campaigns. Mp_a represents the measurement points when exploring the influences of driving routes and passenger number on PM concentrations in the carriage. Mp_b and Mp_c represent the measurement points in the carriage and on the platform when exploring the influence of the door opening and closing on in-carriage PM concentrations, respectively.

For exploring the influence of passenger number on the PM in the carriage, 12 measurements were conducted in four time zones in terms of the passenger flow in the metro carriage. The period of 17:30–19:00 is peak-hour, and the periods of 10:00–11:30, 14:00–15:30, and 21:30–23:00 are off-peak-hour. During each measurement, the number of passengers in the measured carriage was recorded when the train kept running between every two consecutive platforms, which eliminated the influence of the train type, service life, and driving route differences. In all measurements (including peak and off-peak periods), the train was not overcrowded. Therefore, the number of passengers could be accurately counted. The distance between the passengers and the measurement point was 0.5–8.0 m, which prevented the possibility of direct disturbance by a certain individual and aided in representing the in-carriage PM levels. In addition, all 12 measurements were conducted during the days with similar atmospheric PM concentrations in order to avoid the influence of fluctuations by the surrounding PM concentrations (Table A6). The ambient PM concentrations [43] around the measurement route were obtained from nearby air quality monitoring stations before each experiment. The distances between the monitoring sites and the metro line are 5.8 km and 9.2 km, respectively. The measurements were conducted in Sichuan Basin, and the wind speed ranged from light air (level 1) to gentle breeze (level 3) [44]. It has been reported that a wind speed of less than level 4 has little effect on PM concentrations [45]. Meanwhile, the difference caused by the wind direction could be negligible because the wind direction was mainly northeast and southwest, accounting for 71% of the time during the measurement period based on the historical weather forecast data [44]. Hence, the PM data from the monitoring site can be representative in a small area.

To determine the effect of door opening and closing on in-carriage PM concentrations, the in-carriage measurement was continuously conducted near the door (Mp_b in Figure 3) for about 20 min (route: from P1 to P10), and the measurement involving a complete train stop and start process lasted for 3 min on each metro platform (Mp_c in Figure 3). The time points for when the door was opened and closed were recorded. Triplicate measurements were carried out in an off-peak period (21:00–23:00) to reduce the impact of passenger numbers.

2.4. Inhalation Intake Evaluation Method

We evaluated the inhalation intake of $PM_{2.5}$ in the carriage for a further understanding of the impact of in-carriage $PM_{2.5}$ on human health, which can be calculated using Equation (2).

$$\text{Inhalation intake} = \int_{t1}^{t2} C(t) \cdot IR(t) \cdot dt, \tag{2}$$

where $C(t)$ is the real-time exposure concentration at the time point of t (μg/m^3); $t1$ and $t2$ are the start and end time points of exposure (min), respectively, and $IR(t)$ is the inhalation rate (IR) at the time point of t (m^3/min) [39].

IR was influenced by many factors such as age, sex, and weight [46]. Hence, two sexes (male and female) and five age stages (children (0–7), juvenile (7–16.5), youth (16.5–45), middle-aged (45–65), and elderly (65–96)) were involved in this study. The corresponding IR (Table A1) was determined according to a previous study conducted by Brochu et al. [47]. Owing to the different $PM_{2.5}$ concentrations on varied routes, four routes were considered in this study (Table A2), all of which had five platforms but different distributions between the overground and underground platform numbers. Routes a and d consisted of five overground platforms and five underground platforms, respectively. The underground platforms accounted for 2/5 and 3/5 for Routes b and c, respectively (Figure 4). The data of the 10 above measurements on different days were used to evaluate passenger inhalation intakes. There were 40 scenarios for each day in this evaluation. Although the length of the period of each measurement was not very long, it could represent the actual commuting period spent in the metro carriage. Moreover, the in-carriage PM concentrations used to estimate the inhalation intake were repeatedly measured, which could effectively reflect the PM levels in the metro carriage when passing through different routes. Therefore, the inhalation intake calculated from the measured PM concentrations and measurement periods would be representative.

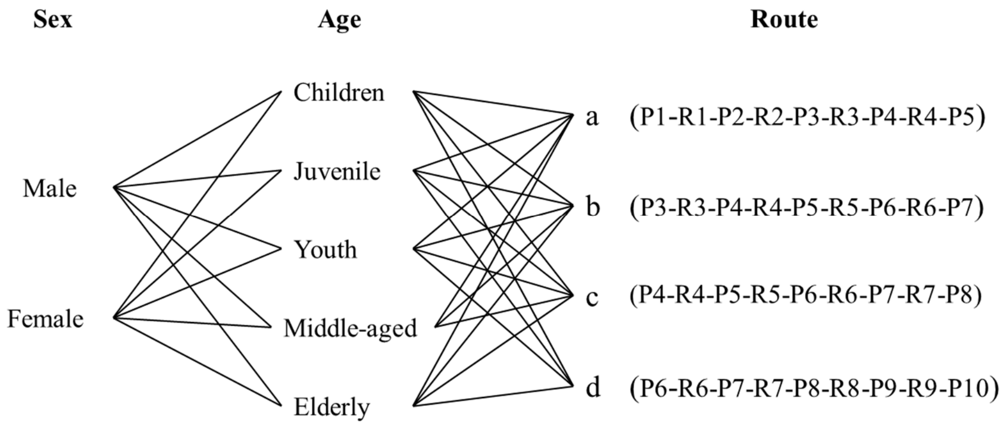

Figure 4. Inhalation intake evaluation scenarios.

