

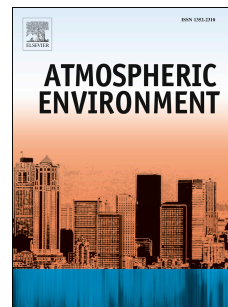


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Heterogeneity of passenger exposure to air pollutants in public transport microenvironments

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1                   **Heterogeneity of passenger exposure to air pollutants in public transport**  
2                   **microenvironments**

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4  
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48 **Abstract**

49 Epidemiologic studies have linked human exposure to pollutants with adverse health effects.  
50 Passenger exposure in public transport systems contributes an important fraction of daily  
51 burden of air pollutants. While there is extensive literature reporting the concentrations of  
52 pollutants in public transport systems in different cities, there are few studies systematically  
53 addressing the heterogeneity of passenger exposure in different transit microenvironments, in  
54 cabins of different transit vehicles and in areas with different characteristics. The present  
55 study investigated PM<sub>2.5</sub> (particulate matter with aerodynamic diameters smaller than 2.5µm),  
56 black carbon (BC), ultrafine particles (UFP) and carbon monoxide (CO) pollutant  
57 concentrations in various public road transport systems in highly urbanized city of Hong  
58 Kong. Using a trolley case housing numerous portable air monitors, we conducted a total of  
59 119 trips during the campaign. Transit microenvironments, classified as 1). busy and  
60 secondary roadside bus stops; 2). open and enclosed termini; 3). above- and under-ground  
61 Motor Rail Transport (MTR) platforms, were investigated and compared to identify the  
62 factors that may affect passenger exposures. The pollutants inside bus and MTR cabins were  
63 also investigated together with a comparison of time integrated exposure between the transit  
64 modes. Busy roadside and enclosed termini demonstrated the highest average particle  
65 concentrations while the lowest was found on the MTR platforms. Traffic-related pollutants  
66 BC, UFP and CO showed larger variations than PM<sub>2.5</sub> across different microenvironments  
67 and areas confirming their heterogeneity in urban environments. In-cabin pollutant  
68 concentrations showed distinct patterns with BC and UFP high in diesel bus cabins and CO  
69 high in LPG bus cabins, suggesting possible self-pollution issues and/or penetration of on-  
70 road pollutants inside cabins during bus transit. The total passenger exposure along selected  
71 routes, showed bus trips had the potential for higher integrated passenger exposure compared  
72 to MTR trips. The present study may provide useful information to better characterize the  
73 distribution of passenger exposure pattern in health assessment studies and the results also  
74 highlight the need to formulate exposure reduction based air policies in large cities.

75  
76 **Keywords:** Black carbon, CO, bus cabins, roadside bus stop, bus terminal, PM<sub>2.5</sub>, subway  
77 platform, ultrafine particles

78

## 79 1. Introduction

80  
81 Numerous epidemiological studies have demonstrated associations between exposure to air  
82 pollution and increased mortality (Dockery et al. 1993, Lin et al. 2013), while airborne fine  
83 particulate matter ( $PM_{2.5}$ ,  $d_p < 2.5 \mu m$ ) plays an especially important role in adverse impact on  
84 pulmonary and cardiovascular outcomes (Dreher 2000). However, many epidemiological  
85 studies have assumed that routinely monitored ambient pollutant concentrations are  
86 surrogates for actual exposure, and few studies have addressed whether there is a predictable  
87 relationship between exposure and concentration in different locations within a city (Cao and  
88 Frey 2011). This is especially true to urban areas where there is a heterogeneous distribution  
89 of pollutant concentrations in the ambient air and the public have different time/activity  
90 patterns in various microenvironments that contribute to daily exposure (Ostro et al. 2006).

91  
92 Hong Kong is a highly urbanized city with a population of over 7 million, and a well-  
93 developed public transport system accounting for some 12 million passenger journeys every  
94 day, of which 41% are by Mass Transit Railway (MTR), followed by 32% with diesel-fuelled  
95 franchised buses and 15% with Liquefied Petroleum Gas (LPG) public light buses (HKTD  
96 2013). Such heavy reliance on public transport makes individual exposure to air pollutants  
97 inside the transport system a potentially significant component of daily integrated exposure.  
98 Although most commuters spend only a short fraction of time daily in the transport system,  
99 high pollution levels experienced during travel may contribute significantly to total individual  
100 exposures (Nieuwenhuijsen, Gomez-Perales and Colville 2007). Seaton et al. (Seaton et al.  
101 2005) investigated commuter exposure to  $PM_{2.5}$  in London and found spending 2 hours in the  
102 metro system per day would increase personal 24-hour exposure by  $17 \mu g m^{-3}$ .

103  
104 Studies in various cities have also shown that public transport system may represent a  
105 combination of unique microenvironments with different source characteristics making them  
106 quite different from those typical outdoors or even indoors (Both et al. 2013, Knibbs, Cole-  
107 Hunter and Morawska 2011). Passengers can be exposed to the air pollutants substantially  
108 different from those at street level air in terms of gas concentrations and PM concentrations  
109 and chemical composition (Aarnio et al. 2005, Kam et al. 2011b). For example, investigators  
110 (Cheng, Liu and Yan 2012, Nieuwenhuijsen et al. 2007) observed a considerable increase (~  
111 20 to 50 % greater) of  $PM_{2.5}$  mass concentration compared to outdoor air. Thus ambient air  
112 monitoring data cannot be effectively used to estimate the daily dose of exposure with  
113 different characteristics of air pollutants in transit system.

