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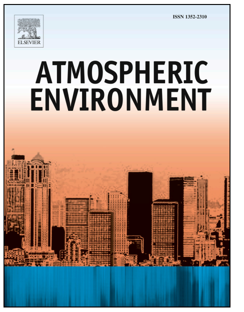

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Heterogeneity of passenger exposure to air pollutants in public transport microenvironments

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Abstract

Epidemiologic studies have linked human exposure to pollutants with adverse health effects. Passenger exposure in public transport systems contributes an important fraction of daily burden of air pollutants. While there is extensive literature reporting the concentrations of pollutants in public transport systems in different cities, there are few studies systematically addressing the heterogeneity of passenger exposure in different transit microenvironments, in cabins of different transit vehicles and in areas with different characteristics. The present study investigated $PM_{2.5}$ (particulate matter with aerodynamic diameters smaller than 2.5μm), black carbon (BC), ultrafine particles (UFP) and carbon monoxide (CO) pollutant concentrations in various public road transport systems in highly urbanized city of Hong Kong. Using a trolley case housing numerous portable air monitors, we conducted a total of 119 trips during the campaign. Transit microenvironments, classified as 1). busy and secondary roadside bus stops; 2). open and enclosed termini; 3). above- and under-ground Motor Rail Transport (MTR) platforms, were investigated and compared to identify the factors that may affect passenger exposures. The pollutants inside bus and MTR cabins were also investigated together with a comparison of time integrated exposure between the transit modes. Busy roadside and enclosed termini demonstrated the highest average particle concentrations while the lowest was found on the MTR platforms. Traffic-related pollutants BC, UFP and CO showed larger variations than $PM_{2.5}$ across different microenvironments and areas confirming their heterogeneity in urban environments. In-cabin pollutant concentrations showed distinct patterns with BC and UFP high in diesel bus cabins and CO high in LPG bus cabins, suggesting possible self-pollution issues and/or penetration of on-road pollutants inside cabins during bus transit. The total passenger exposure along selected routes, showed bus trips had the potential for higher integrated passenger exposure compared to MTR trips. The present study may provide useful information to better characterize the distribution of passenger exposure pattern in health assessment studies and the results also highlight the need to formulate exposure reduction based air policies in large cities.

Keywords: Black carbon, CO, bus cabins, roadside bus stop, bus terminal, $PM_{2.5}$, subway platform, ultrafine particles

1. Introduction

Numerous epidemiological studies have demonstrated associations between exposure to air pollution and increased mortality (Dockery et al. 1993, Lin et al. 2013), while airborne fine particulate matter ($PM_{2.5}$, d_p<2.5 μm) plays an especially important role in adverse impact on pulmonary and cardiovascular outcomes (Dreher 2000). However, many epidemiological studies have assumed that routinely monitored ambient pollutant concentrations are surrogates for actual exposure, and few studies have addressed whether there is a predictable relationship between exposure and concentration in different locations within a city (Cao and Frey 2011). This is especially true to urban areas where there is a heterogeneous distribution of pollutant concentrations in the ambient air and the public have different time/activity patterns in various microenvironments that contribute to daily exposure (Ostro et al. 2006).

Hong Kong is a highly urbanized city with a population of over 7 million, and a well-developed public transport system accounting for some 12 million passenger journeys every day, of which 41% are by Mass Transit Railway (MTR), followed by 32% with diesel-fuelled franchised buses and 15% with Liquefied Petroleum Gas (LPG) public light buses (HKTD 2013). Such heavy reliance on public transport makes individual exposure to air pollutants inside the transport system a potentially significant component of daily integrated exposure. Although most commuters spend only a short fraction of time daily in the transport system, high pollution levels experienced during travel may contribute significantly to total individual exposures (Nieuwenhuijsen, Gomez-Perales and Colvile 2007). Seaton et al. (Seaton et al. 2005) investigated commuter exposure to $PM_{2.5}$ in London and found spending 2 hours in the metro system per day would increase personal 24-hour exposure by 17 μg m^{-3}.

Studies in various cities have also shown that public transport system may represent a combination of unique microenvironments with different source characteristics making them quite different from those typical outdoors or even indoors (Both et al. 2013, Knibbs, Cole-Hunter and Morawska 2011). Passengers can be exposed to the air pollutants substantially different from those at street level air in terms of gas concentrations and PM concentrations and chemical composition (Aarnio et al. 2005, Kam et al. 2011b). For example, investigators (Cheng, Liu and Yan 2012, Nieuwenhuijsen et al. 2007) observed a considerable increase (~ 20 to 50 % greater) of $PM_{2.5}$ mass concentration compared to outdoor air. Thus ambient air monitoring data cannot be effectively used to estimate the daily dose of exposure with different characteristics of air pollutants in transit system.

During the last decade, a few studies in Hong Kong investigated passenger pollution exposure levels. Chan et al. (Chan et al. 2002) measured $PM_{2.5}$ and PM_{10} mass concentrations in four different transport modes including the railway system and buses. Recently, Wong et al. (Wong et al. 2011) measured carbon monoxide and $PM_{2.5}$ concentrations inside bus cabins in Hong Kong. These previous studies clearly demonstrated that $PM_{2.5}$ displayed different characteristics in comparison with ambient environments. However, there were no systematic investigations of the distribution of traffic-related pollutants, such as black carbon (BC), ultrafine particles (UFP) in different transport microenvironments, which limits our accurate understanding of the daily dose of exposure and knowledge of exposure mitigation measures. This study investigates $PM_{2.5}$, BC, UFP and CO distributions in transport microenvironments and in cabins of different transit modes, including diesel franchised buses, LPG public light buses and the MTR system. Total exposure on typical commute routes by different transit modes was also compared. The results of the study should allow more accurate estimates of population daily dose for epidemiologic research and provide a basis for exposure reduction based air policy making.

2. Experimental methodology

2.1 Portable instrumentation

Pollutant concentrations were measured using a Mobile Exposure Measurement System (MEMS) with a trolley case housing portable air monitors, a data acquisition system and a global positioning system (GPS) as shown in Figure 1. A portable condensation particle counter (CPC, TSI 3007) was used to measure ultrafine particle (UFP) number concentration . Although the CPC measured particles in the size range of 10-1000 nm, number concentration is dominated by smaller sized particles (diameter <100 nm) (Morawska et al. 2008). A micro Aethalometer (microAeth® Model AE51, Aethlabs) was used for measuring black carbon (BC) concentration. An Optical Particle Sizer (OPS, TSI® model 3330) was used for $PM_{2.5}$ concentration measurement and a Q-trak (TSI® model 7575) was installed in a backpack to monitor carbon dioxide (CO_2), carbon monoxide (CO), relative humidity (RH) and temperature (T) at high temporal resolution (one second). All instruments were connected to a mini-PC (NUC, Intel®) and the real-time data were collected and transferred to a mobile phone through Bluetooth. The measurements were displayed on the screen through a cell phone application developed by the investigators to track instrument conditions and tag special events during the campaign. Screenshot of the app is included in Figure 1b. All instruments and batteries were wrapped with sponge sheets and fitted snugly into the suitcase. A diffusion dryer was installed upstream of the OPS and microAeth to avoid interference from water vapor (Zieger et al. 2013, Cai et al. 2013), respectively.