2.5. Data Analysis

An independent sample *t*-test was used to compare the differences in in-carriage $PM_{2.5}$ and PM_{10} concentrations between the overground and underground air. The paired sample *t*-test was adopted to evaluate the significance of the in-carriage $PM_{2.5}$ and PM_{10} concentration difference between the door opening and closing conditions. A one-way analysis of variance (ANOVA) was used to determine the differences in inhalation intakes under varied $PM_{2.5}$ inhalation conditions. Pearson correlation coefficient was used to examine the correlation between the in-carriage PM concentrations and passenger number. All statistical significances were accepted at $p < 0.05$.

3. Results and Discussion

3.1. $PM_{2.5}$ and PM_{10} Concentrations in the Carriage

The $PM_{2.5}$ and PM_{10} concentrations of all the measurements involved five overground platforms (P1, P2, P3, P4, and P5) and five underground platforms (P6, P7, P8, P9, and P10) which are summarized in Table 1. All the in-carriage $PM_{2.5}$ and PM_{10} concentrations ranged from 11 to 74 $\mu g/m^3$ and from 13 to 89 $\mu g/m^3$, respectively. The average $PM_{2.5}$ concentration accounted for 91.5% of the average PM_{10} concentration, indicating that $PM_{2.5}$ is the major part of the particles in the metro carriage. The average $PM_{2.5}$ concentration in all measurements (36.7 $\mu g/m^3$) was lower than the 24 h mean concentration limit in residential areas and public transport (75 $\mu g/m^3$) specified in the Ambient Air Quality Standards [48], but higher than the recommended 24 h level (15 $\mu g/m^3$) specified in the air quality guidelines proposed by the World Health Organization [49].

As shown in Table 1, the average in-carriage $PM_{2.5}$ concentration in this study was lower than those in Nanchang [50], Taipei [51], Shanghai [31], Seoul [23], Athens L2 [52], Oporto LA [52], Istanbul [26], and Mexico [53], higher than those in Tianjin [54], Barcelona L10 [25], and Los Angles [21], and close to that in New York [55]. Moreover, the PM_{10} concentrations measured in the metro carriage on all routes were lower than those in Tianjin [54], Taipei [51], Seoul [23], and Rome [27], and higher than that in Los Angles [21].

Table 1. Average $PM_{2.5}$ and PM_{10} concentrations in metro carriages worldwide.

City	Measurement Year	$PM_{2.5}$ (μg/m^3) Mean	Range	PM_{10} (μg/m^3) Mean	Range	Reference
Chengdu (all routes)	2021	36.7	11–74	40.1	13–89	This study
Tianjin	2021	23	-	69	-	[54]
Nanchang	2019	179	72–516	-	-	[50]
Taipei	2016	47	2–112	55	3–135	[51]
Shanghai	2013	84	-	-	-	[31]
Seoul	2004–2005	126	115–136	312	29–359	[23]
Barcelona L10	2014	26	20–31	-	-	[25]
Athens L2	2014	125	-	-	-	[52]
Oporto LA		54	-	-	-	
Rome	2010	-	-	275	-	[27]
Istanbul	2007–2008	73	22–241			[26]
Los Angeles (underground)	2010	24	3–62	31	6–107	[21]
New York	2008	39	34–44	-	-	[55]
Mexico	2002	61	31–99	-	-	[53]

The metro lines in Seoul have been in operation for a long time, and the PM yield was related to the aging of facilities in the subway system and the dispersion of inorganic metal dust generated by the friction between trains and wheels during normal operation [23]. This could contribute to the fact that the in-carriage PM concentration in the Seoul metro system was higher than that in Chengdu metro system. On the other hand, the red and gold subway line in Los Angeles [21] and the metro line 10 in Barcelona [25] were comparatively new, with more advanced technology, and therefore, their ventilation system and braking technology were more effective than the older one. Meanwhile, the average ambient $PM_{2.5}$ concentration in Los Angeles (20 μg/m^3) was lower than that in Chengdu (Average, 30.5 μg/m^3) during the measurement [21]. This could be the reason for why the in-carriage PM concentrations in these cities were lower than those in Chengdu. These studies revealed that in-carriage PM concentrations were affected by many factors such as the monitoring conditions (i.e., measurement time, place, equipment, and the year of subway construction), wheel materials, ventilation levels, and braking systems [23,25,56,57]. The metro line in this study, currently one of the newest metro lines in Chengdu, has an efficient ventilation system and an advanced braking system, which might lead to the fact that the PM levels in this metro line were relatively low among different subway systems worldwide.

