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Commuter exposure to particulate matter in public transportation modes in Hong Kong

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Abstract

This study examined commuter's exposure to respirable suspended particulate matters while commuting in public transportation modes. The survey was conducted between October 1999 and January 2000 in Hong Kong. A total of eight public transportation modes, that are bus, tram, public light bus, taxi, ferry, Kowloon–Canton Railway, Mass Transit Railway and Light Rail Transit, were selected in the study. They were grouped into four categories: (T1) railway transport; (T2) non-air-conditioned roadway transport; (T3) air-conditioned roadway transport and (T4) marine transport. Both PM_{10} and $PM_{2.5}$ levels were investigated. The results indicate that the particulate level is greatly affected by the mode of transport as well as the ventilation system of the transport. The overall average PM_{10} concentration level in T2 ($147\,\mu g\,m^{-3}$) is the highest and is followed by T4 ($81\,\mu g\,m^{-3}$) and T3 ($65\,\mu g\,m^{-3}$). The PM_{10} level in T1 ($50\,\mu g\,m^{-3}$) is the lowest. Notably, the commuter exposure in tram ($175\,\mu g\,m^{-3}$) is the highest among all the monitored commuting modes. Commuting modes such as railway and air-conditioned vehicle are recommended as a substitute for non-air-conditioned vehicle. The $PM_{2.5}$ to PM_{10} ratio in transports ranged from 63% to 78%. Higher $PM_{2.5}$ to PM_{10} ratio is found in vehicles with air-conditioning system. For the double deck vehicle, higher PM_{10} level has resulted in the lower deck. The average upper-deck to lower-deck PM_{10} ratio is 0.836, 0.751 and 0.738 in air-conditioned bus, non-air-conditioned bus and non-air-conditioned tram, respectively. Typical concentration profiles in different transports are also presented. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Public transportation modes; PM_{10}; $PM_{2.5}$; Commuter exposure; Vehicle exhaust

1. Introduction

Exposure to airborne particulate matter has become an increasing concern to the general public. In the last decade, several studies revealed that the exposure to elevated level of respirable suspended particulate is closely linked to the increase of daily mortality, hospital admission and respiratory problems (Dockery and Pope, 1994; HKEPD, 1999; Ostro, 1993; Tony, 1995).

Only few oversea studies examined the exposure to particulate matter while commuting. In Manchester, UK, Gee and Raper (1999) reported that the PM_4 level measured by the cyclist were much lower than levels inside buses. In Southampton, UK, exposure to respirable suspended particulate while commuting by bicycle was found to be higher on urban route than on sub-urban route (Bevan et al., 1991). Praml and Schierl (2000) investigated the PM_{10} exposure in buses and trams in Munich, Germany. Results indicated that the particulate concentrations in vehicles depend on external sources including outdoor concentration and road traffic. The dust concentration inside vehicles exceeded the ambient values by 3–5 times, even when sampling stations are located near roads. In Kuopio, Finland, Alm et al. (1999) stated that the PM level inside automobile was slightly affected by the

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number of stops at traffic lights along the travelling route.

Respirable particulate matter has found to be a serious air pollution problem in Hong Kong. In 1999, the daily average of PM_{10} levels recorded at most of the air quality monitoring stations frequently approached or exceeded the Hong Kong Air Quality Objectives (HKAQO) level of $180\,\mu g\,m^{-3}$ (HKEPD, 1999). Hong Kong's ambient PM_{10} levels are about 30–50% higher than those of cities in developed countries such as New York and Tokyo (HKEPD, 2000). The pollutants emitted by vehicles have found to be the main contributors to local air pollution in Hong Kong (Chan and Wu, 1993; Chan and Kwok, 2000; HKEPD, 2000). According to the emission inventory of Hong Kong, the total particulate emission in 1999 was 9879 tonnes and 58% of them came from motor vehicle. Diesel vehicles account for 98% of the respirable suspended particulates emitted by vehicles (HKSARG, 1999).

Hong Kong is situated at the southeastern tip of China. The population in Hong Kong is about 6.7 million but the total area of Hong Kong is just $1100\,km^2$. There are 503, 974 licensed vehicles and 1885 km of public road in December 1999. The traffic density in Hong Kong is 267 vehicles per kilometer of road and is among the highest in the world. However, private car ownership is relatively low. In 1998, there are about 56 private cars per 1000 population in Hong Kong, corresponding to $\frac{1}{9}$ and $\frac{1}{7}$ of the value in United States and United Kingdom, respectively (International Road Federation, 2001). About 90% of Hong Kong citizens rely on public transport facilities for commuting. There is a well-developed public transport system in Hong Kong. Everyday, more than 10 million passenger journeys are made on the public transport system, which includes bus, tram, public light bus (PLB), taxi, ferry Kowloon–Canton Railway (KCR), Mass Transit Railway (MTR) and Light Rail Transit (LRT) (Transport Department, 2000). Therefore, the primary interest of this study is to investigate the exposure levels of airborne particulate matter in these commuting microenvironments.