Fig. 1. Setup of Mobile Exposure Measurement System (MEMS)

2.2 Description of transport microenvironments

The campaign covered three dominant transit modes of the public transport system of Hong Kong: the MTR, diesel franchised buses and LPG public light buses. During transit, a passenger may experience a variety of microenvironments depending on the mode of transport, the characteristics of surrounding sources and the built environment. Thus the air pollutant concentrations experienced are characterised by a unique pattern of local activities. The present study investigated six main microenvironments including busy and secondary roadside bus stops, open and enclosed bus termini, aboveground (AG) and underground (UG) MTR platforms. Detailed descriptions of the microenvironments characteristics are listed below and Figure 2 shows the coverage of the microenvironments in the study areas and routes.

Fig. 2. The transport microenvironments and integrated exposure based routes and areas.

Busy and secondary roadside bus stops

Transport by diesel franchised buses and LPG public light buses carries 3.8 and 1.9 million daily passenger journeys (HKTD 2013). Waiting at roadside bus stops is an important component of a commuter's daily exposure because of the proximity to road traffic emissions. We separated the roadways by their annual average daily traffic (AADT) into busy road (AADT>30,000 vehicles per day) and secondary road (AADT<20,000 vehicles per day), which also reflects the distribution of the public transport such as bus routes and number of bus stops, as well as roadway characteristics (HKTD 2013).

Open and enclosed termini

Different from roadside bus stops where there exists continuous flow of traffic during a passenger's wait, the bus terminus is a unique microenvironment as a transport interchange busy with buses collecting or discharging passengers and exposure can be enhanced by emissions during vehicles idling, acceleration and deceleration. Dependent on the ventilation and the surrounding built environment, the termini were categorized as open or enclosed. The open termini are in effect open outdoor spaces, while enclosed termini are confined or semi-confined environments often located on the ground floor of large building complexes. A total of ten open and twelve enclosed termini were investigated in this study.

Above- and under-ground MTR platforms

The rail-based MTR is the most used mode of public transport in Hong Kong, carrying 4.9 million daily passengers (HKTD 2013). There are both above- and under-ground platforms along the different MTR lines. The aboveground platforms are built at ground level or elevated and directly open to the atmosphere. The underground platforms are enclosed with active ventilation and platform screen doors installed for passenger safety. These feature full height glass and metal separating partitions that run from the station floor to ceiling. A total of twenty nine aboveground and thirty nine underground platforms were surveyed in the present study covering five different MTR lines.

The six microenvironments were distributed in major populated residential, commercial and industrial areas. Residential areas are characterized by high population density; commercial areas with intensive traffic and pedestrian flow, commonly featured high rise buildings forming street canyons. Industrial areas in this study include districts that host warehouses and small scale industrial activities. These areas are also close to active cargo ports and heavy duty trucks shuttle goods containers. The distribution of the areas is shown in Figure 2 and the entire study areas encompass more than 60% of total permanent population of Hong Kong (HKCSD 2013).

2.3 Route design

Microenvironment and in-cabin measurement routes

Trips in public transport typically include several activities that contribute to a passenger's exposure including walking to a transit stop, waiting for the vehicle, riding it and often changing transport modes. In this study we included waiting for transit and riding to a destination, as both were expected to represent important components in a commuter's daily exposure profile. Figure 2a shows the study routes and areas covered during the campaign. A total of five diesel franchised bus routes, five LPG bus routes and six MTR routes were chosen to represent typical journeys that connect residential neighbourhoods with commercial and industrial areas (Fig. 2a). Each bus route crosses different areas and includes bus stops and/or termini with different characteristics. The MTR routes include different lines with both AG and UG platforms. Busses and trains are frequent in Hong Kong (every ~1-15 min during non-peak hours), which makes wait times short so it is difficult to assure that measurements of air quality are representative of the microenvironment. Measurements were made for at least ten minutes for each microenvironment where passengers waited for transport in each route trip. .

Time integrated exposure measurement routes

In addition to monitoring distinct microenvironments, two routes were designed to simulate a passenger exposure in point-to-point travel while taking different transport options as shown in Figure 2b. One route connects Mongkok (MK) to Tsin Sha Tsui (TST) along Nathan Road, a busy commercial corridors with more than 30% of total traffic flow being franchised buses (Legco 2010). The other route connects Sheung Wan (SW) to Causeway Bay (CB) along Des Voeux Road and Causeway Road, with about 35% of total traffic flow as franchised buses (Legco 2010). This represents a typical trip between residential and commercial areas. Both routes were undertaken as round trips; one way using diesel franchised bus and the return by MTR for multiple trips. Bus trips started with a wait at the roadside bus stop and ended with arrival at the destination, while MTR trips started at the street level entrance to the MTR station closest to the bus stop, and ended at the ground-level street exit of the station.

2.4 Measurement protocol

The campaign was performed over 45 weekdays between May 27th and September 11th, 2013. Each measurement day ran between 1000 to 1700 hours, and a trained researcher carried the MEMS along the designated routes. In order to cover the heterogeneity of air pollutant concentrations in various microenvironments, the measurement period was primarily non-peak hours of public transport operations since rush hour measurements were practically difficult due to limitations of crowding and carrying the MEMS into the vehicles. Our main objective is to evaluate the air pollution characteristics in various microenvironments in different transport modes to form a basis for more accurate estimation of daily dose of exposure. The schedule of the trips was randomized to avoid the systemic bias of sampling by different times of the day. Total of 119 trips were carried out for the microenvironment routes, 113 of which were successful including 36 MTR, 60 diesel bus and 17 LPG bus trips with each measurement trip covering 5-10 transport microenvironments. The unsuccessful trips were due to incomplete data and malfunctioning instruments. Each of the two time integrated exposure routes was repeated three times on different days, all during non-peak hours. For each route, the round trips were repeated 3-5 times consecutively lasting for about two hours in order to allow the comparison between the bus trip and MTR trip in the same time window. Although smoking is strictly forbidden in any of the bus or MTR conveyances as well as at MTR platforms and bus termini, a special attention was dedicated to the possible surrounding smoking event during the field measurement and a tag of smoking was marked in the mobile app as shown in Figure 1b for data screening prior to data analysis.

