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Comparisons of PM_{10}, $PM_{2.5}$, Particle Number, and CO_2 Levels inside Metro Trains Traveling in Underground Tunnels and on Elevated Tracks

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ABSTRACT

Commuters spend considerable time, in some cases up to 1–2 h a day, traveling in metro trains. However, few studies have compared air quality between trains traveling above-ground and underground. This study measures the PM_{10}, $PM_{2.5}$, particle number (PN) and CO_2 levels inside metro trains traveling in underground tunnels and on elevated tracks on a metro line in the Taipei metro system. The results demonstrated that PM_{10}, $PM_{2.5}$ and CO_2 levels inside metro trains traveling in underground environments are approximately 20–50% higher than those in above-ground environments. However, PN levels inside metro trains traveling in underground environments are approximately 20% lower than those in above-ground ones. These measurement results reveal that levels of pollutant species inside the metro trains are significantly affected by traveling environmental conditions—in underground tunnels or on elevated tracks. Moreover, the levels of pollutant species inside the metro trains traveling on the same route are also different in different traveling directions. Fine PM inside the metro trains is transferred from the outside and significantly influenced by the surrounding conditions of the trains. Additionally, a high fraction of large coarse PM (> 10 μm) is observed inside the metro trains, possibly due to re-suspension by the movement of commuters. The measurement results show that, unlike PM, which is transferred from outside environments, CO_2 inside metro trains is elevated internally by exhalation from commuters. Clearly, CO_2 exhaled by commuters could accumulate inside metro trains and, compared to PM, is not as easily removed by the ventilation system when air circulation does not provide enough fresh air in the metro trains, particularly in trains traveling in underground environments.

Keywords: Metro trains; Underground; Above-ground; PM_{10}; $PM_{2.5}$; Particle number; CO_2.

INTRODUCTION

Metro systems are a major transportation mode and typically serve billions of commuters annually in metropolitan areas worldwide. Commuters usually spend considerable time, in some cases up to 1–2 h a day, using a metro system. The issues related to commuter exposure to particulate matter (PM) inside the metro systems are very important. Because suspended PM is recognized to have a strong impact on health (Pope *et al*., 2004; Dominici *et al*., 2006). Exposure to fine PM is known to induce oxidative DNA damage in toxicological studies (Risom *et al*., 2005). Karlsson *et al*. (2005) also reported that, compared to street PM, metro PM is more genotoxic and induces oxidative stress in cultured human lung cells. The PM concentrations in metro systems whether on platforms or inside trains are generally higher compared to those in outdoor air (Nieuwenhuijsen *et al*., 2007). Levels of PM_{10}, $PM_{2.5}$ or particle number (PN) have been measured on platforms or inside trains in many metro systems, including those in London (Pfeifer *et al*., 1999; Sitzmann *et al*., 1999; Adams *et al*., 2001; Seaton *et al*., 2005), Berlin (Fromme *et al*., 1998), Tokyo (Furuya *et al*., 2001), Boston (Levy *et al*., 2002), Hong Kong (Chan *et al*., 2002a), Guangzhou (Chan *et al*., 2002b), Stockholm (Johansson and Johansson, 2003), New York (Chillrud *et al*., 2004), Helsinki (Aarnio *et al*., 2005, Asmi *et al*., 2009), Prague (Braniš, 2006), Rome (Ripanucci *et al*., 2006), Budapest (Salma *et al*., 2007), Beijing (Li *et al*., 2006; Li *et al*., 2007), Mexico (Gómez-Perales *et al*., 2007), Taipei (Cheng *et al*., 2008; Cheng *et al*., 2009; Cheng and Yan, 2011), Seoul (Kim *et al*., 2008; Park and Ha, 2008), Paris (Raut *et al*., 2009), and Los Angeles (Kam *et al*., 2011). The widely varying PM levels and their sources reported in the different metro systems throughout the world indicates that PM may originate from the outside atmosphere or may be generated internally in the underground portion of the metro system (Pfeifer *et al*., 1999; Sitzmann *et al*., 1999; Johansson and Johansson, 2003; Chillrud *et al*., 2004; Aarnio *et al*.,

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2005; Braniš, 2006; Ripanucci *et al*., 2006; Salma *et al*., 2007; Cheng *et al*, 2008; Kim *et al*., 2008; Salma *et al*., 2009; Cheng and Lin, 2010). Recently, Kam *et al*. (2011), Cheng and Yan (2011) and Wang and Gao (2011) demonstrate that PM levels in the ground-level metro stations are more strongly associated with ambient PM levels than those in the underground. Outdoor traffic exhaust is clearly a major source of PM in ground-level metro stations. However, the PM levels in the underground metro stations are still higher than those in the ground-level results from the generation or accumulation of PM in a confined space.

Regardless of whether it is measured on the above-ground or in the underground portion of a metro system, air quality inside metro trains is an important issue for commuters because of the considerable time they may spend traveling in metro trains each day. However, information related to the characteristics and differences of indoor air quality inside the metro trains in above-ground and underground environments in the metro system is limited. Therefore, the issues related to PM levels inside the metro trains in the metro system must be addressed. This study measures the PM_{10}, $PM_{2.5}$, PN, and CO_2 levels inside metro trains traveling in underground tunnels and on elevated tracks on a metro line in the Taipei metro system. The field measurement results were used to characterize the pollution levels and sources of PM_{10}, $PM_{2.5}$, PN and CO_2 inside the metro trains, and compare the differences of PM_{10}, $PM_{2.5}$, PN, and CO_2 levels inside metro trains between traveling in underground tunnels and on elevated tracks. Analysis of mass size distribution was used to characterize airborne PM inside the metro trains.

MATERIAL AND METHODS

Sampling Location

Fig. 1 presents a map of the Taipei metropolitan area and the Taipei metro system. As of 2010, the Taipei metro system comprised eight metro lines stretching 90.5 km (50% underground), linking 82 stations (63% underground). Currently, over 1.4 million commuters travel on the Taipei metro system each day. In this study, two routes were selected as subjects on a high-capacity metro line (Table 1). This metro line, which was the first high-capacity line in the Taipei metro system, began operating on March 28, 1997. On these two selected routes, trains travel in underground tunnels between the Taipei main (T) station and the Minquan W. Rd. (M) station (R1; approximately 1.73 km) and travel on elevated tracks between the Minquan W. Rd. (M) station and the Jiantan (J) station (R2; approximately 2.54 km). Station M is the connecting station between these two routes, and it is a ground station in which the ticket hall and the platform are on the ground floor (1F) and the first basement floor (B1), respectively. The tracks are elevated from underground to above-ground after trains depart from M station at a distance approximately 100 m in M to J direction. A train running on this high-capacity line links six electric–powered passenger cars which are equipped with electrical regenerative braking systems. Each passenger car is about 23.5 m long, 3.2 m wide and 3.6 m high, and has four doors on each side. Each passenger car can carry up to 180 passengers under dense, crushed conditions. In this study, the monitoring location was the third or fourth passenger car of the metro trains to keep the same sampling condition.