2. Field work design

All major public transportation modes in Hong Kong were selected in this study. The features of the measured commuting microenvironments are summarized in Table 1 and the location of the sampling routes is shown in Fig. 1. The selected transports can be classified into four categories: (T1) railway transport; (T2) air-conditioned roadway transport; (T3) non-air-conditioned roadway transport and (T4) marine transport. Railway transports comprise of KCR, MTR and LRT. These three railway systems served about 30.2% of public transportation journeys in 1999. KCR and LRT mostly traverse on the ground track in the sub-urban districts while MTR is mostly running on the underground track in the urban districts. Centralized air-conditioning system is adopted in these trains. They run on different routes (Route R1–R3) and the average journey time of trains varied from 25 to 50 min. Roadway transports comprise of tram, bus, PLB and taxi, serving more than 60% of public transport passengers. Taxi is classified as public transport in the study, as it is serving 12.3% of public transport passengers in Hong Kong. All the surveyed buses and trams were double decked. Air conditioning was used in taxi while natural ventilation was used in tram. Both air-conditioned and non-air-conditioned buses and public light buses were monitored in the study. A fixed route in the northern part of Hong Kong Island (Route R4) was selected for the roadway transports since it can represent a typical urban commuting route in Hong Kong and cover all the measured roadway public transports. This route traverses urban residential and commercial districts. The road in this route is quite narrow (2–3 lanes in each direction) and with many high-rise buildings on both sides. The traffic volume on this route is very high and the average annual daily traffic (AADT) volume is more than 25,000 vehicles. Traffic congestion and stop-and-go traffic were frequently observed during the sampling period. The average journey time of the roadway transports on the same route ranged from 28 to 50 min. Marine transport only refers to ferry in this study. The ferry was naturally ventilated by the strong wind in the harbour. A cross-harbour route (Route R5), connecting urban districts in Kowloon Peninsula and Hong Kong Island was selected in the survey. The average journey time of ferry was about 18 min.

Field sampling was carried out on weekdays only, in the period between early October 1999 and mid-January 2000. There was no measurement conducted in rainy day or day with pollution episode. Episode day is defined as the Air Pollution Index (API) higher than 100, which equivalent to the breaching of short-term HKAQO established under the Air Pollution Control Ordinance. All the particulate samples were collected at morning (08:00–10:30) or afternoon (16:30–19:00) rush hours in all selected public transports except taxi. Taxi samples were obtained at (10:30–12:30). In some trips, PM_{10} levels were measured simultaneously at the upper and lower deck of the double decked vehicles including bus and tram. The sampling height on the upper deck and lower deck is about 1.5 and 3.5 m above street-level, respectively, in bus and tram. Adding to that, $PM_{2.5}$ levels were also monitored in some trips concurrently with PM_{10} levels. The sampling time, traffic condition, number of passenger and the weather condition were recorded.

Table 1
Features of the measured commuting microenvironments

Type of transport	Route	Average journey time	Characteristics of route
(T1) Railway transport			
Kowloon–Canton Railway (KCR)	Hung Hom–Sheung Shui (Route R1)	40 min	Traverse between Kowloon Peninsula (urban commercial/residential area) and North New Territories (new town residential area) through Beacon tunnel in the middle. Running on its own track and away from other traffic. More than 90% of time run on the ground track
Mass Transit Railway (MTR)	Sheung Wan–Chai Wan (Route R2)	25 min	Traverse between northern part of Hong Kong Island (urban commercial and urban residential area). Running mostly on its own underground track
Light Railway Transit (LRT)	Tuen Mun–Yuen Long (Route R3)	50 min	Traverse in the North West New Territories (new town residential area). Run on ground track only. Part of the track run together with other traffic. Low traffic flow, few stops, and moderate driving speed
(T2) Non-air-conditioned roadway transport			
Tram (*Double deck*)	Sheung Wan–Quarry Bay (Route R4)	50 min	Traverse between the northern part of Hong Kong Island (urban commercial and urban residential area). A 4–6 lane (dual direction) access road with high-rise buildings on both sides. Heavy traffic flow, low driving speed, frequent stops and traffic congestion
Bus (*Double deck*)		42 min	
Public Light Bus (PLB) (*Single deck*)		40 min	
(T3) Air-conditioned roadway transport			
Bus (*Double deck*)	Sheung Wan–Quarry Bay (Route R4)	42 min	Same as above
Public light bus (PLB) (*Single deck*)		40 min	
Taxi		28 min	
(T4) Marine transport			
Ferry	Central–Tsim Sha Tsui (Route R5)	18 min	Crossing Victoria harbour. Connecting urban centres in Kowloon Peninsula and Hong Kong Island