Time synchronization, zeroing and flow checks were carried out on all particle instruments at the beginning of each day. The wick in the CPC was recharged with isopropanol and a new filter strip was installed in the microAeth. During field work, the conditions of instruments were monitored by the phone app which issued an alert if maintenance was necessary. The Q-trak was calibrated with standard gases (Linde) at the beginning of the campaign in addition to weekly zero and span checks. The diffusion dryer was refilled with the fresh desiccant each day. During the campaign, research staff recorded the time and duration in each microenvironment, noted surrounding activities and possible smoking events along the details of the route written in a log sheet. Data and notes were downloaded to a computer each day.

2.5 Data analysis

The OPS reports particle number size distribution from 0.3 to 10 μm. For this study, the particle size channels less than 2.5 μm were used to calculate the $PM_{2.5}$ mass concentration assuming particle density of 1 g/cm^3. A side by side comparison test with a $PM_{2.5}$ cyclone equipped Beta Attenuation Monitor (BAM, Model 1020, Metone), was performed in ambient conditions in urban area of Kowloon Tong, allowing an estimate of the correction factor for $PM_{2.5}$. We understand this may depend on particle characteristics, but, individual calibration for different microenvironments was not feasible in the study. We have applied the same correction factor to all OPS data. The raw BC data from the microAeth were adjusted to compensate for filter loading effects and UFP number concentrations higher than 100,000 particles cm^{-3} were corrected for coincidence error by the following equation (Westerdahl et al. 2005):

$y=38456*e^{0.00001x}$ (R^2=0.817)

Where x is the raw UFP number concentration in unit particles cm^{-3} and y is the corrected UFP number concentration in unit particles cm^{-3}.

The pollutant concentration measured in the six microenvironments and three in-cabin environments were first identified in the database and separated into different routes and organized for statistical analysis. For microenvironments that cover different residential, commercial and industrial areas, the measurements were also categorized by area to investigate the spatial variation of the pollutant concentrations. Unpaired *t*-tests estimated statistical confidence for differences in concentrations. The coefficients of variance (COV) were calculated to account for the variance of pollutant concentrations in the various microenvironments. This provides information on the degree of spatial uniformity of pollutant concentrations, with COV approaching zero representing uniformity.

For exposure route measurements, the integrated exposure (*IE*) was calculated from:

$$IE=\Sigma C_i \times T_i \times AR \qquad \text{Equation 1.}$$

Where, C_i represents the pollutant concentration in different microenvironments, while T_i represents the time of stay in the microenvironment and *AR* is the aspiration rate, here 4.8 L min^{-1} (EPA 2011).

3. Results and Discussions

3.1 Pollutant concentration in various microenvironments

Fig. 3. Pollutant concentration in various microenvironments in public transport systems.

Figure 3 shows box plots and histograms of pollutant concentrations measured in bus stops, bus termini and on MTR platforms. Overall, enclosed termini and busy roadside environments had the highest pollutant concentrations for $PM_{2.5}$, BC, UFP and CO, while the AG and UG platforms showed consistently lower pollutant concentrations than other microenvironments. For example, the average pollutant concentrations in enclosed termini are 2.1, 2.4, 2.9 and 2.3 times of those on underground platforms for $PM_{2.5}$, BC, UFP and CO, respectively, indicating the important differences in passenger's exposure in different transport systems. Although AG platforms may be more affected by the local urban environments as they show a larger concentration range for different pollutants, there is no significant difference in average concentrations observed between AG and UG platforms for either gases or particles (p>0.05) possibly due to varying ventilation conditions in different underground environments as reported earlier (Cheng and Yan 2011, Kam et al. 2011a). The COVs of average concentrations are 0.23, 0.43, 0.42 and 0.46 for $PM_{2.5}$, BC, UFP and CO, respectively. $PM_{2.5}$ had a much lower COV value than BC and UFP, an indication of more homogeneous distribution of $PM_{2.5}$ in urban areas (Wilson et al. 2005). It may also be possible that there exists a slight underestimation of the smaller sized ultrafine particles due to the limitation of OPS measurement that induces less variation from vehicle emission contributions. BC and UFP had similar COV values due to their common sources from vehicle emissions, especially diesel fuelled vehicles (Quintana et al. 2014), as is also seen in the strong correlation (R=0.95) between their average concentrations in different microenvironments (Data not shown). Variation of BC and UFP concentrations in urban atmosphere has been reported by studies on ambient environments (Moore et al. 2009, Wang, Hopke and Utell 2011). The large COVs values observed among different transport microenvironments in this study also confirms that such heterogeneity exists in urban commuter's daily exposure pattern choosing different public transport modes. CO had similar COV levels to BC and UFP, and its average concentrations were also higher in busy roadside and enclosed termini microenvironments. Although CO has been frequently used as vehicle emission marker, it is not a distinct tracer for diesel vehicles compared with gasoline and LPG fueled vehicles (Chan et al. 2007, Ning and Chan 2007). The similar distribution patterns of CO, BC and UFP clearly showed the impact of overall traffic emissions on commuter's daily exposure.

3.2 Distribution of microenvironment pollutant concentrations in different areas

Fig. 4. Box plots of pollutant concentrations in different urban areas.

The spatial variation of pollutants in different places were further grouped and shown as box plots for industrial, commercial and residential areas in Fig. 4. Busy roadside bus stops in industrial areas had significantly higher average $PM_{2.5}$ concentrations than other areas, while commercial and residential areas were similar (Fig. 4). The same trend was also observed for BC and UFP, showing the dominant impact of traffic on roadside air quality, especially that the predominant flow of diesel fuelled goods fleets in industrial areas (Legco 2010). However, secondary roadside environments showed less variation of pollutant concentrations than busy roadside. The measured average UFP concentrations among different microenvironments were in reasonable range of reported varying values (Morawska et al. 2008, Kumar et al. 2014) . As shown in the Figure 4, very high UFP concentrations of up to >100,000 particles cm^{-3} were measured in the busy roadside and enclosed terminus with high occurrence of diesel bus fleet, but UFP concentrations were much lower in the subway platforms and secondary roadside with less diesel fleet influence. The finding was consistent with an earlier study in Hong Kong(Tsang, Kwok and Miguel 2008). The diversity of local environments and fleet intensity/composition greatly contributes to the heterogeneity of the UFP not only among different cities but also in different microenvironments within a city. There were no significant spatial differences observed for BC, UFP and CO (p >0.05), while industrial secondary roadside areas showed slightly higher concentrations than commercial and residential areas, perhaps due to additional source from industrial and port activities. In open termini where diesel and LPG buses dominate, there was less variation in particle concentrations among different areas, and lower levels overall compared to busy roadside bus stops. Enclosed terminus had significantly higher pollutant concentrations than open-air facilities in all areas, suggesting that limited ventilation conditions would contribute to enhanced exposure.