Sampling Equipment

A Grimm Series 1.108 OPC (Grimm Tech., Inc., Douglasville, GA, USA) was used to measure the levels of the PM_{10}, $PM_{2.5}$ and particle mass size distributions on the metro trains. At the same time, a TSI Model 3007 CPC (TSI Inc., Shoreview, MN, USA) was used to measure PN levels, and a TSI Model 7565 Q-Trak (TSI Inc., Shoreview, MN, USA) was used to measure the indoor air quality parameters, including CO_2 levels, temperatures, and relative humidity.

The Grimm OPC measures particle mass concentrations according to an optical size of 0.23–20 μm in 15 different size ranges. The Grimm OPC has a sensitivity of 1 $\mu g/m^3$ with a reproducibility of ± 2% and its range for the measurement of concentration is 1–100000 $\mu g/m^3$. The responses of the Grimm OPC may depend on the refractive index, and the shape, density and size of particles in different environments. However, the Grimm OPC provides good temporal resolution of particle mass size distribution. In previous studies, PM measurement results obtained by a Grimm OPC approximated (± 15%) those of a reference sampler at urban sites (Chan *et al*., 2004; Giugliano *et al*., 2005; Grimm and Eatough, 2009; Cheng and Li, 2010; Hansen *et al*. 2010; Cheng *et al*., 2011). In this study, the measured particle mass size distribution was determined using DistFit software (Chimera Tech., Inc., Forest Lake, MN, USA), and the PM_{10} and $PM_{2.5}$ levels were calculated as fractions of particle mass size distribution (Cheng and Lin, 2010). Additionally, the TSI 3007 CPC measured particles 0.01 to > 1.0 μm, with a maximum concentration detection limit of 10^5 particles/cm^3, and a 50% size detection threshold of 0.01 μm. According to the manufacturer, the accuracy of concentration readings for up to 10^5 particles/cm^3 is ± 20%. Hämeri *et al*. (2002) suggested that coincidental loss of the TSI 3007 CPC would be serious at concentrations up to 4 × 10^5 particles/cm^3 and measurements must be corrected. Nevertheless, this CPC is portable and convenient for the measurements of environmental particle numbers in the field. The TSI Model 7565 Q-Trak measures CO_2 from 0–5,000 ppm at ± 3% of the reading using a NDIR sensor. In this study, the sensor was calibrated using zero gas and 3000 ppm CO_2 standard gas before each sampling to avoid the measurements of CO_2 levels drifted.

Table 1. Features of selected routes.

Selected route	Traveling distance	Traveling time	Track
Route 1: T Station ↔ M Station	1.73 km	4.5 min	Underground
Route 2: M Station ↔ J Station	2.54 km	4.2 min	Above-ground

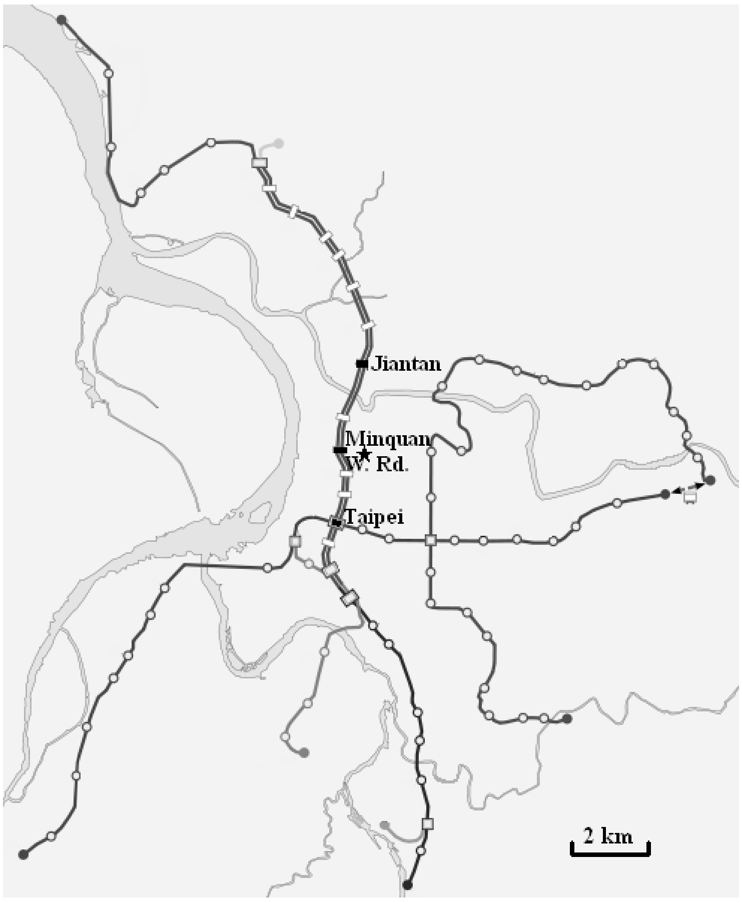

Fig. 1. Map of the Taipei metropolitan area showing the Taipei metro system and the selected routes. The Zhongshan ambient air-quality monitoring station is represented by the asterisk.

Data Collection

The PM_{10}, $PM_{2.5}$, PN, and CO_2 levels inside the metro trains were measured by a subject carrying monitors in a backpack. The Tygon tube was used to connect the inlet and instrument, and the air sampling tube between the inlet and instrument was shorter than 0.2 m for the Grimm OPC to reduce particles deposited on the sampling tube. All air samples were collected roughly 1.5 m above the car floor and measured inside the metro trains on selected routes. The logging interval for all measurements was set at 1 min. The measurements were taken between 06:00 and 24:00 on weekdays and weekends from August 20 to November 12, 2010. Monitoring was performed 80 times on each route. Measurements were taken by a subject who boarded a train traveling from T station to M station on R1 and then transferred to another train traveling from M station to J station on R2. In the opposite direction, measurements were taken by the subject who traveled back to T station from J station in one hour on the same day. That is, the monitoring was completed in two hours at each sampling section. Additionally, the measurements were not performed in the same order to avoid sampling bias. The number of commuters in the monitored car was recorded at each monitoring session. The outdoor PM_{10}, $PM_{2.5}$, PN and CO_2 levels at the T, M and J metro stations were measured approximately 15 min at each sampling time and were considered as the corresponding levels in the outdoor ambient. The measurement results of the outdoor PM_{10} and $PM_{2.5}$ levels of the metro stations were compared with those measured by the ambient air-quality monitoring station at Zhongshan station which is near the M station (Fig. 1).

An independent sample t-test was performed to measure differences in PM (or CO_2) levels between the selected routes. A significance level of 0.05 was used for all statistical tests. The Pearson product moment correlation coefficient ($R_{Pearson}$) was also applied to determine the strength of correlations between commuter number and CO_2 levels inside the metro trains.

RESULTS AND DISCUSSION

Comparison of PM_{10} and $PM_{2.5}$ Levels inside Metro Trains under Different Environmental Conditions

Table 2 presents the PM_{10} and $PM_{2.5}$ levels inside metro trains on selected routes. Measurement results show that the PM_{10} and $PM_{2.5}$ levels inside the metro trains on R1 (in underground tunnels) were significantly higher than those on R2 (on elevated tracks) (all $p < 0.001$). It is clear that PM_{10} and $PM_{2.5}$ levels inside the metro trains in underground tunnels were greater than those on elevated tracks approximately 1.4–1.5 times. Kam *et al*. (2011) also demonstrated that PM_{10} and $PM_{2.5}$ levels inside metro trains in above-ground environments were lower than those in underground environments even those measured in different metro lines.