3. Sampling method and quality assurance

Gravimetric sampling of respirable suspended particulate inside commuting microenvironments were widely used by researchers in previous studies (Bevan et al., 1991; Gee and Raper, 1999). However, gravimetric measurement of particulate mass concentration in the commuter's breathing zone required several hours per measurement. During this sampling time, the weather condition (e.g. raining, wind direction and wind speed) and the driving condition (e.g. traffic volume, traffic speed and traffic pattern) may vary substantially. The method is not capable of investigating the temporal variation of the particulate levels. Large error may easily result for short sampling duration. Instead, DustTrak (TSI Model 8520) portable aerosol monitor was used to measure RSP (PM_{10}) and fine particulate ($PM_{2.5}$) level in this study. It is a real-time laser photometric instrumentation for the determination of aerosol mass concentrations, thus capable of measuring short-term exposure level and concentration profile during daily commuting trips. The measurement is performed using a light scattering technique. Different impactors are available for the inlet of DustTrak allowing measurements of PM_{10} and $PM_{2.5}$. Recently, DustTrak aerosol monitor has been applied for the determination of particulate mass concentration in in-vehicle (Leutwyler et al., 2002), indoor (Lee et al., 1999) and outdoor (Hitchins et al., 2000) microenvironments.

All the air samples were collected at respiratory level and the sampling location was carefully selected to ensure free of any obstruction. Smoking inside public

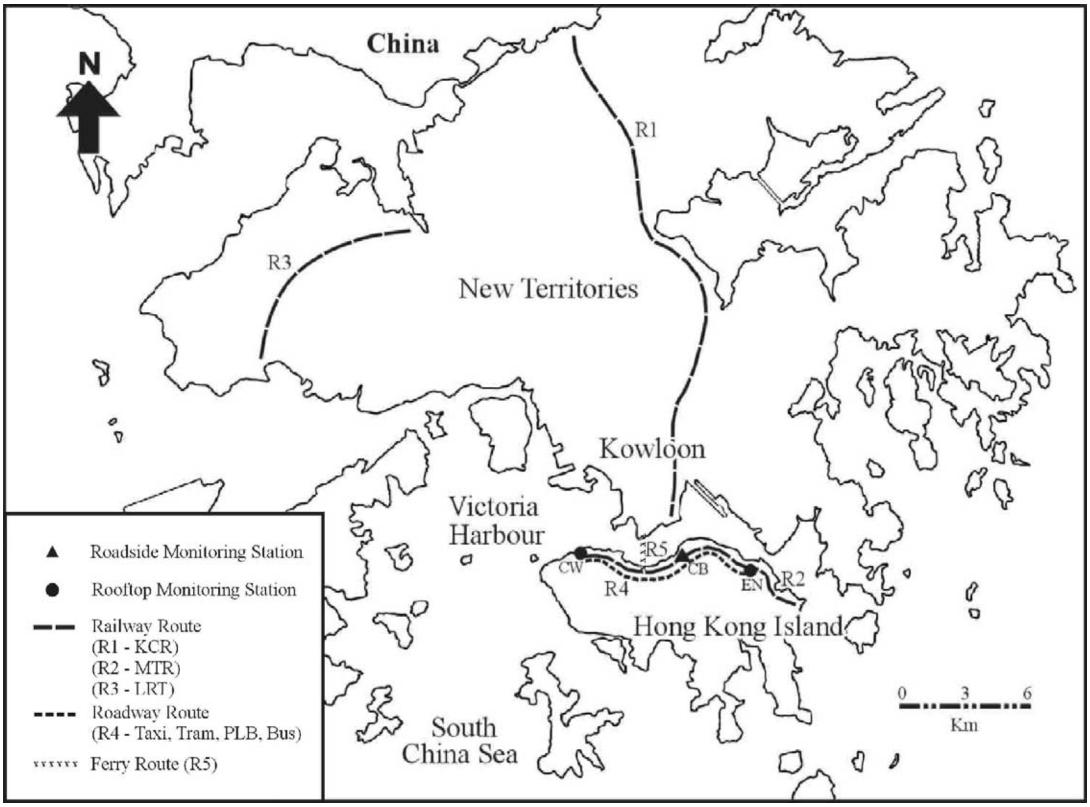

Fig. 1. Location of sampling routes and monitoring stations.