114  
115 During the last decade, a few studies in Hong Kong investigated passenger pollution  
116 exposure levels. Chan et al. (Chan et al. 2002) measured  $PM_{2.5}$  and  $PM_{10}$  mass concentrations  
117 in four different transport modes including the railway system and buses. Recently, Wong et  
118 al. (Wong et al. 2011) measured carbon monoxide and  $PM_{2.5}$  concentrations inside bus cabins  
119 in Hong Kong. These previous studies clearly demonstrated that  $PM_{2.5}$  displayed different  
120 characteristics in comparison with ambient environments. However, there were no systematic  
121 investigations of the distribution of traffic-related pollutants, such as black carbon (BC),  
122 ultrafine particles (UFP) in different transport microenvironments, which limits our accurate  
123 understanding of the daily dose of exposure and knowledge of exposure mitigation measures.  
124 This study investigates  $PM_{2.5}$ , BC, UFP and CO distributions in transport microenvironments  
125 and in cabins of different transit modes, including diesel franchised buses, LPG public light  
126 buses and the MTR system. Total exposure on typical commute routes by different transit  
127 modes was also compared. The results of the study should allow more accurate estimates of

128 population daily dose for epidemiologic research and provide a basis for exposure reduction  
129 based air policy making.

130

## 131 **2. Experimental methodology**

### 132 **2.1 Portable instrumentation**

133 Pollutant concentrations were measured using a Mobile Exposure Measurement System  
134 (MEMS) with a trolley case housing portable air monitors, a data acquisition system and a  
135 global positioning system (GPS) as shown in Figure 1. A portable condensation particle  
136 counter (CPC, TSI 3007) was used to measure ultrafine particle (UFP) number concentration .  
137 Although the CPC measured particles in the size range of 10-1000 nm, number concentration  
138 is dominated by smaller sized particles (diameter <100 nm) (Morawska et al. 2008). A micro  
139 Aethalometer (microAeth<sup>®</sup> Model AE51, Aethlabs) was used for measuring black carbon  
140 (BC) concentration. An Optical Particle Sizer (OPS, TSI<sup>®</sup> model 3330) was used for PM<sub>2.5</sub>  
141 concentration measurement and a Q-trak (TSI<sup>®</sup> model 7575) was installed in a backpack to  
142 monitor carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), relative humidity (RH) and  
143 temperature (T) at high temporal resolution (one second). All instruments were connected to  
144 a mini-PC (NUC, Intel<sup>®</sup>) and the real-time data were collected and transferred to a mobile  
145 phone through Bluetooth. The measurements were displayed on the screen through a cell  
146 phone application developed by the investigators to track instrument conditions and tag  
147 special events during the campaign. Screenshot of the app is included in Figure 1b. All  
148 instruments and batteries were wrapped with sponge sheets and fitted snugly into the suitcase.  
149 A diffusion dryer was installed upstream of the OPS and microAeth to avoid interference  
150 from water vapor (Zieger et al. 2013, Cai et al. 2013), respectively.

151

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

153

### 154 **2.2 Description of transport microenvironments**

155

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

166

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

168

#### 169 *Busy and secondary roadside bus stops*

170 Transport by diesel franchised buses and LPG public light buses carries 3.8 and 1.9 million  
171 daily passenger journeys (HKTD 2013). Waiting at roadside bus stops is an important  
172 component of a commuter's daily exposure because of the proximity to road traffic emissions.  
173 We separated the roadways by their annual average daily traffic (AADT) into busy road  
174 (AADT>30,000 vehicles per day) and secondary road (AADT<20,000 vehicles per day),

175 which also reflects the distribution of the public transport such as bus routes and number of  
176 bus stops, as well as roadway characteristics (HKTD 2013).

177

### 178 *Open and enclosed termini*

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

187

### 188 *Above- and under-ground MTR platforms*

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

197

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

206

## 207 **2.3 Route design**

208

### 209 *Microenvironment and in-cabin measurement routes*

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

224

### 225 *Time integrated exposure measurement routes*

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

237

### 238 **2.4 Measurement protocol**

239

240 The campaign was performed over 45 weekdays between May 27th and September 11th,  
241 2013. Each measurement day ran between 1000 to 1700 hours, and a trained researcher  
242 carried the MEMS along the designated routes. In order to cover the heterogeneity of air  
243 pollutant concentrations in various microenvironments, the measurement period was  
244 primarily non-peak hours of public transport operations since rush hour measurements were  
245 practically difficult due to limitations of crowding and carrying the MEMS into the vehicles.  
246 Our main objective is to evaluate the air pollution characteristics in various  
247 microenvironments in different transport modes to form a basis for more accurate estimation  
248 of daily dose of exposure. The schedule of the trips was randomized to avoid the systemic  
249 bias of sampling by different times of the day. Total of 119 trips were carried out for the  
250 microenvironment routes, 113 of which were successful including 36 MTR, 60 diesel bus and  
251 17 LPG bus trips with each measurement trip covering 5-10 transport microenvironments.  
252 The unsuccessful trips were due to incomplete data and malfunctioning instruments. Each of  
253 the two time integrated exposure routes was repeated three times on different days, all during  
254 non-peak hours. For each route, the round trips were repeated 3-5 times consecutively lasting  
255 for about two hours in order to allow the comparison between the bus trip and MTR trip in  
256 the same time window. Although smoking is strictly forbidden in any of the bus or MTR  
257 conveyances as well as at MTR platforms and bus termini, a special attention was dedicated  
258 to the possible surrounding smoking event during the field measurement and a tag of smoking  
259 was marked in the mobile app as shown in Figure 1b for data screening prior to data analysis.