Figs. 2(a)–(d) shows PM_{10} and $PM_{2.5}$ levels, and the indoor/outdoor ratios of PM_{10} and $PM_{2.5}$ inside the metro trains traveling in different directions on selected routes. It is interesting to note that the highest PM_{10} and $PM_{2.5}$ levels inside the metro trains were observed on R1 when trains

Table 2. Levels of PM_{10} and $PM_{2.5}$ inside metro trains on selected routes.

Environment	PM_{10}, μg/m^3			$PM_{2.5}$, μg/m^3		
	Mean	S.D.[a]	Range[b]	Mean	S.D.	Range
Underground (R1)	37	10	13–58	28	8	11–48
Above-ground (R2)	25	12	6–58	19	11	3–47

a: Standard deviation
b: Minimal value–maximal value

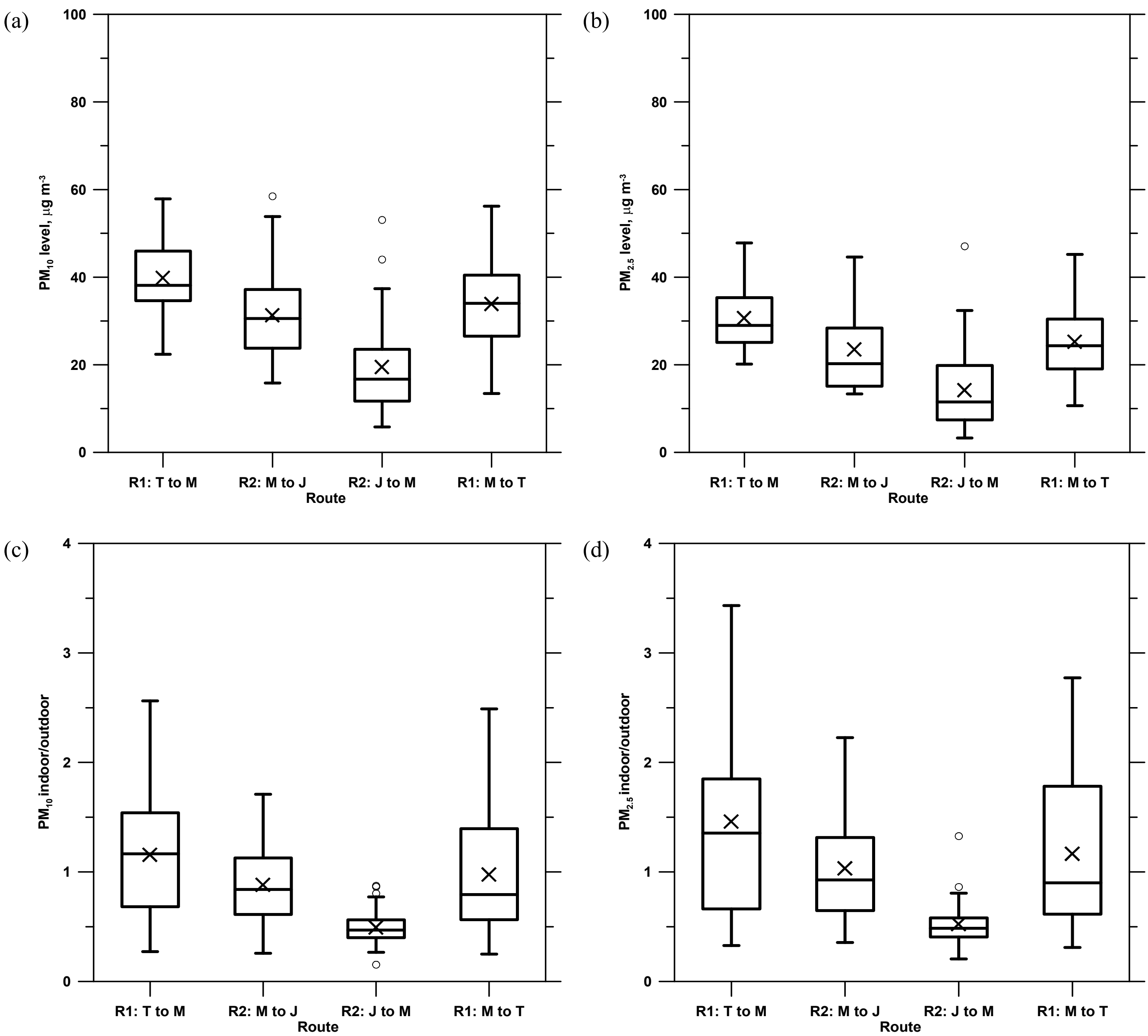

Fig. 2. Levels of PM and indoor/outdoor ratios of PM inside metro trains traveling in different directions on selected routes (a) PM_{10} levels (b) $PM_{2.5}$ levels (c) indoor/outdoor ratios of PM_{10}, and (d) indoor/outdoor ratios of $PM_{2.5}$. The central box comprises values between the 25th and 75th percentiles, and whiskers show the range of values falling within 1.5 times the inter-quartile range beyond the box. The solid line and cross symbol within the box mark the median and mean, respectively. Open circular symbols show outliers defined as data points beyond the inner fence.

traveling from T station to M station (underground) and the lowest PM_{10} and $PM_{2.5}$ levels inside the metro trains were observed on R2 while trains traveling from J station to M station (above-ground). These measurement results indicate that PM_{10} and $PM_{2.5}$ levels inside the metro trains were significantly affected by the surrounding conditions of the trains traveling, such as on the underground platforms, in underground tunnels, and on elevated tracks. The PM inside the trains could be transferred from platforms through open gate doors that allow commuters to board trains or alight from trains. Additionally, the PM_{10} and $PM_{2.5}$ levels inside the metro trains traveling on the same route were also different in different traveling direction (Fig. 2). For example, PM_{10} and $PM_{2.5}$ levels inside the metro trains on R2 when trains traveling from M station to J station were higher than those on R2 in the opposite direction from J station to M station because trains which just traveled from underground environments in M to J direction have higher PM_{10} and $PM_{2.5}$ levels compared to trains which only traveled on above-ground environments in the opposite direction. Similar results were observed on R1. Cheng and Yan (2011) suggested that PM levels on underground platforms were significantly higher than those on above-ground platforms. According to the measurement results of Cheng and Yan (2011), that is why the PM levels inside the metro trains in underground environments were higher than those in above-ground environments.