transportation modes was strictly prohibited in Hong Kong. As a quality control measure, duplicate samples were collected in each measured commuting microenvironment for parallel testing of monitors (side-by-side monitoring) in order to study the precision of the sampling equipment. The relative mean deviation of duplicates was within 10% for both PM_{10} and $PM_{2.5}$. Also, zero calibration of the monitor was performed before each survey trip. The monitor was turned on to stabilize for several minutes before start of sampling. DustTrak was pre-calibrated against Arizona Test Dust (ISO 12103-1) in the manufacture company (TSI). This test dust has a wide size distribution covering the entire detected size range of the DustTrak. As vehicle exhaust is the major source of airborne particulate in Hong Kong, particulates are small in size. Therefore, this calibration cannot apply directly in the Hong Kong situation. In order to obtain more accurate mass concentration data, all the sampling results from DustTrak were calibrated against gravimetric samplers (Greasby–Anderson high-volume air sampler for PM_{10} and R&P Partisol 2000 air sampler for $PM_{2.5}$). The correlation investigations were conducted at the Hong Kong Polytechnic University boundary site before the field study. The particulate levels were measured concurrently by PM_{10} DustTrak aerosol sampler, PM_{10} high-volume sampler, $PM_{2.5}$ DustTrak aerosol sampler and $PM_{2.5}$ Partisol sampler at the same location and similar sampling height over a 24-h sampling period. These samplers were placed on the pavement at about 1.5 m away from the roadside. Both correlation curves were plotted using the 24-h averaged concentrations. The correlation coefficient (r) between DustTrak-PM_{10} and high-volume sampler, DustTrak-$PM_{2.5}$ and Partisol sampler were 0.96 and 0.97, respectively (Fig. 2a and b). Similar correlation curve in was found in a local study (Tung et al., 1999) for PM_{10} samples by using DustTrak against Mini-Volume. In this study, all the data collected by DustTrak were converted to high-volume sampler and partisol sampler scale accordingly to facilitate their comparison with other studies.

4. Results and discussion

4.1. *Inter-microenvironment variation*

During the sampling period, a total of 209 PM_{10} samples and 72 $PM_{2.5}$ samples were collected in the eight transportation modes. Table 2 summarizes the statistical

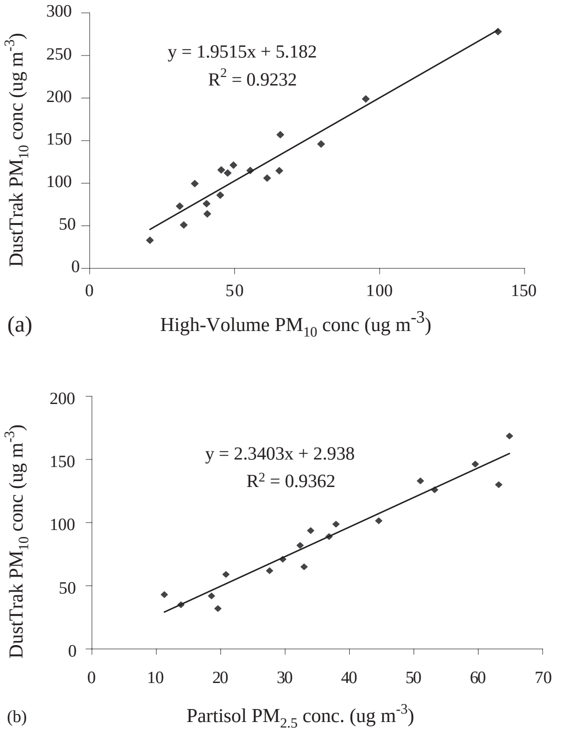

Fig. 2. (a) Calibration of DustTrak PM_{10} by high-volume PM_{10}; (b) Calibration of DustTrak $PM_{2.5}$ by Partisol $PM_{2.5}$.

results of PM_{10} and $PM_{2.5}$ levels in different transports. The average PM_{10} level in (T2) non-air-conditioned roadway transport ($147\,\mu g\,m^{-3}$) is the highest and is followed by (T4) marine transport ($81\,\mu g\,m^{-3}$). The PM_{10} exposure level of (T1) railway transport commuter is the lowest ($50\,\mu g\,m^{-3}$). Similar ranking is also found in the results of $PM_{2.5}$. Judging from the concentration levels and the standard deviations of transports in each category, the classification of the transport is found to be reasonable. Chan et al. (1999) revealed that the commuter exposure to traffic-related gaseous pollutants is greatly influenced by the choice of commuting microenvironments. The results of the present study revealed similar features for suspended particulate matter.

For the non-air-conditioned roadway transports, the average PM_{10} level in tram, PLB and bus was 175, 137 and $112\,\mu g\,m^{-3}$, respectively. Higher levels were obtained in this category since they all run on a busy road (Route R4) with heavy traffic and very deep street canyon configuration. Strong vehicular sources and poor ventilation effect on this route (Route R4) do not favour dispersion of pollutants. With the windows opened in these transports, the vehicle exhausts emitted by the adjacent vehicles easily penetrated the vehicle interior, especially during stop-and-go traffic. The exposure level in tram is the highest in this study, as it always run on the fixed track in the middle of the road with a relatively low speed. It is greatly affected by the exhausts emitted by vehicles running on both sides. The exposure level of the bus is lower than the PLB. The large compartment size of bus may help to disperse the particulates further than the PLB, and hence, is less affected by the immediate intrusion of neighbouring vehicle exhaust.

Ferry, the only transport classified as (T4) marine transport, has exposure levels just follow category T2. However, the mean PM_{10} level in marine transport was about half the value in non-air-conditioned transports. It traverses across the harbour and is away from the main air pollution sources. Therefore, the exposure level in ferry is mainly affected by the ambient level rather than the vehicular pollution. Although the ferry is heavy-diesel-fuelled, the black smoke exhaust is discharged vertically through the chimney installed on the top of the compartment. And under normal situation, the buoyancy force and the inertia of the exhaust make it blowing away from the compartment while the ferry is running.