3.2. Influencing Factors

3.2.1. Underground and Overground

PM concentrations were affected by the driving routes. As shown in Figure 5, there was only one person in the carriage when the metro train passed through the seven routes involving R1, R2, R3, R4, R5, R6, and R7, and the average passenger number was three and five when passing through R8 and R9, respectively. Therefore, the CO_2 level dominantly influenced by human breath remained almost unchanged during the measurement, indicating that the influence of the passenger number can be ignored. There was a significant average PM concentration difference between the overground ($PM_{2.5}$: 33.9; PM_{10}: 38.6 μg/m^3) and underground ($PM_{2.5}$: 44.2; PM_{10}: 51.3 μg/m^3) routes ($PM_{2.5}$: $p = 0.002$; PM_{10}: $p < 0.05$). As the metro train ran from the overground route to the underground route, the $PM_{2.5}$ and PM_{10} levels in the carriage increased by 30.4% and 32.9%, respectively.

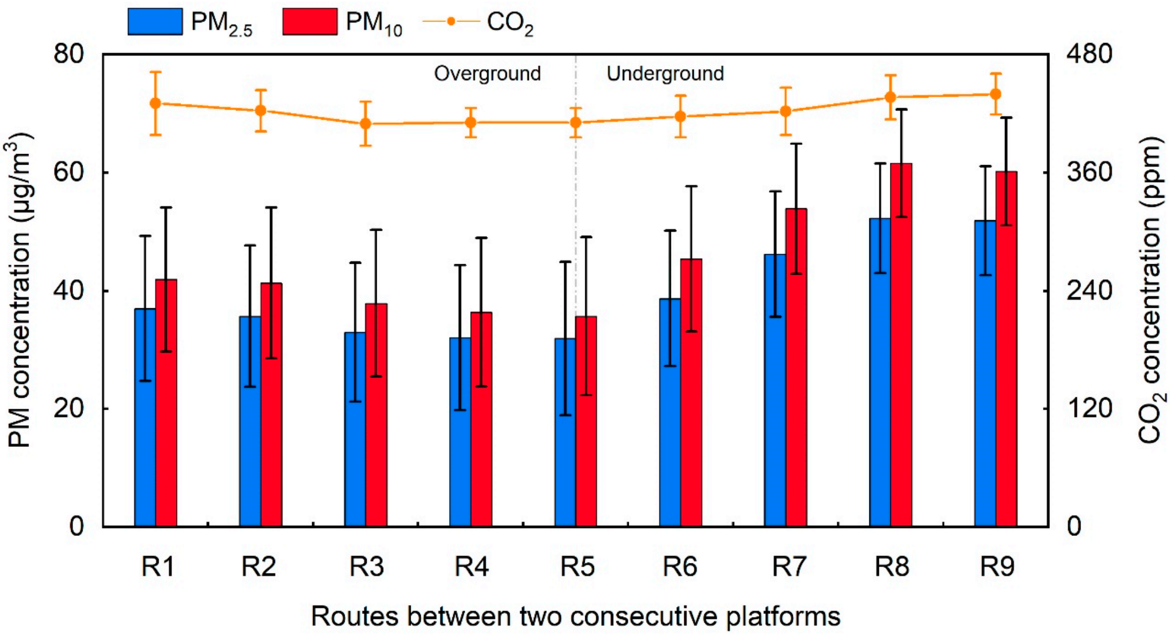

Figure 5. Average in-carriage PM and CO_2 concentrations between every two consecutive platforms including overground and underground conditions.

Figure 6 presents the dynamic in-carriage PM concentrations for the overground and underground conditions for six days. When the metro train ran from R1 to R5, the in-carriage PM concentrations showed a slightly decreasing trend during each measurement. As the metro train passed from R5 to R9, the in-carriage PM concentrations increased rapidly to reach a peak in R8, and then decreased.