The mean PM_{10} and $PM_{2.5}$ levels at outdoor of the T, M, and J metro stations were approximately 42–46 $\mu g/m^3$ and 28–31 $\mu g/m^3$, respectively, during the sampling period. The PM levels at outdoor among these three metro stations were not significantly different (all $p \geq 0.668$ for PM_{10} and all $p \geq 0.560$ for $PM_{2.5}$) and were strongly positively correlated (all $R_{Pearson} \geq 0.803$ and $p < 0.001$ for PM_{10} and all $R_{Pearson} \geq 0.822$ and $p < 0.001$ for $PM_{2.5}$), suggesting that variations in PM levels in outdoor environments were similar among these three metro stations. Compared with PM_{10} and $PM_{2.5}$ levels measured at Zhongshan monitoring station near the M station, both PM_{10} and $PM_{2.5}$ levels between outdoor of the M station and the Zhongshan monitoring station also did not differ significantly ($p = 0.258$ for PM_{10} and $p = 0.730$ for $PM_{2.5}$), indicating that the measurement results of the Grimm OPC were reliable for this study. Additionally, measurement results show that levels of PM_{10} and $PM_{2.5}$ inside metro trains in above-ground environments were lower than those in outdoor air, particularly on R2 when trains traveling from J station to M station, but levels of PM_{10} and $PM_{2.5}$ inside metro trains in underground environments were higher than those in outdoor air, particularly on R1 while trains traveling from T station to M station.

Table 3 presents the PM_{10} and $PM_{2.5}$ levels inside the metro trains for different metro systems worldwide. It is worth noting here that PM_{10} and $PM_{2.5}$ levels inside the metro trains in the Taipei metro system are lower than those measured in London (Adams *et al*., 2001; Seaton *et al*., 2005), Berlin (Fromme *et al*., 1998), Beijing (Li *et al*., 2006; Li *et al*., 2007) and Seoul (Kim *et al*., 2008; Park and Ha, 2008), and similar to those measured in Helsinki (Aarnio *et al*., 2005; Asmi *et al*., 2009) and Los Angeles (Kam *et al*., 2011). However, PM_{10} and $PM_{2.5}$ levels measured inside the metro trains in these metro systems vary widely according to monitoring conditions such as the time, place, or season of the measurements, the measurement equipment used, and the outdoor climate (Kim *et al*., 2008). High levels of PM could be observed in underground environments resulting from the generation or accumulation of PM in a confined space, particularly in old subway systems (Nieuwenhuijsen *et al*., 2007). Cheng *et al*. (2008) demonstrated that mean PM_{10} and $PM_{2.5}$ levels inside the metro trains in the Taipei metro system were approximately 41 $\mu g/m^3$, and 35 $\mu g/m^3$, respectively, during Oct.–Dec., 2007. Compared with those acquired by Cheng *et al*. (2008), mean PM_{10} and $PM_{2.5}$ levels inside the metro trains in this study during Aug.–Nov., 2010 were approximately 30–40% lower than those acquired by Cheng *et al*. (2008). Fang and Chang (2010) and Chang *et al*. (2010) demonstrated that atmospheric PM_{10} and $PM_{2.5}$ levels in winter season were significantly higher than those in autumn season approximately 1.2–1.3 times in the Taipei metropolitan area. According to measurement results of Fang and Chang (2010) and Chang *et al*. (2010), variations in PM_{10} and $PM_{2.5}$ levels inside the metro trains in different seasons could be significantly influenced by outdoor ambient PM_{10} and $PM_{2.5}$ levels.

Comparison of Particle Mass Size Distributions and $PM_{2.5}$-to-PM_{10} Ratios inside Metro Trains under Different Environmental Conditions

Particle size distributions inside metro trains are also seldom reported. Fig. 3 shows the average particle mass size distributions measured inside metro trains traveling in different directions. Here, the measured particle mass size distribution was determined using DistFit software. Fine PM modes measured inside the metro trains on selected routes remained consistent except that on R2 when trains traveling from J station to M station. The fine PM mode measured inside the metro trains on R2 while trains traveling from J station to M station was smaller than those on R1, and similar to that measured in outdoor ambient. Cheng and Yan (2011) demonstrated that the fine PM mode of the particle size distribution measured on the underground platform was approximately 0.45 µm and larger than those in outdoor ambient. Compared with measurement results reported by Cheng and Yan (2011), the fine PM mode measured inside the metro trains on R1 was similar to those acquired by Cheng and Yan (2011) on the underground platform. The measurement results indicate that fine PM inside the metro trains was transferred from outside and associated with their surrounding conditions of the trains. Furthermore, the particle size distribution in outdoor ambient was similar to those measured by Morawska *et al*. (1999) and Cheng and Li (2010). Morawska *et al*. (1999) and Cheng and Li (2010) demonstrated particle size distribution with a bimodal distribution pattern in outdoor environments, showing a dominant mode at approximately 0.3 µm and a minor mode at approximately 3.5 µm near the source of traffic. Fine and coarse PM could be attributed primarily to traffic emissions and the re-suspension of road dust by

Table 3. Range and mean PM_{10} and $PM_{2.5}$ levels inside the metro trains for different metro systems worldwide.

City	PM level (μg/m³)		Reference
	Range	Mean	
PM_{10}			
Beijing	–	250	Li *et al*. (2007)
Beijing	36–373	108	Li *et al*. (2006)
Berlin	–	147	Fromme *et al*. (1998)
Guangzhou	26–123	67	Chan *et al*. (2002b)
Hong Kong	23–85	44	Chan *et al*. (2002a)
Los Angeles	6–107	24	Kam *et al*. (2011)
Prague	24–218	114	Braniš (2006)
Seoul		144	Park and Ha (2008)
Seoul	287–356	312	Kim *et al*. (2008)
Taipei	–	65	Tsai *et al*. (2008)
Taipei	10–97	41	Cheng *et al*. (2008)
Taipei	6–58	31	Current study
$PM_{2.5}$			
Beijing	–	86	Li *et al*. (2007)
Beijing	13–111	37	Li *et al*. (2006)
Boston	36–104	65	Levy *et al*. (2002)
Guangzhou	–	44	Chan *et al*. (2002b)
Helsinki	–	14	Asmi *et al*. (2009)
Helsinki	17–26	21	Aarnio *et al*. (2005)
Hong Kong	21–48	33	Chan *et al*. (2002a)
Los Angeles	3–62	19	Kam *et al*. (2011)
London	12–371	228	Adams *et al*. (2001)
London	130–200	170	Seaton *et al*. (2005)
Mexico	8–68	–	Gómez-Perales *et al*. (2007)
New York	34–44	40	Wang and Gao (2011)
New York	–	62	Chillrud *et al*. (2004)
Seoul	–	118	Park and Ha (2008)
Seoul	115–136	126	Kim *et al*. (2008)
Sydney	–	36	Knibbs and de Dear (2010)
Taipei	–	35	Tsai *et al*. (2008)
Taipei	8–68	35	Cheng *et al*. (2008)
Taipei	3–48	24	Current study

traffic, respectively. Compared with measurement results reported by Morawska *et al*. (1999) and Cheng and Li (2010), a high portion of large coarse PM (> 10 μm) is observed inside metro trains. One possibility is that large coarse PM (> 10 μm) inside the metro trains could be attributed from the re-suspended again and again by the movement of commuters when commuters boarding trains or alighting from trains. These re-suspended particles from cabin floor could be aggregated to become large particles. That is, the coarse mode of particle mass size distribution inside the metro trains was larger than those at outdoor.