The CO concentrations showed a unique profile while comparing area variation as shown in Figure 4, in which open and enclosed termini in residential area had the highest concentrations. The road public transport network in Hong Kong is primarily served by franchised diesel buses and the rail-based MTR, while public light LPG buses play a supplementary role in the provision of public transport services and termini in residential areas are more populated by LPG buses (HKTD 2014). Previous investigations of LPG bus fleets (Chan et al. 2007) have shown their predominant CO emissions compared to other fleets, and a recent study by our group also showed evidence that catalytic converters LPG buses frequently malfunction (Ning, Wubulihairen and Yang 2012). The high CO concentrations observed in residential termini indicate tailpipe emissions from these vehicles could enhance passenger exposure. While not measured in this study, VOC emissions from incomplete combustion in combination with malfunctioning catalysts might also increase exposure in these microenvironments although further investigations are much needed to understand the magnitude of this contribution. Railway platforms show lower overall concentrations than other microenvironments in all areas, except aboveground platforms in the commercial area (Fig. 4), which has PM concentrations comparable or higher than other areas. This probably arises because the stations in commercial areas are designed with easy access by the pedestrians from roadways and direct connections with other roadway public transport. As a result, the stations have their aboveground platforms surrounded by narrow streets with high density of tall buildings, high traffic intensity with diesel fleets and crowded pedestrians. The CO concentrations on platforms, was at the lower end of the concentration range found in the microenvironments.

3.3 In-cabin pollutant concentrations in different transport systems

Fig. 5. In-cabin pollutant concentrations by different transport systems. (a) $PM_{2.5}$, (B) Black carbon (BC), (c) Ultrafine particle (UFP), (d) CO

Figure 5 presents the in-cabin pollutant concentrations measured while travelling by different modes of transport. As shown in Figure 5a, the $PM_{2.5}$ concentrations in the three cabins have comparable averages of 11.7, 8.2 and 10.2 μg/m^3 for LPG bus, diesel bus and MTR cars, respectively. BC and UFP pollutants displayed identical concentration profiles, but substantially different compared to $PM_{2.5}$, with diesel bus cabins showing significantly higher concentrations than LPG buses (p<0.01) and MTR cars (p<0.01) for both pollutants. This observation suggests pollutants from traffic penetrate into the bus cabins during travel. BC and UFP are tracers for diesel exhaust emissions (Quintana et al. 2014), so their higher concentrations in diesel buses may be due to the self-pollution of diesel engine emissions (Rim et al. 2008) or because nearby vehicles emit these pollutants. Bus age, type and the position of the ventilation inlet are important variables affecting the degree of self-pollution (Behrentz et al. 2004, Sabin et al. 2005). The large variation of pollutant concentrations in diesel bus cabins may arise because the local buses have mixed fleets with more than 60% of Euro I and II, and 17% of Euro IV and V standards (HKENB 2013). It is also possible that franchised diesel and LPG public light buses serve different commuter groups and operate on different routes, resulting in more diesel traffic volume for the diesel bus routes (Kaur and Nieuwenhuijsen 2009). Nevertheless, it should be noted that the BC concentrations inside diesel and LPG bus cabins (11.6 ± 7.6 μg/m^3 and 7.5 ± 3.2 μg/m^3, respectively) were on the lower end of the reported values (range ~ 5-50 μg m^{-3}) in the literature (Fruin, Winer and Rodes 2004, Janssen et al. 2011). A few investigators (Knibbs and de Dear 2010, Zuurbier et al. 2010) have also found much higher concentrations of UFPs inside buses and attributed these to cabin ventilation and leakage. Figure 5d shows that the average concentrations of CO were highest inside LPG buses (~2.9±1.8 ppm) followed by diesel buses (1.0 ± 0.5 ppm) and MTR cars (0.3 ± 0.1 ppm), significantly different for all combinations (p < 0.01). Chan and Liu (Chan and Liu 2001) carried out exposure assessment in similar microenvironments in Hong Kong in 1999 and reported in-cabin CO concentrations to be 1.8~2.9 ppm for diesel buses, much higher than the observed in the present study, probably attributed to the improved air ventilation condition for on-road vehicles and more effective vehicle emission controls added since that study.

Fig. 6. Typical time series of pollutant concentrations while travelling by different transport systems.

Figure 6 shows typical time series of the measured pollutant concentrations by different transport modes. Four trip-based measurements were presented to cover (a). diesel bus; (b). LPG bus; (c). aboveground and (d). underground railway routes with representative microenvironments. In addition to $PM_{2.5}$, BC, UFP and CO pollutants, CO_2 concentration was also included as an indicator of in-cabin and ambient environments. As shown in Figure 6a, the in-cabin concentrations of BC and UFP in diesel bus routes recorded both high (50.7±15.5 μg/m^3 and 4.1±1.3 ×10^4 particles cm^{-3}, respectively) and low (11.1±4.0 μg/m^3 and 2.4±0.4×10^4 particles cm^{-3}, respectively) levels while taking two different buses in separate roadway sections, a clear indication of the large span of their distribution as discussed in previous section. Meanwhile, substantial variation of their concentrations were observed while waiting in closed termini and busy roadside showing the direct impact of vehicle emissions on the passenger exposure to these pollutants. In other transport modes (Figure 6b to 6d), BC and UFP showed much lower in-cabin concentrations compared to the ambient microenvironments, except for an interesting observation of increased BC inside MTR car while travelling through an underground tunnel. A similar pattern was observed for $PM_{2.5}$, but not for UFP. It may be attributed to the pressure change between the in-cabin and outside while entering tunnel that changes the penetration rate of particle pollutants. Diesel bus routes seems to show elevated BC and UFP concentrations when compared to other modes, with lower levels in AG and UG MTR routes, and in LPG bus route. $PM_{2.5}$ concentrations, however, showed relatively less variation in different transport modes and there is no significant difference observed of their in-cabin concentrations by the routes. For CO, LPG bus route observations showed much higher average concentrations in open termini as shown in Figure 6b. The contrast between CO versus BC and UFP concentrations profiles in enclosed termini (Figure 6a) and open termini (Figure 6b) suggest the dominant impact of vehicle emissions for passengers while waiting for boarding.

3.4 Inter-comparison by different transport modes

Fig. 7. Comparison of integrated exposure to pollutants by diesel bus and by MTR.

The total integrated exposure by two public transport routes through busy business districts on franchised bus and the MTR is shown in Fig. 7 as a time series for travel from Monkok (MK) to Tsim Sha Tsui (TST) (Figure 7a) and from Sheung Wan (SW) to Causeway Bay (CB) (Figure 7b). Each trip includes waiting at stops and platforms and in-cabin exposure. The pollutant patterns were consistent between the multiple runs so only one profile is presented. In general, the traffic related pollutants of BC, UFP and CO had much higher average concentrations during the bus trip than on the MTR. The TST to MK trip, for example, has average BC, UFP and CO concentrations of 5.3±5.0 μg/m^3, 2.9±2.7×10^4 particles cm^3 and 1.0±0.7 ppm for bus trip, but only 3.6±2.1 μg/m^3, 0.9±0.5×10^4 particles cm^3 and 0.4±0.5 ppm for MTR trip. Their concentrations inside bus cabins increased when the door opens at bus stops followed by a gradual decay as seen in the PM time series (Fig 7). The time spent in different microenvironments is an important component in estimating exposure. On average, the total trip time by bus and by MTR is 24 ± 2 minutes and 14± 1 minutes, respectively, between MK and TST; and 29± 2 minutes and 19 ±1 minutes, respectively, between SW and CB during this study.-While the waiting time in bus stops was comparable with those in platform for MTR trip, the longer trip time by bus due to the travel time on congested roadways highlights the importance of the in-cabin exposure to pollutants. It is also worth noting that the monitoring route was carried out during non-peak hours so even longer times are expected for bus trips during peak hours when most commuters use the transport system.