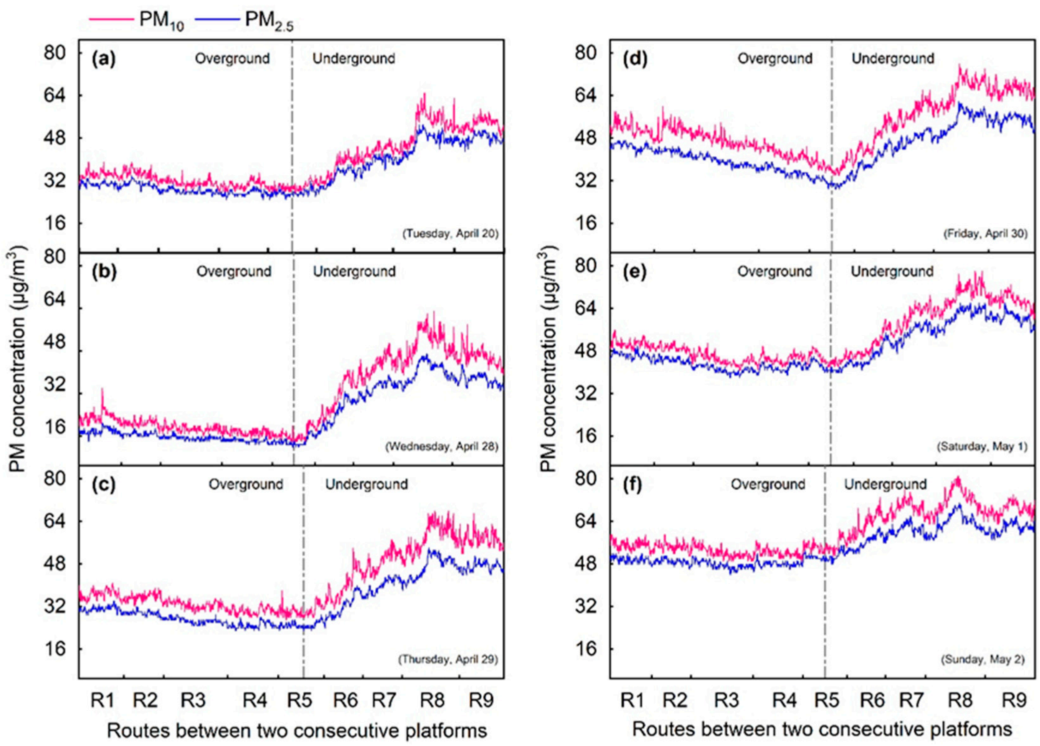

Figure 6. Dynamic PM concentrations in the metro carriage in overground and underground conditions on six selected days. (**a**) Tuesday, 20 April. (**b**) Wednesday, 28 April. (**c**) Thursday, 29 April. (**d**) Friday, 30 April. (**e**) Saturday, 1 May. (**f**) Sunday, 2 May.

Kam et al. [21] have demonstrated that in-carriage PM levels in the overground environment were remarkably affected by the atmospheric surroundings. The main external influencing factor for the in-carriage PM concentrations was the air in the tunnel when the metro train was on the underground route [51]. Poor ventilation contributed to PM accumulation in the tunnel [20,50], and suspended particles would enter the carriage through the train cracks and the mechanical ventilation system [58]. An additional measurement in the tunnel exhaust and the ambient environment on another platform showed that the $PM_{2.5}$ concentration in the tunnel was much higher than that in the ambient (85.6 μg/m^3 in the tunnel and 27.8 μg/m^3 for the ambient). Meanwhile, the metro train was exposed to a relatively clean atmospheric environment when running on the overground route in this study. These are the main reasons behind the fact that, in-carriage, the PM concentrations on the underground route were higher than those on the overground route. This result was contrary to the study of Xu et al. [31], who found that the in-carriage $PM_{2.5}$ concentration increased as the metro train passed from underground to overground. The reason for this might be that the outdoor $PM_{2.5}$ concentrations in Chengdu ($PM_{2.5}$: 10–57 μg/m^3) were much lower than those in Shanghai ($PM_{2.5}$: 133 μg/m^3) during the experiment [31].

3.2.2. Passenger Number

Table 2 presents the correlation between the passenger number and the PM concentrations in the metro carriage when the train passed through eight different routes. R1, R2, R3, and R4 were overground routes, and R6, R7, R8, and R9 were underground routes. During the measurements, the in-carriage passenger number ranged from 1 to 38. The correlation coefficients of the passenger number and $PM_{2.5}$ ranged from −0.343 to 0.067, and the significance (Sig.) ranged from 0.275 to 0.963 (>0.05). The correlation coefficients of the passenger number and PM_{10} ranged from −0.548 to −0.143 and the Sig. ranged from 0.065 to 0.657 (>0.05). The results indicated that the $PM_{2.5}$ and PM_{10} concentrations had weak correlations with the passenger number in the metro carriage. Some additional measurements on other routes of the same Chengdu Metro Line (R10, R11, and R12) during peak hours when in-carriage passenger number ranged from 43 to 70 also presented the same conclusion (Tables A3 and A4). However, Ren et al. [54] and Gao et al. [20] found that the in-carriage PM concentrations were linearly correlated with the passenger number.

Table 2. The correlation coefficient analysis results between passenger number and average PM concentrations in the same metro carriage on different routes.

Routes	R1		R2		R3		R4		R6		R7		R8		R9	
Factors	**R**	**Sig.**	**R**	**Sig.**	**R**	**Sig.**	**R**	**Sig.**	**R**	**Sig.**	**R**	**Sig.**	**R**	**Sig.**	**R**	**Sig.**
$PM_{2.5}$	−0.243	0.446	−0.174	0.59	0.067	0.837	−0.049	0.879	−0.136	0.673	−0.216	0.501	−0.343	0.275	0.015	0.963
PM_{10}	−0.419	0.176	−0.344	0.274	−0.143	0.657	−0.217	0.498	−0.263	0.408	−0.411	0.184	−0.548	0.065	−0.145	0.654

The opposite conclusion in this study has several possible explanations. First, all passengers wore masks during our measurement period, owing to COVID-19, which was different from some previous studies [20,31,59] and might have prevented the formation and growth of particles related to suspended exhaled droplets [60,61]. Moreover, Kam et al. [21] and Huang et al. [50] reported that passengers' activities caused PM that had accumulated over time in the metro carriage to resuspend. In this study, few passengers moved in the carriage when the train was running, which reduced the PM resuspension. Meanwhile, different research methods used in the exploration of the correlation between passenger number and PM concentrations in the metro carriage may have different results due to using data from different metro lines [29] and a limited number of samples [31,54]. The PM atmospheric concentrations around different routes, train models, and years of operation will affect the in-carriage PM concentrations. Therefore, some existing studies, which did not control all of these variables, might limit the exploration of the accurate correlation between the passenger number and the in-carriage PM concentrations. In this study, the number of variables was minimized to make it as close to a univariate experiment as possible, which could directly reflect the influence of passenger number on in-carriage

PM concentrations. In addition, the data from 12 measurements were used to conduct the statistical analysis. This relatively large sample size would help to improve the reliability of the results.