260

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

270

### 271 **2.5 Data analysis**

272

273 The OPS reports particle number size distribution from 0.3 to 10  $\mu\text{m}$ . For this study, the  
274 particle size channels less than 2.5  $\mu\text{m}$  were used to calculate the  $\text{PM}_{2.5}$  mass concentration



275 assuming particle density of  $1 \text{ g/cm}^3$ . A side by side comparison test with a  $\text{PM}_{2.5}$  cyclone  
 276 equipped Beta Attenuation Monitor (BAM, Model 1020, Metone), was performed in ambient  
 277 conditions in urban area of Kowloon Tong, allowing an estimate of the correction factor for  
 278  $\text{PM}_{2.5}$ . We understand this may depend on particle characteristics, but, individual calibration  
 279 for different microenvironments was not feasible in the study. We have applied the same  
 280 correction factor to all OPS data. The raw BC data from the microAeth were adjusted to  
 281 compensate for filter loading effects and UFP number concentrations higher than 100,000  
 282 particles  $\text{cm}^{-3}$  were corrected for coincidence error by the following equation (Westerdahl et  
 283 al. 2005):

$$284 \quad y = 38456 * e^{0.00001x} \quad (R^2 = 0.817)$$

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

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

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

297

$$298 \quad IE = \sum C_i \times T_i \times AR \quad \text{Equation 1.}$$

299

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

### 303 3. Results and Discussions

#### 304 3.1 Pollutant concentration in various microenvironments

305

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

307

308 Figure 3 shows box plots and histograms of pollutant concentrations measured in bus stops,  
 309 bus termini and on MTR platforms. Overall, enclosed termini and busy roadside  
 310 environments had the highest pollutant concentrations for  $\text{PM}_{2.5}$ , BC, UFP and CO, while the  
 311 AG and UG platforms showed consistently lower pollutant concentrations than other  
 312 microenvironments. For example, the average pollutant concentrations in enclosed termini  
 313 are 2.1, 2.4, 2.9 and 2.3 times of those on underground platforms for  $\text{PM}_{2.5}$ , BC, UFP and CO,  
 314 respectively, indicating the important differences in passenger's exposure in different  
 315 transport systems. Although AG platforms may be more affected by the local urban  
 316 environments as they show a larger concentration range for different pollutants, there is no  
 317 significant difference in average concentrations observed between AG and UG platforms for  
 318 either gases or particles ( $p > 0.05$ ) possibly due to varying ventilation conditions in different  
 319 underground environments as reported earlier (Cheng and Yan 2011, Kam et al. 2011a). The  
 320 COVs of average concentrations are 0.23, 0.43, 0.42 and 0.46 for  $\text{PM}_{2.5}$ , BC, UFP and CO,  
 321 respectively.  $\text{PM}_{2.5}$  had a much lower COV value than BC and UFP, an indication of more  
 322 homogeneous distribution of  $\text{PM}_{2.5}$  in urban areas (Wilson et al. 2005). It may also be

323 possible that there exists a slight underestimation of the smaller sized ultrafine particles due  
324 to the limitation of OPS measurement that induces less variation from vehicle emission  
325 contributions. BC and UFP had similar COV values due to their common sources from  
326 vehicle emissions, especially diesel fuelled vehicles (Quintana et al. 2014), as is also seen in  
327 the strong correlation ( $R=0.95$ ) between their average concentrations in different  
328 microenvironments (Data not shown). Variation of BC and UFP concentrations in urban  
329 atmosphere has been reported by studies on ambient environments (Moore et al. 2009, Wang,  
330 Hopke and Utell 2011). The large COVs values observed among different transport  
331 microenvironments in this study also confirms that such heterogeneity exists in urban  
332 commuter's daily exposure pattern choosing different public transport modes. CO had similar  
333 COV levels to BC and UFP, and its average concentrations were also higher in busy roadside  
334 and enclosed termini microenvironments. Although CO has been frequently used as vehicle  
335 emission marker, it is not a distinct tracer for diesel vehicles compared with gasoline and  
336 LPG fueled vehicles (Chan et al. 2007, Ning and Chan 2007). The similar distribution  
337 patterns of CO, BC and UFP clearly showed the impact of overall traffic emissions on  
338 commuter's daily exposure.

### 339 **3.2 Distribution of microenvironment pollutant concentrations in different areas**

340

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

342

343 The spatial variation of pollutants in different places were further grouped and shown as box  
344 plots for industrial, commercial and residential areas in Fig. 4. Busy roadside bus stops in  
345 industrial areas had significantly higher average  $PM_{2.5}$  concentrations than other areas, while  
346 commercial and residential areas were similar (Fig. 4). The same trend was also observed for  
347 BC and UFP, showing the dominant impact of traffic on roadside air quality, especially that  
348 the predominant flow of diesel fuelled goods fleets in industrial areas (Legco 2010). However,  
349 secondary roadside environments showed less variation of pollutant concentrations than busy  
350 roadside. The measured average UFP concentrations among different microenvironments  
351 were in reasonable range of reported varying values (Morawska et al. 2008, Kumar et al.  
352 2014). As shown in the Figure 4, very high UFP concentrations of up to  $>100,000$  particles  
353  $cm^{-3}$  were measured in the busy roadside and enclosed terminus with high occurrence of  
354 diesel bus fleet, but UFP concentrations were much lower in the subway platforms and  
355 secondary roadside with less diesel fleet influence. The finding was consistent with an earlier  
356 study in Hong Kong (Tsang, Kwok and Miguel 2008). The diversity of local environments  
357 and fleet intensity/composition greatly contributes to the heterogeneity of the UFP not only  
358 among different cities but also in different microenvironments within a city. There were no  
359 significant spatial differences observed for BC, UFP and CO ( $p > 0.05$ ), while industrial  
360 secondary roadside areas showed slightly higher concentrations than commercial and  
361 residential areas, perhaps due to additional source from industrial and port activities. In open  
362 termini where diesel and LPG buses dominate, there was less variation in particle  
363 concentrations among different areas, and lower levels overall compared to busy roadside bus  
364 stops. Enclosed terminus had significantly higher pollutant concentrations than open-air  
365 facilities in all areas, suggesting that limited ventilation conditions would contribute to  
366 enhanced exposure.