The PM_{10} levels of (T3) air-conditioned roadway transport and (T1) railway transport were found to be lower than (T2) and (T4). It could be attributed to the use of air-conditioning system in these commuting modes. Air-conditioning system reduces particulate level in two ways. Firstly, the closed window can acts as a physical barrier to separate the vehicle interior air from the roadway air, thus to prevent direct influence of vehicle exhaust. Secondly, part of the coarse size particulate is filtered out from the air stream by filter during fresh air intaking or interior air recirculating. Among all the air-conditioned roadway transports, exposure level of taxi commuter is the lowest as it is a common practice for the taxi drivers to totally recirculate the air. Higher level of particulate re-suspension and commuter exposure in bus than in PLB and taxi could due to the frequent passenger movement and frequent opening of the door for passenger alighting and boarding the bus.

The PM_{10} levels in category T1 are slightly lower than in T3. This may due to the fact that these three railway systems have their own tracks, often located away from busy road or other traffic. Adding to that, they all draw relatively less polluted fresh air from the top of the compartment. On the contrary, roadway transports run on busy route and with the position of the fresh air intake installed at low level and closed to the exhaust emission.

As all the samples were collected in winter, the variation of ambient air quality was low, thus the standard deviation (S.D.) in different commuting modes were reasonably low. The S.D. in T2 and T4 was significantly higher than in T1 and T3. This can be

Table 2
Statistical result of PM_{10} and $PM_{2.5}$ in different transportation modes

Transport	PM_{10} ($\mu g\,m^{-3}$)				$PM_{2.5}$ ($\mu g\,m^{-3}$)			
	n	Mean	Range	S.D.	*n*	Mean	Range	S.D.
T1—Railway transport								
KCR	30	60	41–89	12	13	46	29–68	11
MTR	25	44	23–85	16	6	33	21–48	10
LRT	15	41	30–57	7	9	34	26–47	6
Average		50				39		
T2—Non-air-conditioned roadway transport								
Tram	17	175	110–240	36	8	109	68–163	31
Bus	12	112	80–161	28	6	93	78–109	12
Public Light Bus (PLB)	7	137	74–204	49	6	97	48–137	38
Average		147				101		
T3—Air-conditioned roadway transport								
Taxi	30	58	20–110	25	n/a[a]	n/a	n/a	n/a
Bus	24	74	40–137	23	17	51	30–98	19
Public Light Bus (PLB)	7	63	44–82	14	7	45	27–67	14
Average		65				49		
T4—Marine transport								
Ferry	15	81	29–127	27	n/a	n/a	n/a	n/a

[a] n/a—No measurement.

explained by the fact that vehicle without air-conditioning system was influenced by the day-to-day variation to a larger extent.

Table 3a compares the present study with other studies. In general, the in-vehicle levels measured in this study are lower than or comparable with the levels measured in several western cities. For the bus commuter, the averaged air-conditioned bus particulate level in the present study (PM_{10}, 74 $\mu g\,m^{-3}$) was lower than the Munich (PM_{10}, 110–165 $\mu g\,m^{-3}$) (Praml and Schierl, 2000) study, but much lower than the Manchester (PM_4, 250–350 $\mu g\,m^{-3}$) (Gee and Raper, 1999) study. However, if the comparison is based on the non-air-conditioned bus samples (PM_{10}, 112 $\mu g\,m^{-3}$) study, the result was more closed to the above studies. For the tram commuter, the result of present study (PM_{10}, 175 $\mu g\,m^{-3}$) was comparable to the Munich (PM_{10}, 161 $\mu g\,m^{-3}$) study. For other measured transports not listed in the table, the particulate levels are comparatively low in Hong Kong.

As shown in Table 3, the results of the roadway transports were also simply compared with two rooftop-stations and one roadside-station data installed along the travelling route (Route R4). Location of the stations is also shown in Fig. 1. The hourly monitoring station data were acquired from the Hong Kong Environment Protection Department. The mean particulate concentration in each station was calculated by averaging the hourly PM_{10} level at that particular station during the entire sampling period (08:30–10:00 and 17:00–19:30; 01/10/99–15/01/00). The simple comparison revealed that the PM_{10} level in non-air-conditioned roadway transports (112–175 $\mu g\,m^{-3}$) is in the same order of magnitude to the roadside monitoring station data (127 $\mu g\,m^{-3}$), but significantly deviated from the rooftop monitoring stations data (71 and 65 $\mu g\,m^{-3}$). The PM_{10} level inside air-conditioned roadway transports is comparable to the rooftop monitoring stations. Among all the measured transports, only tram and non-air-conditioned PLB PM_{10} level is greater than the level in these monitoring stations. The comparison results seem to indicate that the in-vehicle air quality regarding the PM_{10} level in most of roadway public transportation modes in Hong Kong is better than the roadside ambient air.