3.2.3. Door Opening and Door Closing

Three periods including the period from the opening to closing of the door, the period before the opening of the door, and the period after the closing of the door were determined, which were the periods from the time point of the door opening to the time point of the door closing, before the door opening point, and after the door closing point, respectively. The last two periods were as long as the first one on the corresponding platform.

When the train arrived at each platform and upon the opening of the doors, the in-carriage PM concentrations decreased (Figure 7). The PM concentrations in the period from the opening to the closing of the door were significantly different compared to those in the period before the opening of the door ($PM_{2.5}$: $p = 0.001$; PM_{10}: $p < 0.05$). The in-carriage $PM_{2.5}$ concentrations on P2, P3, P4, P5, P6, P7, P8, and P9 decreased from 25.9 to 25.4, 25.2 to 24.8, 23.7 to 23.4, 23.5 to 23.0, 28.1 to 26.7, 35.9 to 35.1, 39.9 to 39.0, and 48.0 to 45.2 ($\mu g/m^3$), respectively. Similarly, PM_{10} levels in the same places decreased from 32.3 to 31.9, 33.3 to 32.1, 30.9 to 30.1, 29.9 to 29.7, 34.5 to 33.1, 45.1 to 44.1, 49.9 to 49.5, and 59.5 to 56.7 ($\mu g/m^3$), respectively. The PM concentrations on the platform were higher than those in the carriage as the train stopped at the overground platforms, but were lower than those in the carriage when the train stopped at the underground platforms, which indicated that the PM concentrations difference between the carriage and the platform was not the dominant factor causing this decreasing trend. The experiment was conducted during off-peak hours, and thus, few passengers entered or left the metro carriages and would not yield a slight air disturbance. Due to the pressure difference between the carriage and the platform caused by the ventilation system inside the train, the air in the carriage would diffuse to the platform. Meanwhile, the in-carriage air supply was at a cleaner level after being filtered by the ventilation system. Opening and closing of doors had a great impact on the pressure difference between indoor and outdoor environments, and the variation of the pressure difference would affect the diffusion velocity of particulate matter [62,63]. That is, the air pressure difference between the carriage and the platform might play an important role on decreasing trends of in-carriage PM concentrations after the carriage doors were opened when the train stopped at the overground platforms. On the contrary, the PM concentrations on the underground platform were lower than those in the carriage owing to the operating ventilation system in the relatively confined underground platforms. Therefore, the synergistic effect of air pressure and concentration differences between the metro carriages and platforms might contribute more significantly to this result.

On the other hand, once the door was closed and the train started running on each platform, the in-carriage PM concentrations increased (Figure 7). The PM concentrations in the period from the opening to closing of the door were significantly different compared to those in the period after the closing of the door ($PM_{2.5}$: $p = 0.004$; PM_{10}: $p < 0.05$). The in-carriage $PM_{2.5}$ concentration on P2, P3, P4, P5, P6, P7, P8, and P9 increased from 25.4 to 25.7, 24.8 to 25.0, 23.4 to 23.9, 23.0 to 23.8, 26.7 to 27.3, 35.1 to 36.1, 39.0 to 40.0, and 45.2 to 45.7 ($\mu g/m^3$), respectively. Similarly, PM_{10} levels in the same places increased from 31.9 to 32.2, 32.1 to 32.7, 30.1 to 30.6, 29.7 to 30.3, 33.1 to 35.0, 44.1 to 45.9, 49.5 to 51.5, and 56.7 to 58.4 ($\mu g/m^3$), respectively. This might be attributed to the fact that the ambient air had higher PM concentrations than the air supply filtered by a mechanical ventilation system in the metro train, and it infiltrated the carriage from the train cracks when the train started running on overground platforms (P2, P3, P4, and P5). The underground platforms in this experiment were equipped with fully enclosed platform screen doors (PSDs), and the train doors and PSDs were simultaneously opened and closed. After the doors were closed, all the external surroundings of the metro train were underground tunnels. Due to the lack of a mechanical ventilation system in the tunnel, the particles inside were more likely to accumulate and concentrate, leading to a much higher concentration than those on the platform and outdoors [19,24]. Due to restrictions in train operation safety, the measurement of ventilation in the tunnel was not conducted in this study. However, additional measurements of PM in the tunnel exhaust and the ambient environment on another platform were conducted. The results showed that the $PM_{2.5}$ concentration in the tunnel exhaust was much higher than that in the ambient environment (85.6 μg/m^3 in the tunnel and 27.8 μg/m^3 for the ambient). High PM concentrations in the tunnel could penetrate into the carriage after the doors were closed and the train started running at underground platforms [58], which might be responsible for an increase of in-carriage PM concentrations (P6, P7, P8, and P9).