367

368 The CO concentrations showed a unique profile while comparing area variation as shown in  
369 Figure 4, in which open and enclosed termini in residential area had the highest  
370 concentrations. The road public transport network in Hong Kong is primarily served by  
371 franchised diesel buses and the rail-based MTR, while public light LPG buses play a

372 supplementary role in the provision of public transport services and termini in residential  
 373 areas are more populated by LPG buses (HKTD 2014). Previous investigations of LPG bus  
 374 fleets (Chan et al. 2007) have shown their predominant CO emissions compared to other  
 375 fleets, and a recent study by our group also showed evidence that catalytic converters LPG  
 376 buses frequently malfunction (Ning, Wubulihairan and Yang 2012). The high CO  
 377 concentrations observed in residential termini indicate tailpipe emissions from these vehicles  
 378 could enhance passenger exposure. While not measured in this study, VOC emissions from  
 379 incomplete combustion in combination with malfunctioning catalysts might also increase  
 380 exposure in these microenvironments although further investigations are much needed to  
 381 understand the magnitude of this contribution. Railway platforms show lower overall  
 382 concentrations than other microenvironments in all areas, except aboveground platforms in  
 383 the commercial area (Fig. 4), which has PM concentrations comparable or higher than other  
 384 areas. This probably arises because the stations in commercial areas are designed with easy  
 385 access by the pedestrians from roadways and direct connections with other roadway public  
 386 transport. As a result, the stations have their aboveground platforms surrounded by narrow  
 387 streets with high density of tall buildings, high traffic intensity with diesel fleets and crowded  
 388 pedestrians. The CO concentrations on platforms, was at the lower end of the concentration  
 389 range found in the microenvironments.

### 390 3.3 In-cabin pollutant concentrations in different transport systems

391  
 392 Fig. 5. In-cabin pollutant concentrations by different transport systems. (a) PM<sub>2.5</sub>, (B) Black  
 393 carbon (BC), (c) Ultrafine particle (UFP), (d) CO

394  
 395 Figure 5 presents the in-cabin pollutant concentrations measured while travelling by different  
 396 modes of transport. As shown in Figure 5a, the PM<sub>2.5</sub> concentrations in the three cabins have  
 397 comparable averages of 11.7, 8.2 and 10.2 µg/m<sup>3</sup> for LPG bus, diesel bus and MTR cars,  
 398 respectively. BC and UFP pollutants displayed identical concentration profiles, but  
 399 substantially different compared to PM<sub>2.5</sub>, with diesel bus cabins showing significantly higher  
 400 concentrations than LPG buses ( $p < 0.01$ ) and MTR cars ( $p < 0.01$ ) for both pollutants. This  
 401 observation suggests pollutants from traffic penetrate into the bus cabins during travel. BC  
 402 and UFP are tracers for diesel exhaust emissions (Quintana et al. 2014), so their higher  
 403 concentrations in diesel buses may be due to the self-pollution of diesel engine emissions  
 404 (Rim et al. 2008) or because nearby vehicles emit these pollutants. Bus age, type and the  
 405 position of the ventilation inlet are important variables affecting the degree of self-pollution  
 406 (Behrentz et al. 2004, Sabin et al. 2005). The large variation of pollutant concentrations in  
 407 diesel bus cabins may arise because the local buses have mixed fleets with more than 60% of  
 408 Euro I and II, and 17% of Euro IV and V standards (HKENB 2013). It is also possible that  
 409 franchised diesel and LPG public light buses serve different commuter groups and operate on  
 410 different routes, resulting in more diesel traffic volume for the diesel bus routes (Kaur and  
 411 Nieuwenhuijsen 2009). Nevertheless, it should be noted that the BC concentrations inside  
 412 diesel and LPG bus cabins ( $11.6 \pm 7.6 \mu\text{g}/\text{m}^3$  and  $7.5 \pm 3.2 \mu\text{g}/\text{m}^3$ , respectively) were on the  
 413 lower end of the reported values (range ~ 5-50 µg m<sup>-3</sup>) in the literature (Fruin, Winer and  
 414 Rodes 2004, Janssen et al. 2011). A few investigators (Knibbs and de Dear 2010, Zuurbier et  
 415 al. 2010) have also found much higher concentrations of UFPs inside buses and attributed  
 416 these to cabin ventilation and leakage. Figure 5d shows that the average concentrations of CO  
 417 were highest inside LPG buses ( $\sim 2.9 \pm 1.8$  ppm) followed by diesel buses ( $1.0 \pm 0.5$  ppm) and  
 418 MTR cars ( $0.3 \pm 0.1$  ppm), significantly different for all combinations ( $p < 0.01$ ). Chan and  
 419 Liu (Chan and Liu 2001) carried out exposure assessment in similar microenvironments in  
 420 Hong Kong in 1999 and reported in-cabin CO concentrations to be 1.8~2.9 ppm for diesel

421 buses, much higher than the observed in the present study, probably attributed to the  
 422 improved air ventilation condition for on-road vehicles and more effective vehicle emission  
 423 controls added since that study.

424  
 425 Fig. 6. Typical time series of pollutant concentrations while travelling by different transport  
 426 systems.