4.2. $PM_{2.5}$ and PM_{10} relationship

The relationship between PM_{10} and $PM_{2.5}$ was investigated in all transports except taxi and ferry. Table 4 presents the $PM_{2.5}$ to PM_{10} ratio and the $PM_{2.5}$–PM_{10} correlation for each category of transport.

Table 3
Comparison of particulate concentration
(a) Comparison of particulate concentration with other studies

	Location	PM size	Mean concentration ($\mu g\,m^{-3}$)
Current study	A/C bus[a]	PM_{10}	74
	Non-A/C bus[b]	PM_{10}	112
	Tram	PM_{10}	175
	A/C PLB	PM_{10}	63
	Non-A/C PLB	PM_{10}	137
Munich (2000)[c]	Bus	PM_{10}	110–165
	Tram	PM_{10}	161
Manchester (1999)[d]	Bus	PM_4	250–350
	Bicycle	PM_4	54
Los Angeles (1998)[e]	Automobile	PM_{10}	46–105
	Automobile	$PM_{2.5}$	29–107
Amsterdam (1995)[f]	Ambulant monitoring vehicle	PM_{10}	90–194

(b) Comparison of particulate concentration with local monitoring station data along the route

	Transport/monitoring station	PM size	Mean concentration ($\mu g\,m^{-3}$)
Current study	Air-conditioned roadway transport	PM_{10}	58–74
	Non-air-conditioned roadway transport	PM_{10}	112–175
EPD monitoring Station	Causeway Bay [CB] roadside monitoring station (2.0 m above ground at urban roadside with heavy traffic)	PM_{10}	127[g]
	Eastern [EN] rooftop monitoring station (17.0 m above ground in urban residential area)	PM_{10}	71[g]
	Central and Western [CW] rooftop monitoring station (18.0 m above ground in urban commercial and residential area)	PM_{10}	65[g]

[a] A/C—Air-conditioned.
[b] Non-A/C—Non-air-conditioned.
[c] Praml and Schierl (2000).
[d] Gee and Raper (1999).
[e] CARB (1998).
[f] Wijnen et al. (1995).
[g] The value was calculated by averaging the hourly PM_{10} level at that particular station during the entire sampling period (08:30–10:00; 17:00–19:30) and (01/10/99–15/01/00).

The $PM_{2.5}$ to PM_{10} ratios in all measured commuting modes are high (63–78%). These results implicitly imply that the ambient air as well as the in-vehicle air quality is greatly deteriorated by the vehicle exhaust. Vehicle exhaust emitted from the vehicles, especially diesel vehicles is the main source of fine particulate matter at street-level in Hong Kong and other metropolitan cities. A previous local study (Lam et al., 1999) reported that the $PM_{2.5}$ concentration contributed to about 70% of the total PM_{10} at the street-level in the winter of Hong Kong. The $PM_{2.5}/PM_{10}$ of the transports in T2 (63–68%) is significantly lower than in T1 (72–78%) and T3 (71–73%). The filter in the air-conditioning system is capable of removing the larger portion (2.5–10 μm) of PM_{10}, thus the portion of $PM_{2.5}$ is relatively higher in the interior of the air-conditioned vehicle. In a previous US study (Ptak and Fallon, 1994), researchers found that the car's air-conditioning systems can remove between 40% and 75% of the largest PM, but remove only 2–5% of the dangerous particle $<1\,\mu m$. Clearly,

Table 4
$PM_{2.5}$ and PM_{10} relationship

Transport	n	$PM_{2.5}/PM_{10}$	$PM_{2.5}$–PM_{10} correlation (Unit, $\mu g\,m^{-3}$)
T1—Railway transport			
KCR	13	0.721	$PM_{2.5} = 0.7067PM_{10} + 1.0$ ($r = 0.954$, $n = 28$)
MTR	6	0.715	
LRT	9	0.779	
Average		0.738	
T2—Non-air-conditioned roadway transport			
Tram	8	0.636	$PM_{2.5} = 0.6760PM_{10} - 2.0$ ($r = 0.974$, $n = 20$)
Bus	6	0.680	
Public Light Bus (PLB)	6	0.681	
Average		0.663	
T3—Air-conditioned roadway transport			
Bus	17	0.728	$PM_{2.5} = 0.7191PM_{10}$ ($r = 0.979$, $n = 24$)
Public Light Bus (PLB)	7	0.709	
Average		0.722	

Table 5
Upper deck and lower deck PM_{10} relationship

Transport	n	Upper deck PM_{10} ($\mu g\,m^{-3}$)	Lower deck PM_{10} ($\mu g\,m^{-3}$)	% Decrease from lower deck[a]	Upper/lower[b]	
					Mean	S.D.
Air-conditioned bus	9	62	74	16.2	0.836	0.093
Non-air-conditioned bus	9	71	95	25.3	0.751	0.111
Non-air-conditioned tram	9	132	175	24.5	0.738	0.122

[a] % Decrease from lower deck = (lower deck PM_{10} − upper deck PM_{10}) × 100%/lower deck PM_{10}.