Integrating the pollutant concentrations and time spent suggests a the trip based average dose of exposure to $PM_{2.5}$, BC, UFP and CO by taking bus from MK to TST were 511.4±219.6 μg, 1.7±1.5 μg, $3.5\pm1.3\times10^{9}$ particles and 235.5±83.2μg, respectively, while the return trip by MTR had average dose of 400.5±97.3 μg, 0.3±0.1 μg, $0.8\pm0.2\times10^{9}$ particles and 12.0±9.1 μg for the pollutants, representing average ratios of 1.3, 5.7, 4.4 and 19.6 times between bus trip and MTR trip for $PM_{2.5}$, BC, UFP and CO, respectively. A similar comparison was also observed in the other route between SW and CB with corresponding ratios of 0.7, 2.0, 2.5 and 3.4 by taking bus versus MTR. The results showed interesting comparison between $PM_{2.5}$ and other pollutants with relatively consistent exposure for $PM_{2.5}$ (ratio of 0.7 to 1.3) but much higher exposure risks for traffic related pollutants of BC, UFP and CO for passengers taking buses in urban public transport systems.

Conclusions

The present study employed a Mobile Exposure Measurement System to investigate $PM_{2.5}$, BC, UFP and CO concentrations in various public transport microenvironments and passenger exposures to these pollutants by different routes in the highly urbanized city of Hong Kong. The heterogeneity of pollutant concentrations in the microenvironment and in-cabin during transit were investigated to identify the factors that may affect the passengers' air pollutants exposure. Busy roadside and enclosed termini were found to have the highest average particle concentrations in contrast to the lowest in the MTR platforms indicating the importance of design and ventilation of built environments. Traffic-related pollutants BC, UFP and CO showed much larger variation than $PM_{2.5}$ across different microenvironment and different areas of the city confirming their heterogeneous nature and stressing the importance of characterizing transit microenvironments exposure in part of daily dose of exposure in epidemiological studies instead of using area pollutant concentrations as indicator of exposure. In-cabin pollutant concentrations showed different patterns by different transport modes with diesel bus cabins having significantly higher BC and UFP concentrations than other modes, suggesting possible self-pollution issues and/or penetration of on-road pollutants inside cabins during bus transit. Higher concentrations of CO inside LPG fuelled buses were also found and could possibly be due to malfunctioning of catalytic convertor and leakage from engine compartment into the cabin. Comparing a passenger's total exposure on different modes transport indicated that bus route showed higher integrated doses than MTR routes, enhanced by longer travel times on roadways.

Current air quality regulation focuses on emission reduction as a mechanism to improve ambient or roadside air quality. However, the heterogeneity of air pollutant concentrations observed in the public transport microenvironments suggests the need for exposure based policy making in addition to tail-pipe solutions, since commuter trips may contribute to an importance fraction of daily exposure especially in cities. Transport optimization to reduce congestion, bus route reorganization to less polluted areas, and encouraging commuter choice for cleaner transport modes may contribute to an effective reduction in a passenger's exposure. Future investigations might usefully examine the effectiveness of bus ventilation systems, inflow when doors are open and the temporal variation of commuter exposure patterns, i.e. peak versus non-peak hours, all of which are needed to develop a better understanding of the comprehensive exposure profiles and provide the basis for cost-effective air and public health policy making.

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Figures and tables

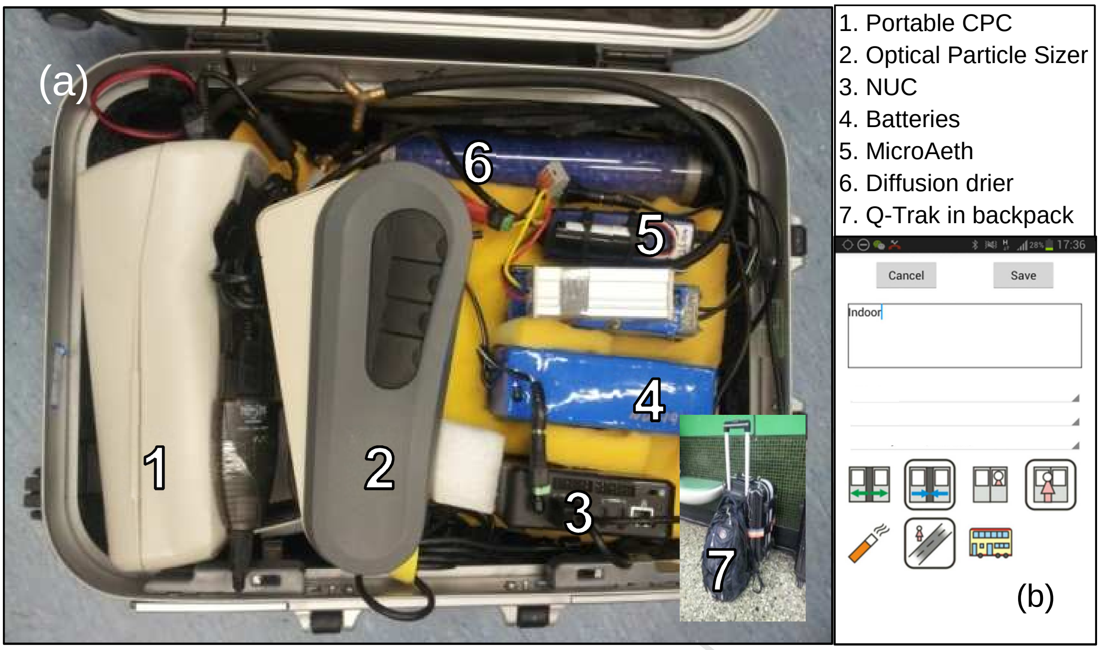

Figure 1 Setup of Mobile Exposure Measurement System (MEMS): (a). The internal setup of the portable instruments; (b). Screenshot of the developed mobile app.