427  
 428 Figure 6 shows typical time series of the measured pollutant concentrations by different  
 429 transport modes. Four trip-based measurements were presented to cover (a). diesel bus; (b).  
 430 LPG bus; (c). aboveground and (d). underground railway routes with representative  
 431 microenvironments. In addition to  $PM_{2.5}$ , BC, UFP and CO pollutants,  $CO_2$  concentration was  
 432 also included as an indicator of in-cabin and ambient environments. As shown in Figure 6a,  
 433 the in-cabin concentrations of BC and UFP in diesel bus routes recorded both high  
 434 ( $50.7 \pm 15.5 \mu\text{g}/\text{m}^3$  and  $4.1 \pm 1.3 \times 10^4 \text{ particles cm}^{-3}$ , respectively) and low ( $11.1 \pm 4.0 \mu\text{g}/\text{m}^3$  and  
 435  $2.4 \pm 0.4 \times 10^4 \text{ particles cm}^{-3}$ , respectively) levels while taking two different buses in separate  
 436 roadway sections, a clear indication of the large span of their distribution as discussed in  
 437 previous section. Meanwhile, substantial variation of their concentrations were observed  
 438 while waiting in closed termini and busy roadside showing the direct impact of vehicle  
 439 emissions on the passenger exposure to these pollutants. In other transport modes (Figure 6b  
 440 to 6d), BC and UFP showed much lower in-cabin concentrations compared to the ambient  
 441 microenvironments, except for an interesting observation of increased BC inside MTR car  
 442 while travelling through an underground tunnel. A similar pattern was observed for  $PM_{2.5}$ ,  
 443 but not for UFP. It may be attributed to the pressure change between the in-cabin and outside  
 444 while entering tunnel that changes the penetration rate of particle pollutants. Diesel bus routes  
 445 seems to show elevated BC and UFP concentrations when compared to other modes, with  
 446 lower levels in AG and UG MTR routes, and in LPG bus route.  $PM_{2.5}$  concentrations,  
 447 however, showed relatively less variation in different transport modes and there is no  
 448 significant difference observed of their in-cabin concentrations by the routes. For CO, LPG  
 449 bus route observations showed much higher average concentrations in open termini as shown  
 450 in Figure 6b. The contrast between CO versus BC and UFP concentrations profiles in  
 451 enclosed termini (Figure 6a) and open termini (Figure 6b) suggest the dominant impact of  
 452 vehicle emissions for passengers while waiting for boarding.

### 453 3.4 Inter-comparison by different transport modes

454  
 455 Fig. 7. Comparison of integrated exposure to pollutants by diesel bus and by MTR.

456  
 457 The total integrated exposure by two public transport routes through busy business districts  
 458 on franchised bus and the MTR is shown in Fig. 7 as a time series for travel from Monkok  
 459 (MK) to Tsim Sha Tsui (TST) (Figure 7a) and from Sheung Wan (SW) to Causeway Bay  
 460 (CB) (Figure 7b). Each trip includes waiting at stops and platforms and in-cabin exposure.  
 461 The pollutant patterns were consistent between the multiple runs so only one profile is  
 462 presented. In general, the traffic related pollutants of BC, UFP and CO had much higher  
 463 average concentrations during the bus trip than on the MTR. The TST to MK trip, for  
 464 example, has average BC, UFP and CO concentrations of  $5.3 \pm 5.0 \mu\text{g}/\text{m}^3$ ,  $2.9 \pm 2.7 \times 10^4$   
 465  $\text{particles cm}^{-3}$  and  $1.0 \pm 0.7 \text{ ppm}$  for bus trip, but only  $3.6 \pm 2.1 \mu\text{g}/\text{m}^3$ ,  $0.9 \pm 0.5 \times 10^4$   
 466  $\text{particles cm}^{-3}$  and  $0.4 \pm 0.5 \text{ ppm}$  for MTR trip. Their concentrations inside bus cabins increased when the  
 467 door opens at bus stops followed by a gradual decay as seen in the PM time series (Fig 7).  
 468 The time spent in different microenvironments is an important component in estimating  
 469 exposure. On average, the total trip time by bus and by MTR is  $24 \pm 2$  minutes and  $14 \pm 1$

470 minutes, respectively, between MK and TST; and  $29 \pm 2$  minutes and  $19 \pm 1$  minutes,  
471 respectively, between SW and CB during this study.-While the waiting time in bus stops was  
472 comparable with those in platform for MTR trip, the longer trip time by bus due to the travel  
473 time on congested roadways highlights the importance of the in-cabin exposure to pollutants.  
474 It is also worth noting that the monitoring route was carried out during non-peak hours so  
475 even longer times are expected for bus trips during peak hours when most commuters use the  
476 transport system.

477  
478 Integrating the pollutant concentrations and time spent suggests a the trip based average dose  
479 of exposure to  $PM_{2.5}$ , BC, UFP and CO by taking bus from MK to TST were  $511.4 \pm 219.6 \mu\text{g}$ ,  
480  $1.7 \pm 1.5 \mu\text{g}$ ,  $3.5 \pm 1.3 \times 10^9$  particles and  $235.5 \pm 83.2 \mu\text{g}$ , respectively, while the return trip by  
481 MTR had average dose of  $400.5 \pm 97.3 \mu\text{g}$ ,  $0.3 \pm 0.1 \mu\text{g}$ ,  $0.8 \pm 0.2 \times 10^9$  particles and  $12.0 \pm 9.1 \mu\text{g}$   
482 for the pollutants, representing average ratios of 1.3, 5.7, 4.4 and 19.6 times between bus trip  
483 and MTR trip for  $PM_{2.5}$ , BC, UFP and CO, respectively. A similar comparison was also  
484 observed in the other route between SW and CB with corresponding ratios of 0.7, 2.0, 2.5 and  
485 3.4 by taking bus versus MTR. The results showed interesting comparison between  $PM_{2.5}$  and  
486 other pollutants with relatively consistent exposure for  $PM_{2.5}$  (ratio of 0.7 to 1.3) but much  
487 higher exposure risks for traffic related pollutants of BC, UFP and CO for passengers taking  
488 buses in urban public transport systems.