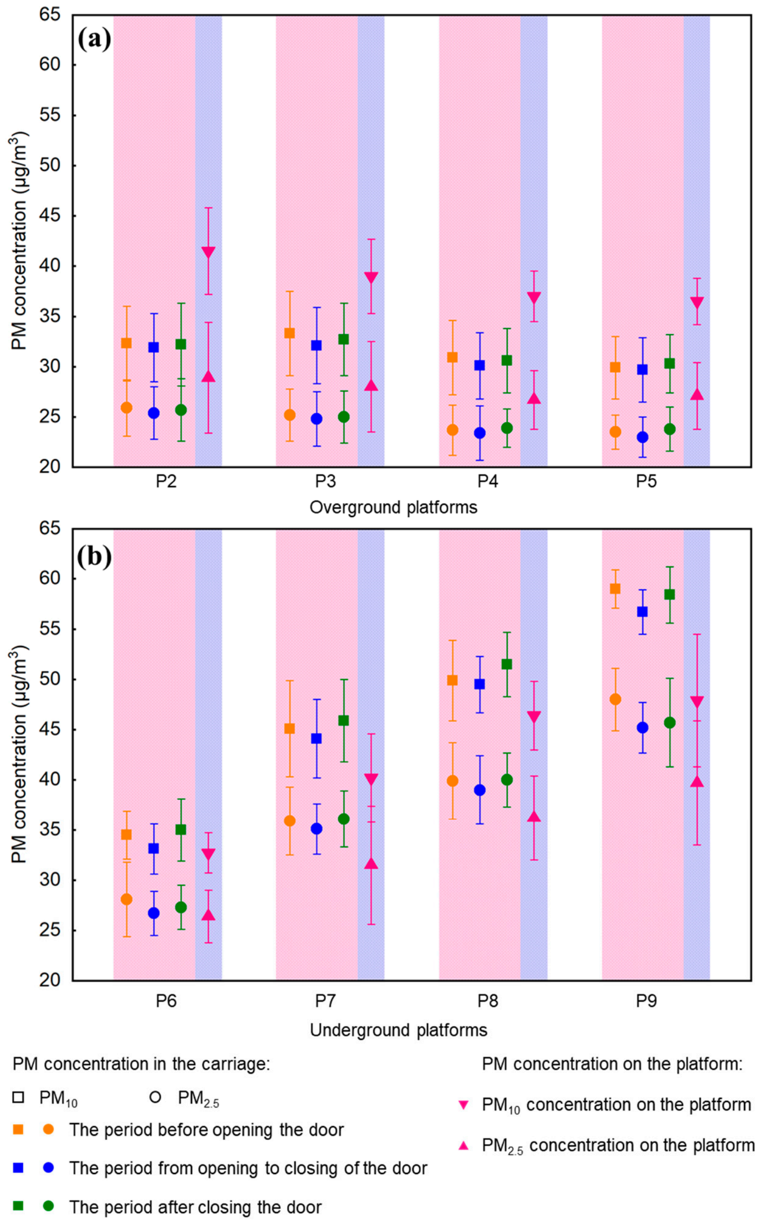

Figure 7. Variations of average PM concentrations in the metro carriage when the door was opened and closed on the platforms. (**a**) Overground platforms. (**b**) Underground platforms. The orange icons represent the average in-carriage PM concentrations for the period before the opening of the door. The blue icons represent the average in-carriage PM concentrations during the period from opening to closing of the door. The green icons represent the average in-carriage PM concentrations for the period after the closing of the door. Two pink triangles represent the PM concentrations on the platforms (one for PM_{10} and another for $PM_{2.5}$).

3.3. Inhalation Intake

$PM_{2.5}$ inhalation intakes ranged from 1.08 to 9.52, with a mean of 4.24 μg (Figure 8). There were significant $PM_{2.5}$ concentration differences between the different age groups ($p < 0.05$) and routes ($p < 0.05$). The average youth inhalation intake (6.77 μg) for males on Route d was the highest, and the average children inhalation intake (2.29 μg) for females on Route a was the lowest. The order of the inhalation intakes for different age groups with the same sex on each route was the same as the IR sequence, because the latter was the only variable. Although children and the elderly inhaled the lowest intakes of $PM_{2.5}$, they were more susceptible to pollution [20,57]; hence, more attention should be paid to the relationship between their inhalation intakes and health. For the passengers with the same age and sex on different days, the average inhaled $PM_{2.5}$ in the metro carriage in four routes followed the decreasing sequence: d > c > b > a. That the in-carriage $PM_{2.5}$ concentration on underground routes was higher than that on overground routes led to this sequence. The $PM_{2.5}$ concentration reached a peak in R8 on 9 of the 10 days selected for evaluation, and its commuting time period was the longest. Therefore, the metro operating agency should pay more attention to the routes such as R8 that caused high $PM_{2.5}$ inhalation intakes in the metro carriage. The PM_{10} inhalation intakes presented the same trend.

Exposure period, inhalation rate, and exposure concentration together result in the inhalation intake level [35,37,39]. For people with the same age and sex, using the data measured on May 19 as an example, the exposure period on Route c (686s) was longer than that of Route d (656s). Nevertheless, the latter inhalation intake of $PM_{2.5}$ was equal to the former. Additionally, the exposure period on Route d (656s) was less than that of Route a (698s), but the former inhalation intake of $PM_{2.5}$ was higher than the latter. The reason for this was that the average $PM_{2.5}$ concentration on Route d was higher than those of Routes a and c (Table A5). Moreover, the IR of middle-aged females (14.46 m^3/day) was less than that of elderly males (15.25 m^3/day), and the exposure duration on Route d was shorter than that of Route a. However, the inhalation intake of $PM_{2.5}$ for middle-aged females on Route d (6.04 μg) was higher than that of elderly males on Route a (5.95 μg), because the $PM_{2.5}$ concentration on Route d was higher. It is worth mentioning that the IR in this study might be underestimated sometimes, because the passengers in a metro carriage may stand during peak hours, and the commuting period might be longer than that in this study, indicating the IR would be larger and the exposure period would be longer under some real conditions. As a result, an inhalation intake evaluation of in-carriage $PM_{2.5}$ over a longer journey on different metro lines should be further explored in the future.