Fig. 4 shows the ratios of $PM_{2.5}$-to-PM_{10} inside metro trains traveling in different directions on selected routes. Based on measurement results, the mean ratios of $PM_{2.5}$-to-PM_{10} inside the metro trains and in outdoor ambient were approximately 0.69–0.77 and 0.64–0.66, respectively. The ratios of $PM_{2.5}$-to-PM_{10} ratios inside metro trains on R2 were smaller than those on R1, particularly on R2 when trains traveling from J station to M station. Furthermore, the ratios of $PM_{2.5}$-to-PM_{10} inside metro trains on R2 when trains traveling from J station to M station were similar to those in outdoor ambient. According to the measurement results, the sources of PM inside the metro trains could be directly affected by the surrounding conditions of the trains. Chan *et al*. (2002a) noted that the $PM_{2.5}$-to-PM_{10} ratios inside the trains were approximately 0.72 in the Hong Kong mass transit railway system. Li *et al*. (2007) presented that $PM_{2.5}$-to-PM_{10} ratios inside the trains were approximately 0.34 in above-ground environments in the Beijing railway transit system. A study of the Seoul subway system by Park and Ha (2008) demonstrated $PM_{2.5}$-to-PM_{10} ratios of 0.87 and 0.80 inside trains in ground-level environments and underground environments, respectively. However, Kim *et al*. (2008) noted that $PM_{2.5}$-to-PM_{10} ratios inside trains in the Seoul subway system were only 0.40. Moreover, Kam *et al*. (2011) demonstrated that the $PM_{2.5}$-to-PM_{10} ratios inside trains in ground-level environments and underground environments in Los Angeles Metro were 0.86 and 0.79, respectively. A remarkable variation in results was observed in previous studies. The different results may have resulted from different environmental conditions at the time and the place of measurement.

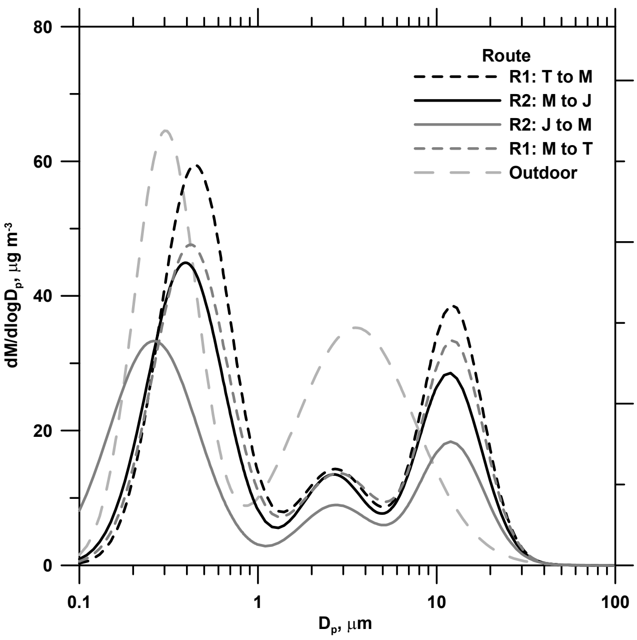

Fig. 3. Average particle mass size distributions measured inside metro trains traveling in different directions on selected routes.

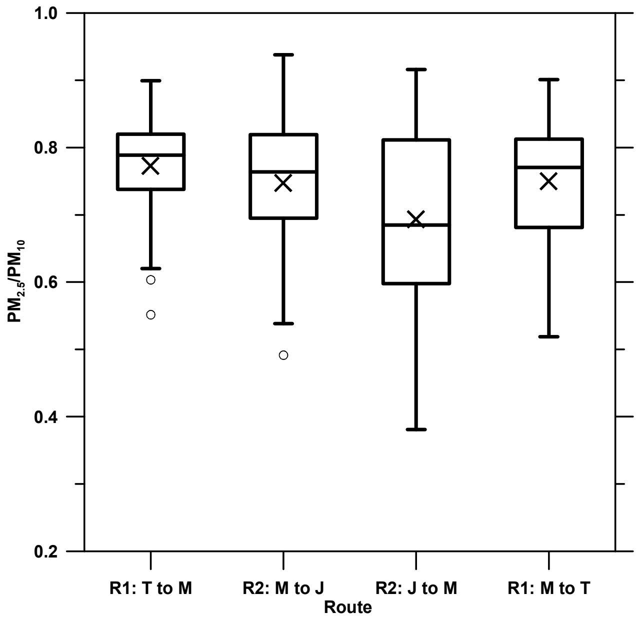

Fig. 4. Ratios of $PM_{2.5}$-to-PM_{10} inside metro trains traveling in different directions on selected routes. The central box comprises values between the 25th and 75th percentiles, and whiskers show the range of values falling within 1.5 times the inter-quartile range beyond the box. The solid line and cross symbol within the box mark the median and mean, respectively. Open circular symbols show outliers defined as data points beyond the inner fence.

Comparison of PN Levels inside Metro Trains under Different Environmental Conditions

Table 4 presents the PN levels inside metro trains on selected routes. PN levels inside the metro trains on R1 were significantly lower than those on R2 ($p < 0.001$). The mean PN levels at outdoor of the T, M, and J metro stations were approximately 3.6×10^4–3.8×10^4 particles/cm^3 during the sampling period. The PN levels at outdoor among these three metro stations were not significantly different (all $p \geq 0.351$). However, the PN levels at outdoor among these three metro stations were less strongly correlated (all $R_{Pearson} \leq 0.480$), suggesting that PN levels were presumably influenced by local traffic and microclimatic conditions. In contrast with the measurement results of the outdoor PN levels, the PN levels inside metro trains were approximately 70% lower than those in outdoor air, particularly in trains traveling in underground environments. Figs. 5(a)–(b) shows PN levels and the indoor/outdoor ratios of PN inside metro trains traveling in different directions on selected routes. Measurement results reveal that the highest PN levels inside the metro trains were observed on R2 when trains traveling from J station to M station and that the lowest PN levels were observed on R1 while trains traveling from T station to M station. The mean indoor/outdoor ratios of PN inside metro trains were approximately 0.24–0.31 and 0.33–0.37 on R1 and R2, respectively. These measurement results indicate that PN levels inside the metro trains were also significantly affected by traveling environmental conditions––in underground tunnels or on elevated tracks. According the measurement results, the PN levels inside metro trains depended on the outdoor ambient PN levels since they were significantly higher in trains travel on above-ground tracks than in those travel in underground tunnels. Moreover, the low PN levels inside the metro trains could be due to the ventilation system effectively filtered out particles in a microenvironment.

Few studies have measured PN levels inside metro trains. Table 5 presents the PN levels inside the metro trains for different metro systems worldwide. Levy *et al*. (2002) reported a mean PN level of approximately 2.2×10^4 particles/cm^3 inside Boston subway trains. Aarnio *et al.* (2005) noted that the average PN level inside the trains in the Helsinki subway system was 2.7×10^4 particles/cm^3. Seaton *et al*. (2005) reported average PN levels of 1.7×10^4–2.3×10^4 particles/cm^3 inside trains in the London

Table 4. Levels of PN inside metro trains on selected routes.