[b] Upper/lower = upper deck PM_{10}/lower deck PM_{10}.

the vehicle's ventilation system and air-conditioning system filter out some of the coarse size particulate, but do little help to protect the commuters from the much more health concerned fine particulate. The linear regression equations of PM_{10} and $PM_{2.5}$ are calculated separately in each category of transport. The PM_{10} level is well correlated with $PM_{2.5}$ no matter in which category of transport. The results indicate that vehicle exhaust was the major source of commuters' exposure to airborne respirable suspended particulate matter while commuting. The in-vehicle $PM_{2.5}$ level could be inferred from the PM_{10} level as the two sets of data were highly correlated to one another. In general, the higher the PM_{10} concentration level, the higher the $PM_{2.5}$ concentration level is obtained. Similar correlation {$PM_{2.5}$ ($\mu g\,m^{-3}$) = $0.67PM_{10}$ ($\mu g\,m^{-3}$) + 10.4, $r = 0.86$} was also found in Lam et al. (1999) at the street-level of Hong Kong.

4.3. Upper deck and lower deck relationship

In Hong Kong, tram and most of the buses are double deck. The investigation of upper- and lower-deck PM_{10} relationship was conducted in three transports which run on the route (Route R4) with heavy traffic and street canyon configuration. As shown in Table 5, all the PM_{10}

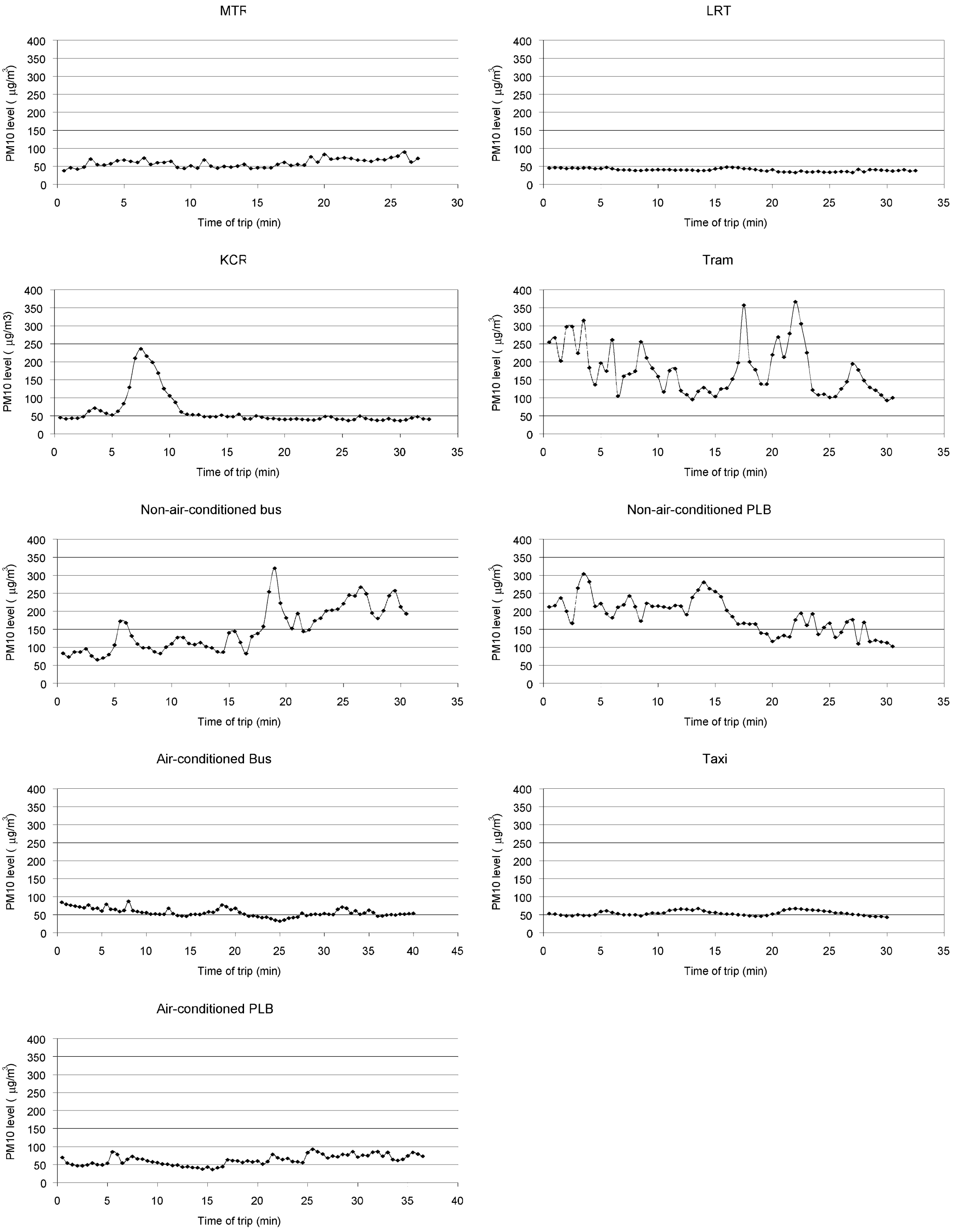

Fig. 3. The typical concentration profile of the measured transports.