3.4. Reduction of In-Carriage PM Concentrations and Inhalation Intakes

According to Equation (2), the inhalation intake of in-carriage PM might decrease with the decrease in PM exposure concentration. PM in the subway tunnel would accumulate with the increase in time and enter the metro carriage through the ventilation system of the train [64]. In addition, outdoor air, platform depth, train speed and frequency, and the operation of the ventilation system also affected the air quality of the subway system. Based on the existing research, it can be found that the PM levels in the carriage are the result of an interaction of multiple factors [57]. Therefore, the treatment of in-carriage particulate matter needs systematic consideration, especially for the underground routes. There are some feasible recommendations. In the initial stage of the subway system project, the design of the platform and the tunnel should be fully considered, namely the installation of screen doors on the platform and the determination of the number and location of piston air shafts in the tunnel, which can enhance the mix of outdoor and tunnel air to decrease the air pollutant concentration in the tunnel. Regular maintenance of the rail during train operation is beneficial for slowing down the friction between rails and wheels so as to reduce the generation of particles. Cleaning the tunnel regularly helps to reduce the particles accumulated in the tunnel. For the ventilation system in the metro carriage, it is necessary to select an efficient filter screen and to regularly clean or replace it.

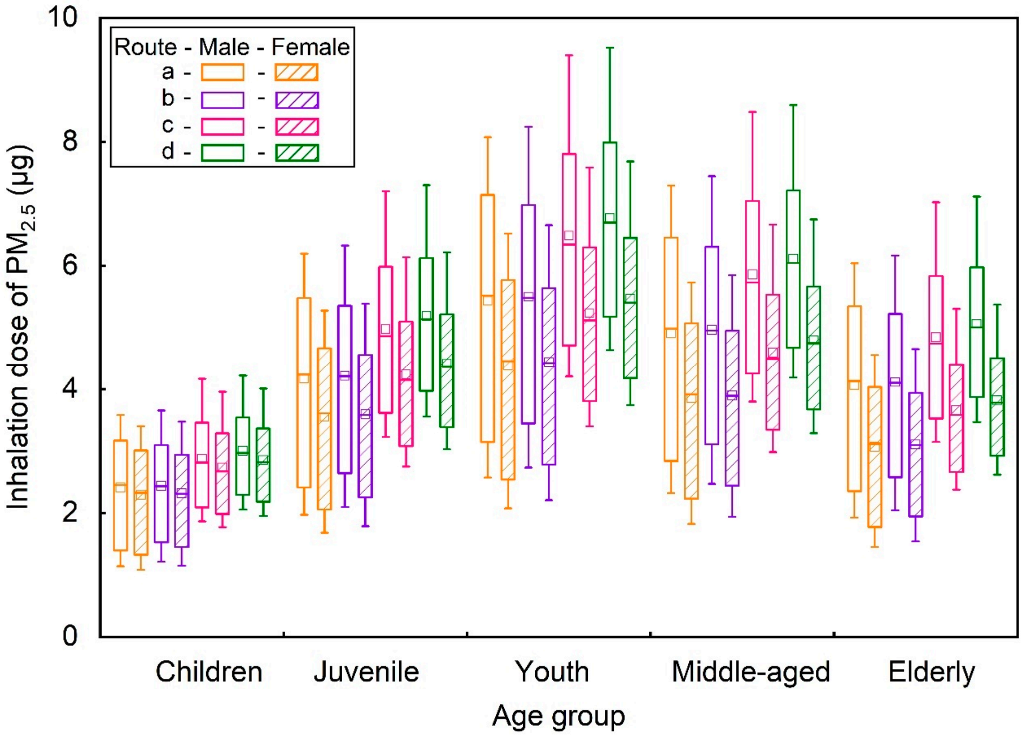

Figure 8. $PM_{2.5}$ inhalation intakes in the metro carriage. Data shown in the box plot are the minimum, maximum, the 1st and 3rd quartile, median (solid line), and arithmetic average values (square).

However, the concrete implementation of the above recommendations cannot be achieved immediately. The health effect of in-carriage PM is more directly related to inhalation intake. Therefore, decreasing the inhaled PM concentration might be an effective way to decrease the health risk, even in an environment with high pollutant concentrations. Wearing masks can filter the particulate matter to clean the inhaled air, especially when passing the underground routes, which might be the most direct and efficient way to reduce the inhalation intake of PM [65].