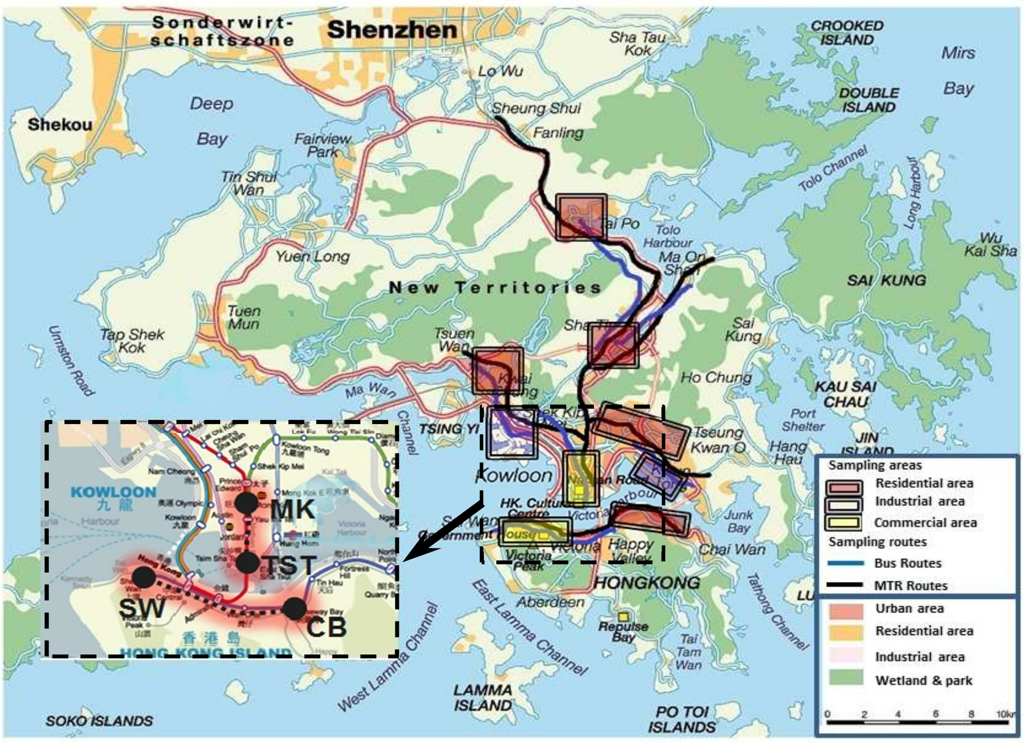

Figure 2 The transport microenvironments (main plot) and integrated exposure based (subplot) sampling routes and areas.
Note: The subplot shows two sampling routes between Mongkok (MK) and Tsin Sha Tsui (TST); and between Sheung Wan (SW) and Causeway Bay (CB).

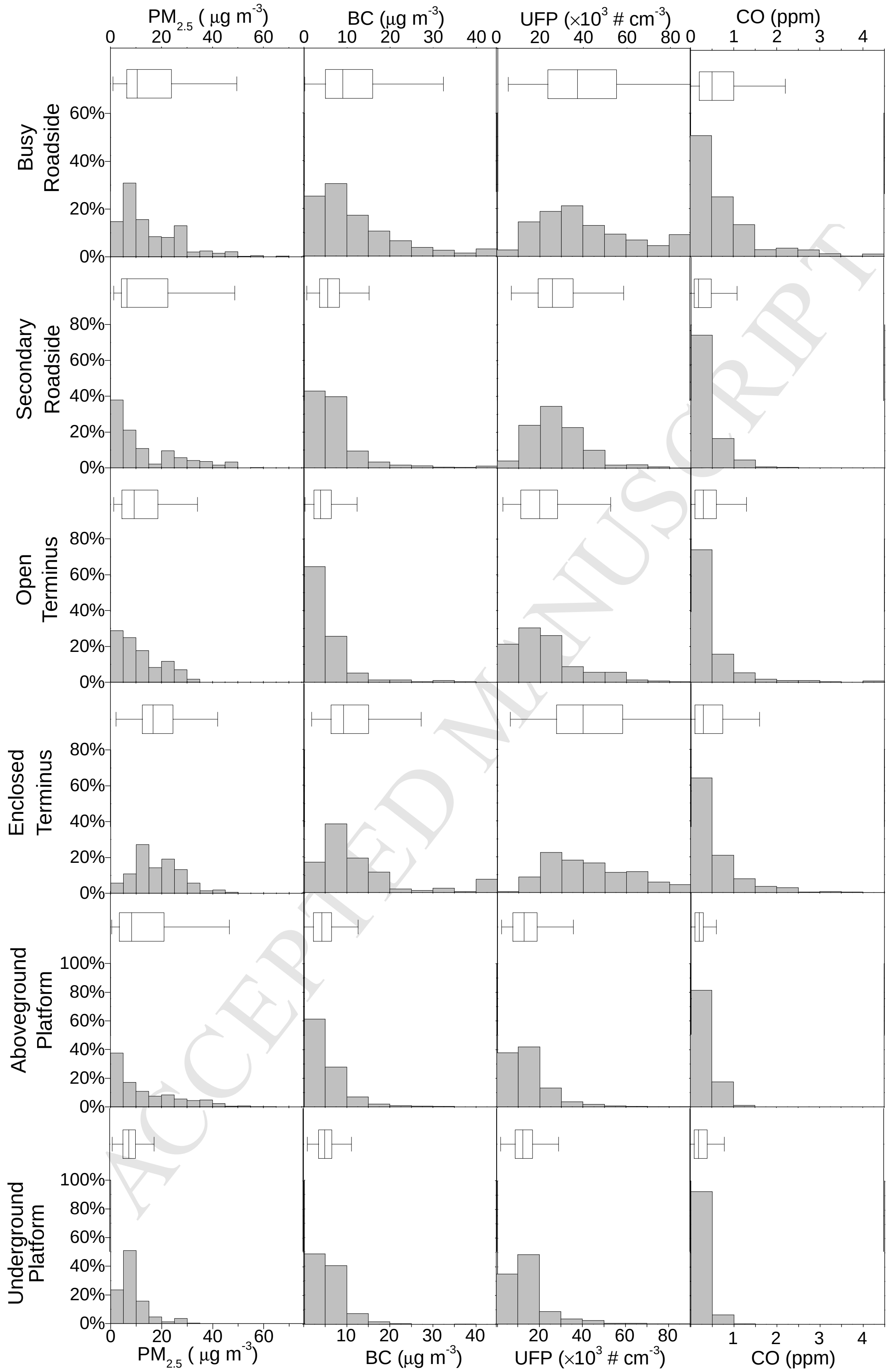

Figure 3 Pollutant concentration in various microenvironments in public transport systems.