Environment	PN, particles/cm^3		
	Mean	S.D.[a]	Range[b]
Underground (R1)	1.0×10^4	3.5×10^3	5.3×10^3–2.1×10^4
Above-ground (R2)	1.3×10^4	4.3×10^3	6.0×10^3–2.4×10^4

a: Standard deviation

b: Minimal value–maximal value

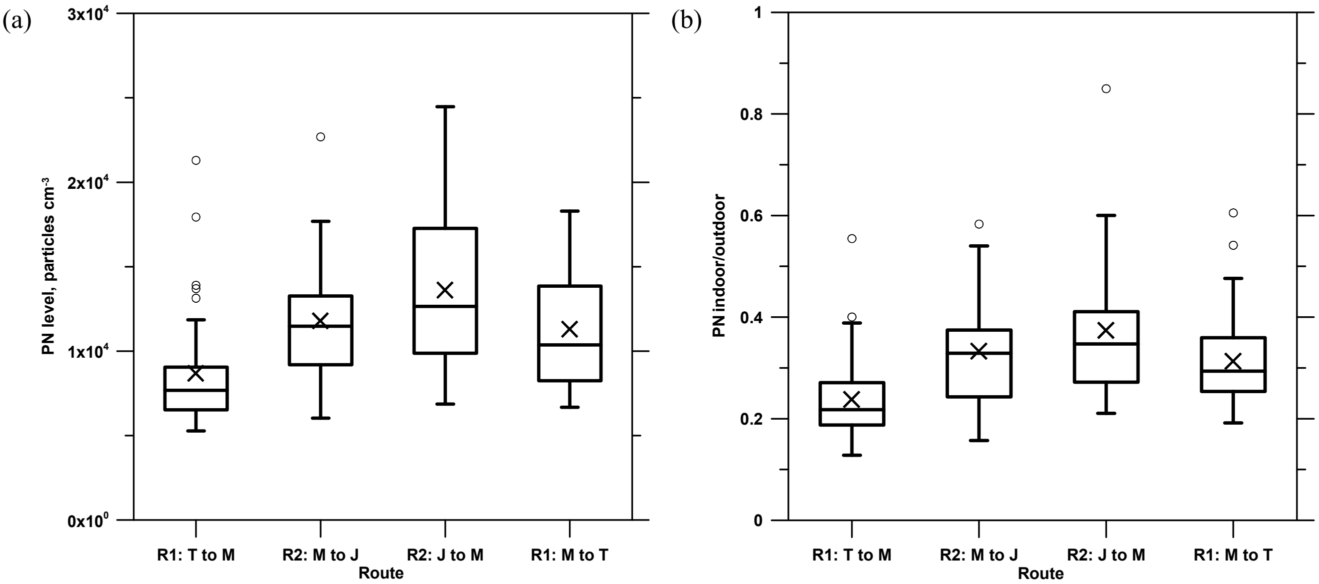

Fig. 5. (a) PN levels and (b) indoor/outdoor ratios of PN inside metro trains traveling in different directions on selected routes. The central box comprises values between the 25th and 75th percentiles, and whiskers show the range of values falling within 1.5 times the inter-quartile range beyond the box. The solid line and cross symbol within the box mark the median and mean, respectively. Open circular symbols show outliers defined as data points beyond the inner fence.

Table 5. Range and mean PN levels inside the metro trains for different metro systems worldwide.

City	PN, particles/cm^3		Reference
	Range	Mean	
Boston[a]	1.3×10^4–3.6×10^4	2.2×10^4	Levy *et al*. (2002)
Helsinki[a]	1.4×10^4–3.4×10^4	2.7×10^4	Aarnio *et al*. (2005)
Helsinki[b]	–	1.6×10^4	Asmi *et al*. (2009)
London[a]	1.7×10^4–2.3×10^4	2.1×10^4	Seaton *et al*. (2005)
New York[c]	1.6×10^4–1.9×10^4	1.7×10^4	Wang and Gao (2011)
Sydney[b]	–	4.6×10^4	Knibbs and de Dear (2010)
Taipei[a]	3.8×10^3–2.8×10^4	1.1×10^4	Cheng *et al*. (2009)
Taipei[b]	5.3×10^3–2.4×10^4	1.2×10^4	Current study

a: Size range: 20 nm–1000 nm
b: Size range: 10 nm–1000 nm
c: Size range: 5 nm–3000 nm.

underground, which were approximately 30–60% lower than those in outdoor environments. Wang and Gao (2011) demonstrated that PN levels inside the trains in the New York subway were 1.7×10^4 particles/cm^3, noting that PN levels inside trains were lowest comparing with other transportation environments. Based on these measurement results, the levels of PN inside metro trains are usually lower than those in outdoor air.

Comparison of CO_2 Levels inside Metro Trains under Different Environmental Conditions

During the sampling period, outdoor temperature was 18–35°C (mean = 28°C), and relative humidity was 51–89% (mean = 71%). The temperature inside the metro trains was 10–15% lower than that in outdoor, and the relative humidity inside the metro trains was 10–20% lower than that in outdoor. Table 6 presents the levels of CO_2 inside metro trains on selected routes. The CO_2 levels inside the metro trains were approximately 1200 ppm in the Taipei metro system. The CO_2 levels inside the metro trains on R1 were significantly higher than those on R2 approximately 20% ($p = 0.013$). The mean CO_2 levels in outdoor environments were 440–450 ppm, and CO_2 levels among these outdoor environments were not significantly different (all $p \geq 0.178$). The CO_2 levels inside the metro trains were approximately 2.7 times higher than those in outdoor environments.

Table 6. Levels of CO_2 inside the metro trains on selected routes.

Environment	CO_2, ppm		
	Mean	S.D.[a]	Range[b]
Underground (R1)	1267	384	634–2282
Above-ground (R2)	1131	394	512–2298

a: Standard deviation
b: Minimal value–maximal value

Regardless of whether it is measured on R1 or R2, CO_2 levels inside metro trains exceeded the limits proposed by the Taiwan EPA (an average of 1000 ppm of 8 h) in December, 2005, indicating that CO_2 levels had accumulated inside the metro trains due to poor ventilation. High CO_2 levels have also been measured in other metro systems. For example, Park and Ha (2008) reported CO_2 levels of 1800 ppm inside Seoul subway trains, and Kam *et al*. (2011) reported CO_2 levels as high as 1200 ppm inside Los Angeles Metro trains, which was 3–4 times higher than ambient CO_2 levels. Li *et al*. (2006) noted that CO_2 levels inside the trains on the ground railway in Beijing were 1110 and 1270 ppm in summer and winter, respectively.

Figs. 6(a)–(b) shows CO_2 levels and the indoor/outdoor ratios of CO_2 inside the metro trains traveling in different directions on selected routes. Measurement results reveal that the highest CO_2 levels inside the metro trains were on R1 when trains traveling from T station to M station and that the lowest CO_2 levels inside the metro trains were on R2 while trains traveling from J station to M station. Additionally, the CO_2 levels inside the metro trains traveling from T station (underground) to J station (above-ground) were significantly higher than those in the opposite direction approximately 1.4 times ($p < 0.001$). Additionally, the mean indoor/outdoor ratios of CO_2 inside the metro trains were 3.1–3.3 when trains traveling from T station (underground) to J station (above-ground) and 2.0–2.5 while trains traveling in the opposite direction. These measurement results indicate that CO_2 levels inside the metro trains were also significantly influenced by the traveling environmental conditions.