3.5. Limitations

There were some limitations in this study. In-carriage PM concentrations and PM concentrations on the platform were not measured concurrently due to the limits of the instruments and the experimental operator. However, the large space of the platforms can result in its PM concentrations being stable when the train door is opened. Therefore, the error caused by a non-simultaneous measurement could be acceptable. The selected IR values are physiological daily inhalation rates, which is the average level of the calculated values of healthy normal-weight individuals in a day, including the sleeping period and daytime activities (24 h). Voluntary and involuntary activities during the daytime were performed by individuals in the sitting or standing position, excluding walking. The IR in a sitting position might be higher than that in a sleeping period, but lower than in a standing position. Therefore, the IR values in Table A1 could reflect the IRs of passengers sitting in the metro carriage in this study to some extent, which might lead to some acceptable errors of the inhalation intake. In addition, the commuting period might be longer than that in this study as the urban environment develops. Therefore, more detailed inhalation intake evaluations should be conducted in the future.

4. Conclusions

In this study, the dynamic $PM_{2.5}$ and PM_{10} concentrations in the carriage of the Chengdu Metro Line were measured. The effects of the main influencing factors were explored, and the inhalation intakes for sex, age, and route differences were estimated. Based on these results, the following conclusions were drawn:

- The in-carriage $PM_{2.5}$ and PM_{10} concentrations were in the ranges of 11–74 μg/m^3 with a mean of 36.7 μg/m^3 and 13–89 μg/m^3 with a mean of 40.1 μg/m^3, respectively.
- The in-carriage PM concentrations increased when the metro train passed from the overground area to the underground area.
- Although PM concentrations in the carriage were higher than those on the overground platforms, in-carriage PM concentrations decreased after the door was opened.
- There was no significant correlation between the passenger number and the in-carriage PM concentrations.
- The inhalation intake of $PM_{2.5}$ on the route with more underground platforms was higher than that on the route with more overground platforms.
- In order to effectively reduce the $PM_{2.5}$ inhaled by passengers in the metro carriage, the metro operating agency should pay more attention to the routes causing high in-carriage PM concentrations and long commuting time periods.

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Appendix A

Table A1. Inhalation rates at different ages.

Sex	IR (m^3/day)				
	Children	Juvenile	Youth	Middle-Aged	Elderly
Male	9.04	15.64	20.39	18.41	15.25
Female	8.59	13.32	16.46	14.46	11.51

Table A2. Description of the four routes.

Routes	Included Platforms	Distance (km)	Number of Platforms	
			Overground	Underground
a	P1, P2, P3, P4 and P5	5.56	5	0
b	P3, P4, P5, P6 and P7	5.263	3	2
c	P4, P5, P6, P7 and P8	4.128	2	3
d	P6, P7, P8, P9 and P10	4.141	0	5

Table A3. Correlation coefficients of passenger number and PM in the metro carriage on some additional routes.

Routes	R10		R11		R12	
Factors	R	Sig.	R	Sig.	R	Sig.
$PM_{2.5}$	0.54	0.46	0.555	0.445	0.448	0.552
PM_{10}	0.636	0.364	0.685	0.315	0.642	0.358

R10 represents route 10; R11 represents route 11; R12 represents route 12.

Table A4. Average $PM_{2.5}$, PM_{10} concentrations (μg/m^3) and passenger number in the metro carriage on some additional routes.

Routes	R10			R11			R12		
Factors	$PM_{2.5}$	PM_{10}	Number	$PM_{2.5}$	PM_{10}	Number	$PM_{2.5}$	PM_{10}	Number
Measurement 1	46	49.3	43	48	51	51	48.5	51.3	48
Measurement 2	47.4	52.2	70	47.7	52.7	68	49.2	53.8	66
Measurement 3	51.9	58.1	66	53.9	62.1	69	53.3	58.8	67
Measurement 4	44.4	48.9	56	45.9	50	58	47.9	52.2	64

Table A5. $PM_{2.5}$ concentrations of four routes in metro carriage on May 19 (μg/m^3).

Pollutant	Route	Average	Median	Range
$PM_{2.5}$	a	48.3	48	43–55
	b	49.1	50	43–55
	c	52.7	52	45–62
	d	55.1	53	49–74

Table A6. Date of experiment and evaluation and corresponding ambient atmospheric PM concentrations.

Experiment and Estimation	Date	Ambient Atmospheric PM Concentrations (μg/m^3)	
		$PM_{2.5}$	PM_{10}
E1	4.20	23	41
	4.28	25	59
	4.29	25	55
	4.30	47	82
	5.1	50	79
	5.2	57	87
E2	5.15	13	24
	5.16	22	40
	5.18	26	39
	5.26	22	36
	6.4	20	48
	6.8	23	36
	6.11	30	47
	6.15	22	33
	6.16	16	23
	6.17	10	17
	6.18	19	35
	6.25	22	31
E3	5.31	43	68
	6.1	37	64
	6.2	37	61

Table A6. *Cont.*

Experiment and Estimation	Date	Ambient Atmospheric PM Concentrations (μg/m^3)	
		$PM_{2.5}$	PM_{10}
Estimation of inhalation intakes	4.20 *	23	41
	4.28 *	25	59
	4.29 *	25	55
	4.30 *	47	82
	5.1 *	50	79
	5.2 *	57	87
	5.8	44	66
	5.10	53	76
	5.18 *	26	39
	5.19	46	63

E1: The experiment of exploring the PM difference between the underground route and the overground route. E2: The experiment of exploring the influence of passenger number on the PM in the carriage. E3: The experiment of exploring the effect of door opening and closing on in-carriage PM concentrations. * Reused data.

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