levels in the upper deck is substantially lower than the lower deck in both air-conditioned and non-air-conditioned vehicles. The upper-deck to lower-deck PM_{10} ratio (upper/lower ratio) ranged from 0.738 to 0.836 and it is strongly associated with the ventilation mode. The concentration difference between the two decks has found to be higher in the transports without air-conditioning system. In the air-conditioned vehicles, the air exchange rate inside the vehicle interior is low, the interior air is mainly recirculated and only several percentage of fresh air is taken from outside. The fresh air is well mixed with the recirculate air in the ventilation system and evenly distributed into the upper and lower deck, thus there is less difference between them. The possible explanation for the higher level in the lower deck is the intrusion of polluted air from frequently opening of gate at the lower deck for passenger alighting and boarding. All the windows of air-conditioned bus are sealed tightly (non-openable) except the one located besides the bus driver for giving hand signal while driving. The pollutants penetrate through this window may also cause higher PM_{10} level at the lower deck in air-conditioned bus. On the contrary, in the vehicles using natural ventilation by open windows, the lower-deck PM_{10} level is directly impacted by the exhaust emission emitted near the ground level as well as the street-level particulate level. Thus, lower upper/lower ratio and higher percentage decrease of PM_{10} level from lower deck are resulted. The upper/lower ratio was also found to vary in a greater extent for non-air-conditioned vehicles. This is because the particulate variation on the non-air-conditioned vehicles are more influenced by the meteorological factors (wind speed, wind direction and weather), the surrounding traffic volume, the speed of the sampling vehicle and the street configuration of the route.

4.4. Typical concentration profile in public transports

Fig. 3 shows the typical PM_{10} concentration profile recorded in all selected transportation modes except ferry. The temporal variation patterns for the commuting microenvironments are greatly influenced by the use of air-conditioning system. Relatively smooth and flatten profiles were obtained in vehicles or railways using air-conditioning system as the air exchange rate in those transports is relatively low, thus, the polluted air can only penetrate the compartment in a low rate. On the other hand, relatively high fluctuation of PM_{10} level was frequently observed in the non-air-conditioned vehicles. The instantaneous and obvious concentration peaks were the result of the occasional intrusion of neighbouring vehicle emission into the vehicle compartment. These peaks were usually observed in the stop-and-go traffic pattern.

A sharp peak was found for KCR while crossing the tunnel between the station of Kowloon Tong and Tai Wai. In some trips, this peak concentration can be over $300\,\mu g\,m^{-3}$. No ventilation system was installed inside the tunnel and the air movement inside the tunnel is only caused by the piston effect of the train. The major source is the re-suspension of particulate matter confined in the tunnel. It is mainly due to the road dust and the particulate derived from diesel powered train. Although all the KCR trains are electrified, a few cargo trains which is diesel powered still use to carry passengers and transport goods between Hong Kong and China daily. Therefore, when a train is moving at high speed through the tunnel, the settled particulate matter will re-suspended again in the air and come into the train through the centralized system, thus resulted in a dramatic increase in PM level. Special ventilation arrangement is needed to protect the passengers when a train stops inside the tunnel during emergency stop or congestion.

5. Conclusion

This study examined the in-vehicle exposure to PM_{10} and $PM_{2.5}$ while commuting in different public transportation modes under typical Hong Kong driving conditions. Particulate samples were collected in eight public transportation modes in Hong Kong during the winter season. We have successfully illustrated that portable aerosol monitor was able to measure the mass concentration of airborne PM_{10} and $PM_{2.5}$ within these vehicles. The in-vehicle particulate exposure level is greatly affected by the choice of commuting microenvironment and the mode of ventilation adopted. The adoption of air-conditioning system was found to be an important factor influencing the in-vehicle particulate level. Particulate level in non-air-conditioned roadway transport, especially in tram is the highest, and is about 3–4 times higher than the value in trains. Hence, alternative commuting options such as railways and air-conditioned vehicles are recommended as a substitute for non-air-conditioned vehicles. The $PM_{2.5}$ to PM_{10} ratios in all measured commuting modes were high, ranged from 63% to 78% and the results implicitly indicated that motor vehicle exhaust emissions were the cause of high particulate exposure level inside the vehicle compartment. Substantial PM_{10} level difference is found between the upper deck and lower deck of the double deck vehicles. The commuter sit on the upper deck exposed to 18–25% lesser PM_{10} level than on the lower deck. The results of this study strongly indicate that Hong Kong commuters are frequently exposed to high level of particulate matter while commuting in some public transport trips.

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