Fig. 7 shows the relationships between commuter number and CO_2 levels inside metro trains traveling in different directions on selected routes. Measurement results show a significant positive relationship between commuter number and CO_2 level inside the metro trains (all $R_{Pearson} \geq 0.77$ and $p < 0.001$). Each commuter could elevate approximately 6–9 ppm of the CO_2 level inside trains. Huang and Hsu (2009) similarly demonstrated that CO_2 levels inside buses correlated positively with the number of passengers. Li *et al*. (2006) also suggested that CO_2 levels inside the trains were significantly positively correlated with the number of passengers. Clearly, CO_2 exhaled by commuters can accumulate inside metro trains with poorly performing air ventilation systems.

Real-Time Variations in PM_{10}, $PM_{2.5}$, PN and CO_2 Levels inside Metro Trains

Figs. 8(a)–(b) shows the real-time variations in PM_{10}, $PM_{2.5}$, PN and CO_2 levels inside metro trains traveling on R1 and R2. The real-time PM_{10}, $PM_{2.5}$, PN and CO_2 levels were measured simultaneously for a selected sampling session. Figs. 8(a)–(b) shows how these concentrations differed for a commuter stepping from a platform to a train, for a commuter riding inside a train, and for a commuter stepping out of a train and onto a platform. Measurement results show similar variations in PM_{10}, $PM_{2.5}$, PN and CO_2 levels inside the metro trains on R1 and R2. A train arriving at a platform could disturb PM_{10}, $PM_{2.5}$ and PN levels by re-suspension of PM as commuters walk in and out the train and as train moves on the platform. After the commuter boarded the train, PM_{10} and $PM_{2.5}$ levels declined gradually, and PN levels declined instantly inside the train. These measurement results reveal that PM_{10}, $PM_{2.5}$ and PN levels inside the metro train were lower than those on the station platform because the ventilation system effectively filtered out particulate matter in a microenvironment. An important observation is a large increase in the CO_2 level inside the train and a rapid drop in the CO_2 level as the

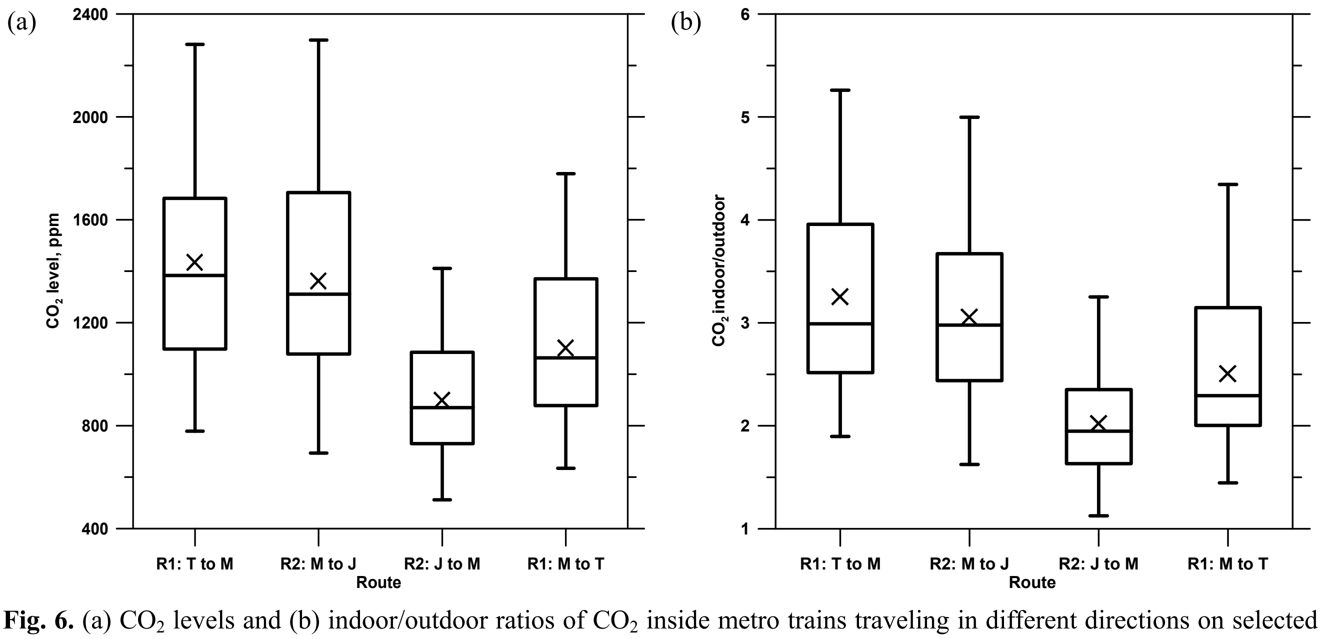

Fig. 6. (a) CO_2 levels and (b) indoor/outdoor ratios of CO_2 inside metro trains traveling in different directions on selected routes. The central box comprises values between the 25th and 75th percentiles, and whiskers show the range of values falling within 1.5 times the inter-quartile range beyond the box. The solid line and cross symbol within the box mark the median and mean, respectively. Open circular symbols show outliers defined as data points beyond the inner fence.

commuter steps out of the train. The measurement results confirm that the CO_2 levels inside the metro train exceeded those on the station platform. Similar results were obtained by Kam *et al*. (2011) in a study of the Los Angeles Metro. These measurement results confirm that CO_2 levels were elevated by the exhalation of commuters and could accumulate inside the metro trains when air was re-circulating without enough fresh air inside the metro trains.

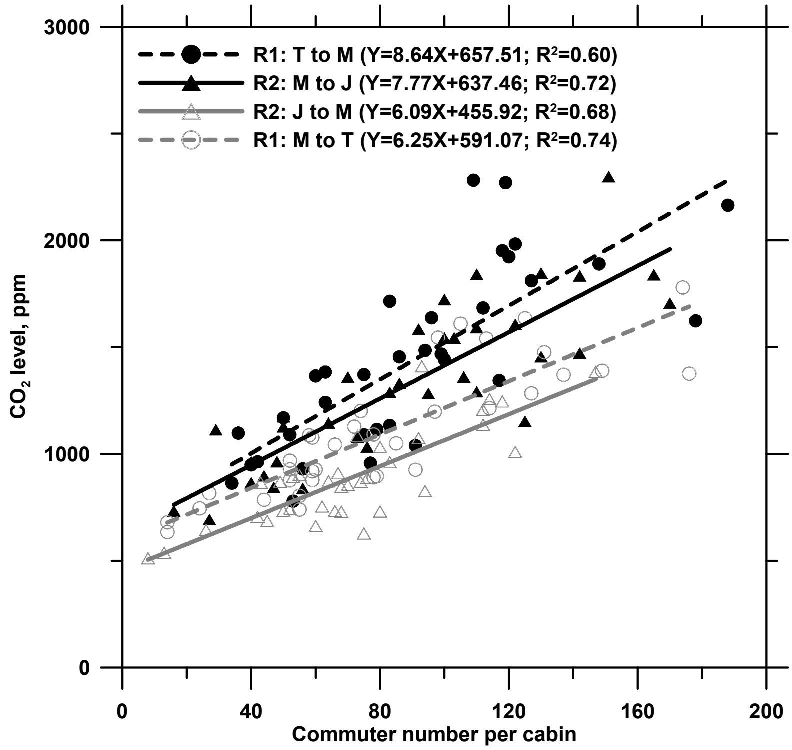

Fig. 7. Relationships between commuter number and CO_2 levels inside metro trains traveling in different directions on selected routes.