## 490 **Conclusions**

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

511  
512 Current air quality regulation focuses on emission reduction as a mechanism to improve  
513 ambient or roadside air quality. However, the heterogeneity of air pollutant concentrations  
514 observed in the public transport microenvironments suggests the need for exposure based  
515 policy making in addition to tail-pipe solutions, since commuter trips may contribute to an  
516 importance fraction of daily exposure especially in cities. Transport optimization to reduce  
517 congestion, bus route reorganization to less polluted areas, and encouraging commuter choice  
518 for cleaner transport modes may contribute to an effective reduction in a passenger's

519 exposure. Future investigations might usefully examine the effectiveness of bus ventilation  
 520 systems, inflow when doors are open and the temporal variation of commuter exposure  
 521 patterns, i.e. peak versus non-peak hours, all of which are needed to develop a better  
 522 understanding of the comprehensive exposure profiles and provide the basis for cost-effective  
 523 air and public health policy making.

524

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531

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## Figures and tables

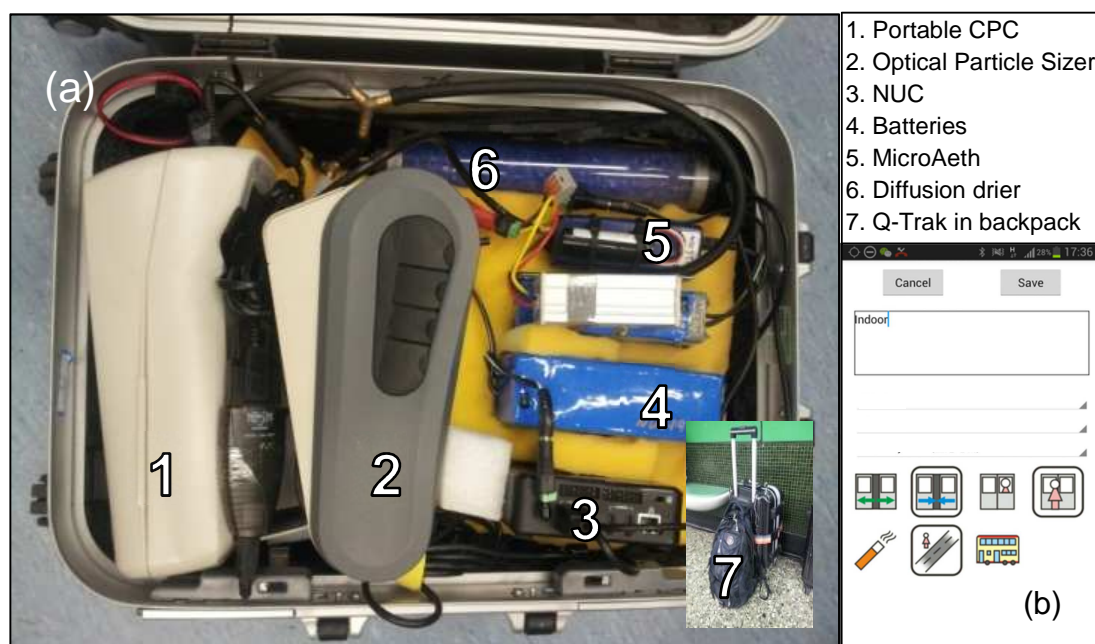


Figure 1 Setup of Mobile Exposure Measurement System (MEMS): (a). The internal setup of the portable instruments; (b). Screenshot of the developed mobile app.