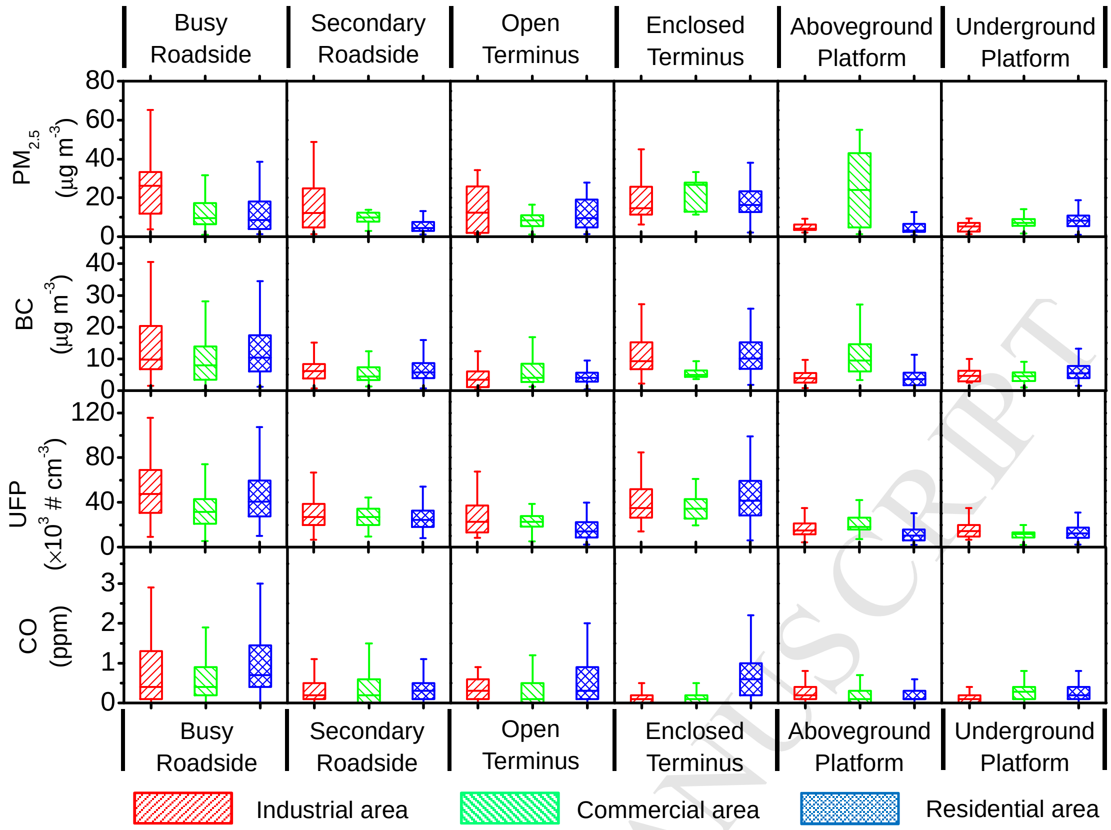

Figure 4 Box plots of pollutant concentrations in different urban areas.

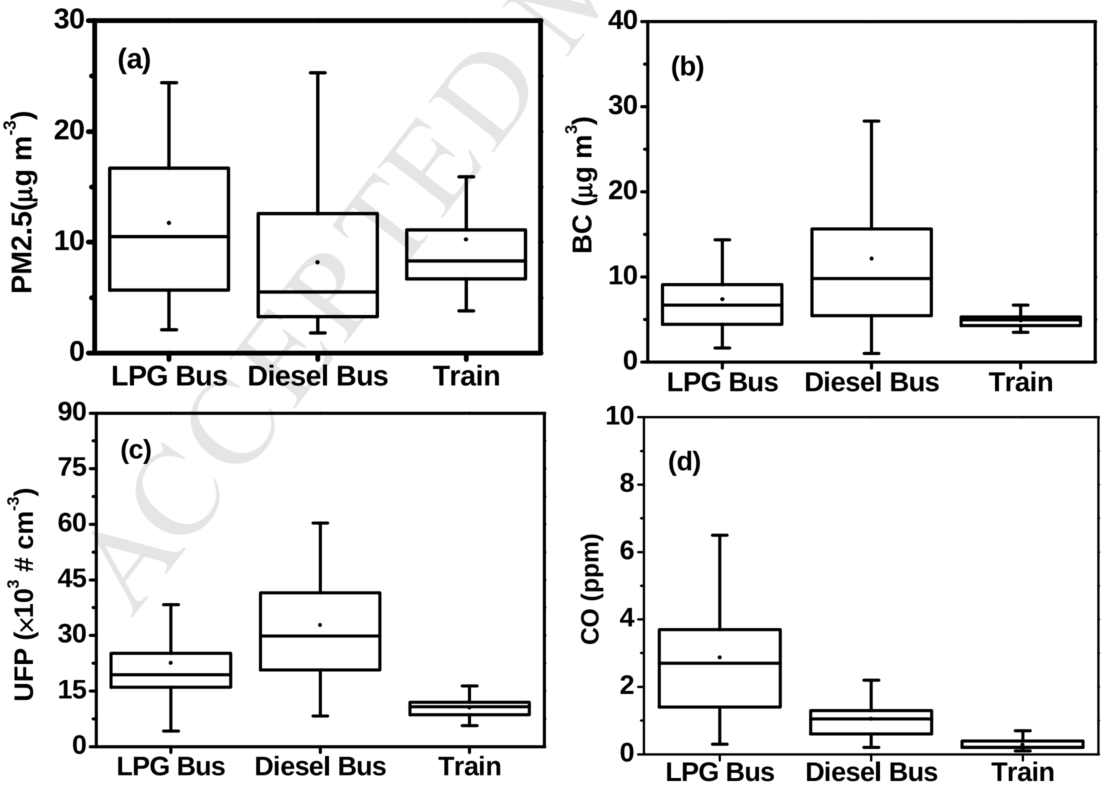

Figure 5 In-cabin pollutant concentrations by different transport systems: (a) $PM_{2.5}$; (b) Black carbon (BC); (c) Ultrafine particles (UFP); (d) CO