(a)

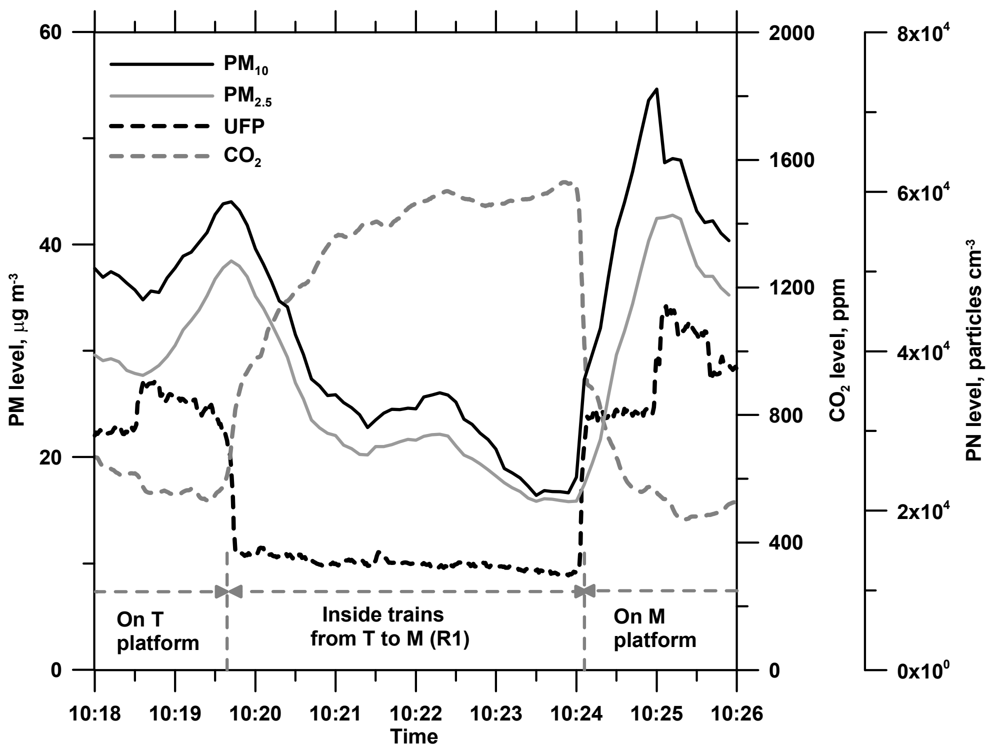

Fig. 8. Real-time variations in PM_{10}, $PM_{2.5}$, PN and CO_2 levels inside metro trains traveling on (a) R1 and (b) R2.

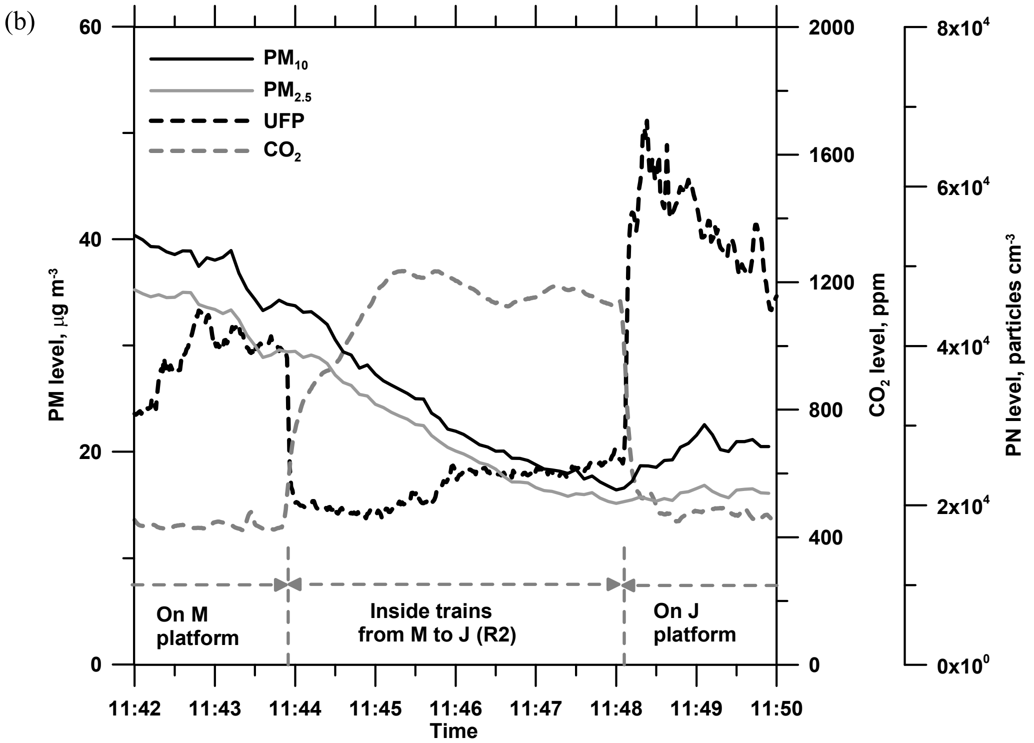

Fig. 8. *(continued).*

CONCLUSIONS

Measurement results demonstrate that PM_{10}, $PM_{2.5}$ and CO_2 levels inside metro trains in underground environments are higher than those in above-ground environments approximately 1.2–1.5 times. The PN levels inside metro trains in underground environments are lower than those in above-ground environments approximately 20%. These measurement results reveal that levels of pollutant species inside the metro trains are significantly influenced by the traveling environmental conditions—in underground tunnels or on elevated tracks. Moreover, the levels of pollutant species inside the metro trains traveling on the same route are also different in different traveling direction. According to measurement results, variations in PM_{10} and $PM_{2.5}$ levels inside the metro trains in different seasons are significantly influenced by outdoor ambient PM_{10} and $PM_{2.5}$ levels. Fine PM inside the metro trains is transferred from the outside and significantly influenced by the surrounding conditions of the trains. Additionally, a high fraction of large coarse PM (> 10 µm) is observed inside the metro trains, possibly due to re-suspension by the movement of commuters. Furthermore, CO_2 levels inside the metro trains are 2.7 times higher than those in outdoor environments. The measurement results show that, unlike PM, which is transferred from outside environments, CO_2 inside metro trains is elevated internally by exhalation from commuters. Additionally, CO_2 exhaled by commuters clearly accumulates inside the metro trains when air circulation is insufficient and is less easily removed by the ventilation system compared to PM, particularly in trains traveling in underground environments.

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