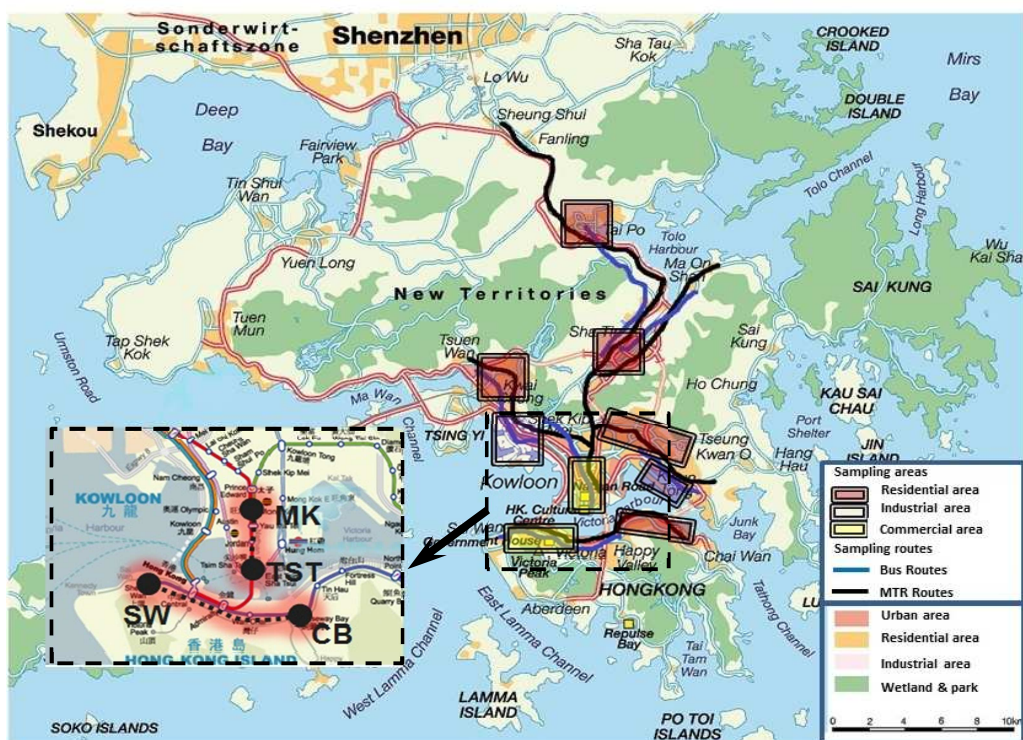


Figure 2 The transport microenvironments (main plot) and integrated exposure based (subplot) sampling routes and areas.

Note: The subplot shows two sampling routes between Mongkok (MK) and Tsin Sha Tsui (TST); and between Sheung Wan (SW) and Causeway Bay (CB).

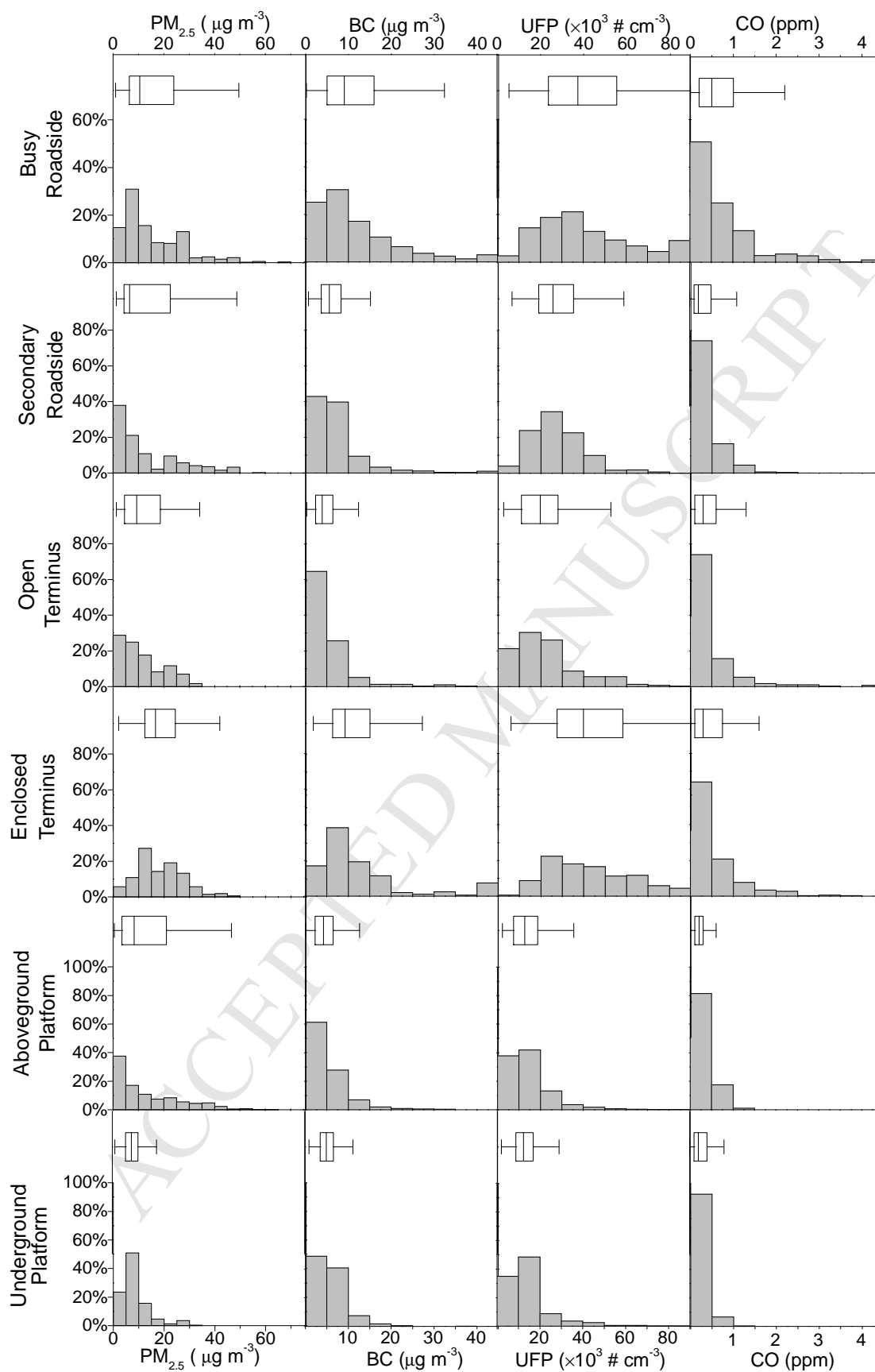


Figure 3 Pollutant concentration in various microenvironments in public transport systems.