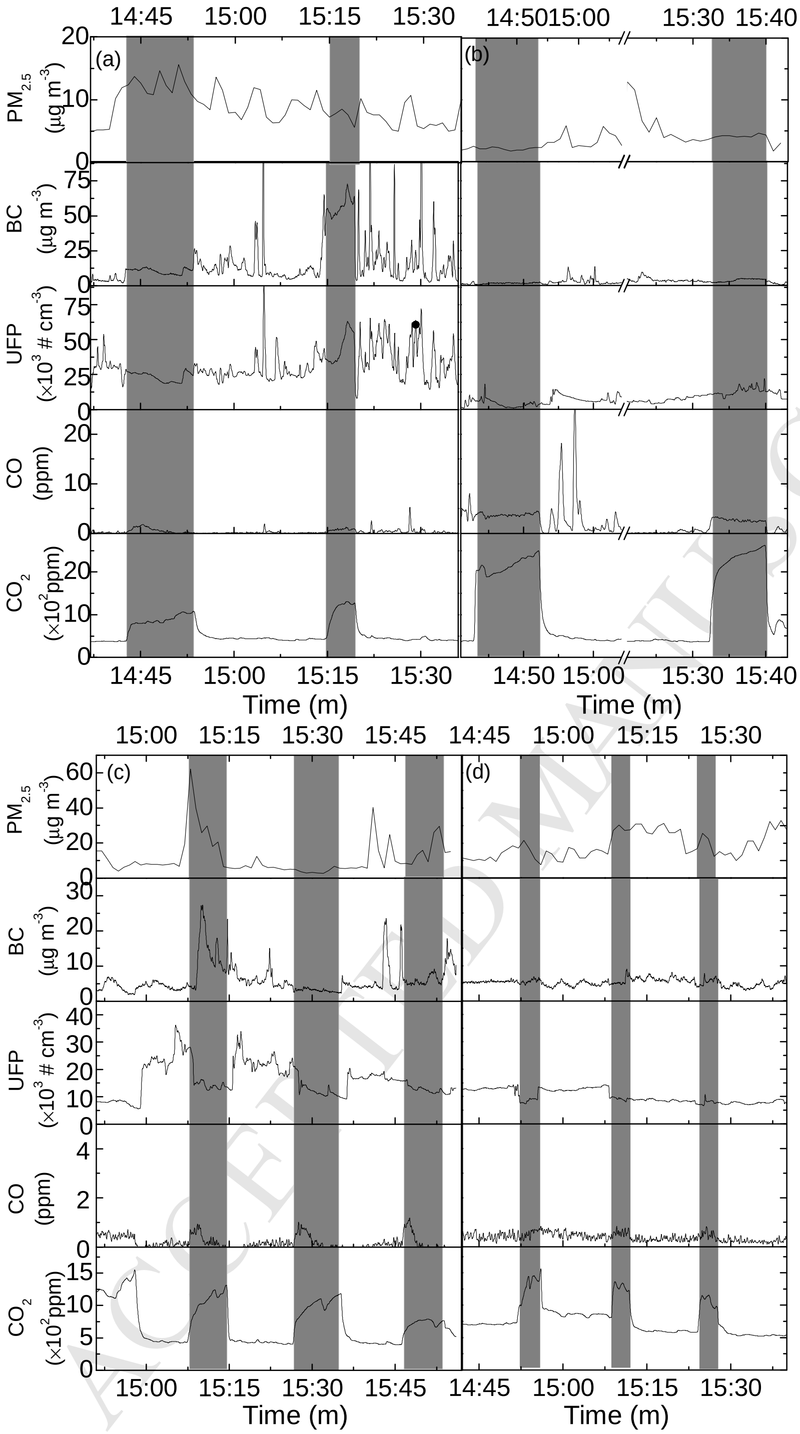

Figure 6 Typical time series of pollutant concentrations while travelling by different transport systems. (a) Diesel Bus; (b) LPG Bus; (c) MTR AG Platform; (d) MTR UG Platform

Note: Dark gray color represents the time in the bus or MTR cabin.

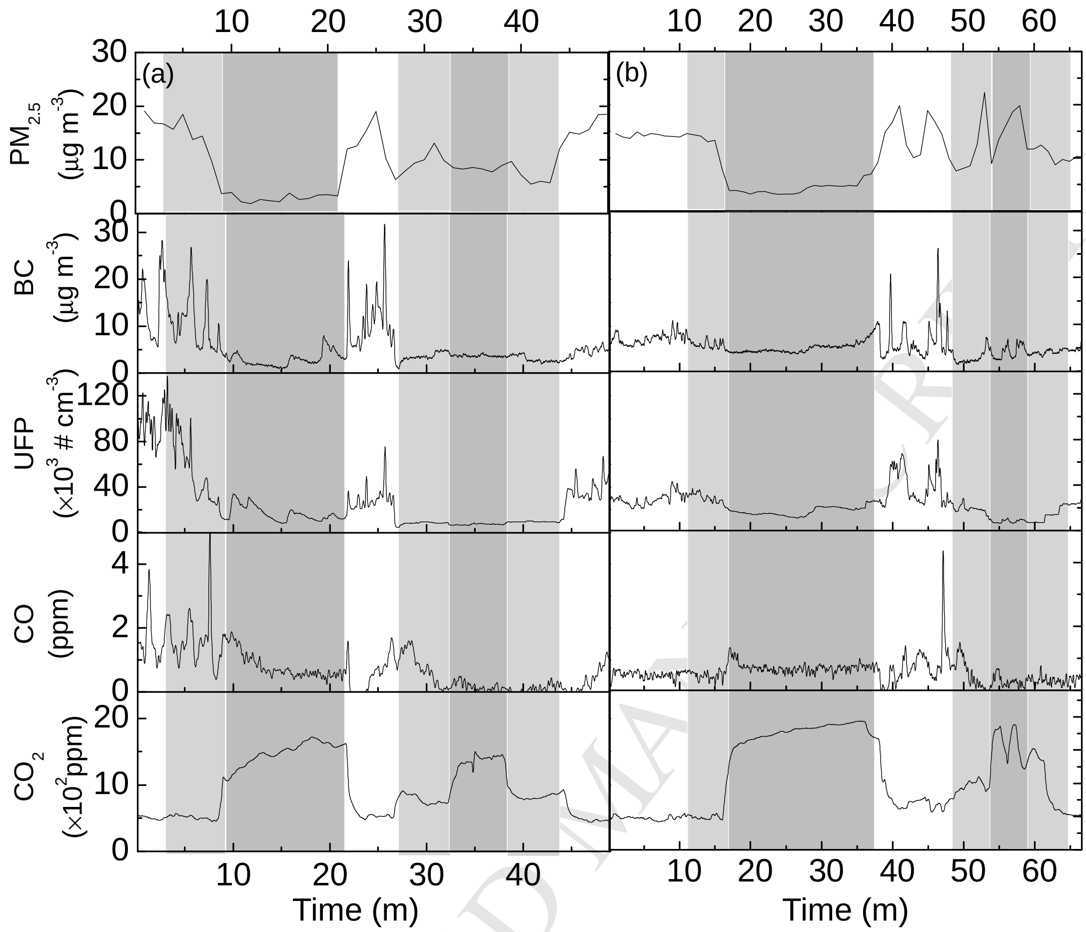

Figure 7 Comparison of integrated exposure to pollutants by diesel bus and by MTR. (a) From Mongkok (MK) to Tsim Sha Tsui (TST); (b) From Sheung Wan (SW) to Causeway Bay (CB)

Note: Dark gray color represents the time in the bus or MTR cabin while the light gray color represents the time waiting at the roadside stops and platforms or walking inside the MTR stations.

- Air pollutants were measured in categorized public transport microenvironments
- High heterogeneity of pollutants concentrations exists in public transport system
- Bus riders have higher integrated dose of exposure than railway riders
- Self-pollution may be an important source of in-cabin pollutants in buses