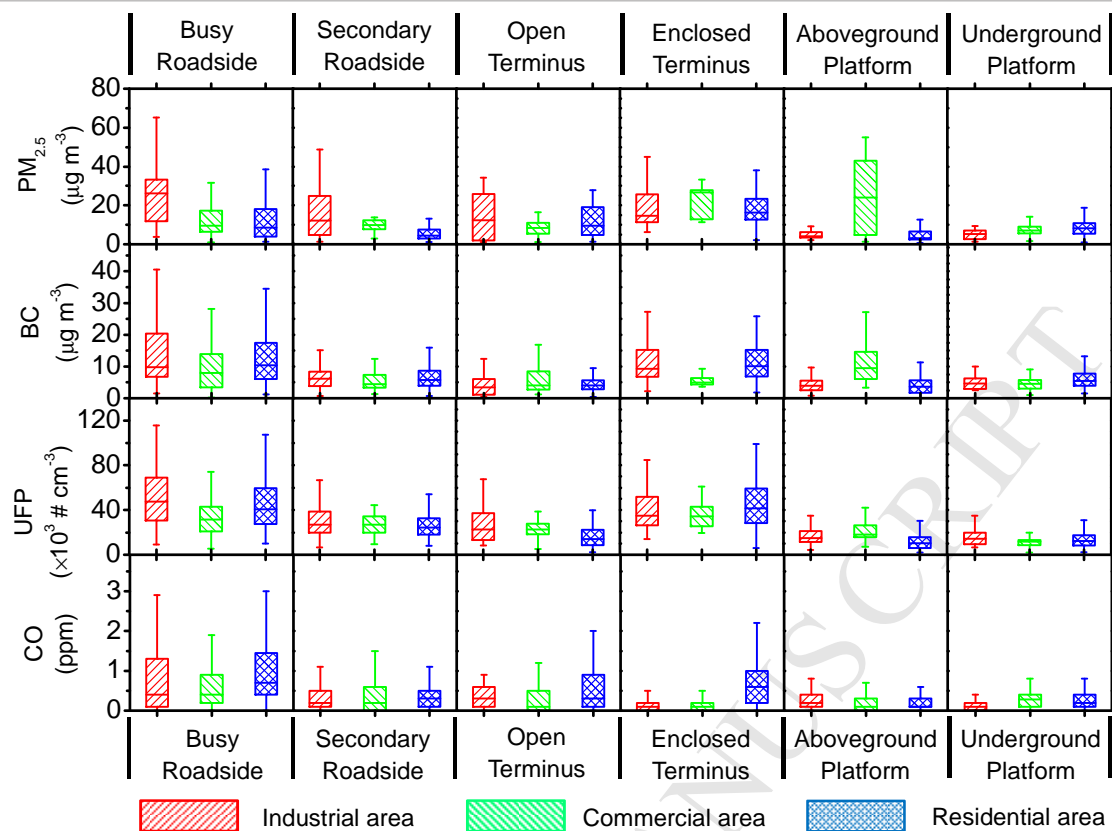


Figure 4 Box plots of pollutant concentrations in different urban areas.

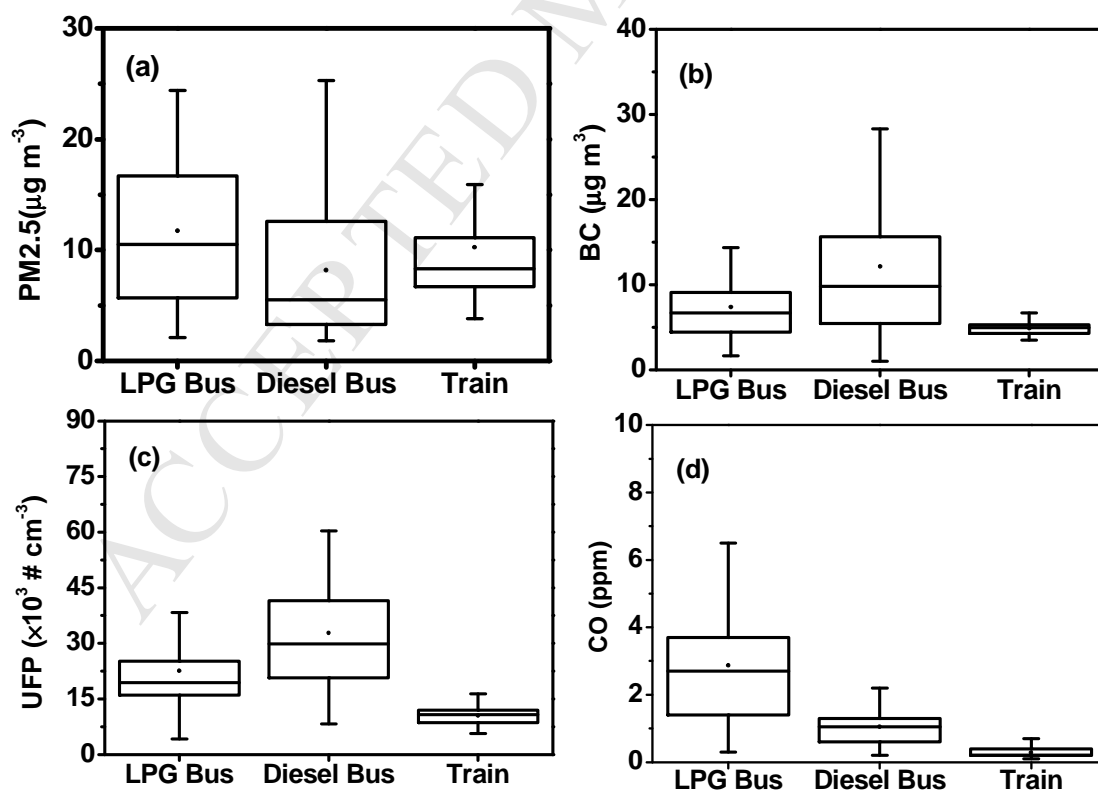


Figure 5 In-cabin pollutant concentrations by different transport systems: (a) PM<sub>2.5</sub>; (b) Black carbon (BC); (c) Ultrafine particles (UFP); (d) CO

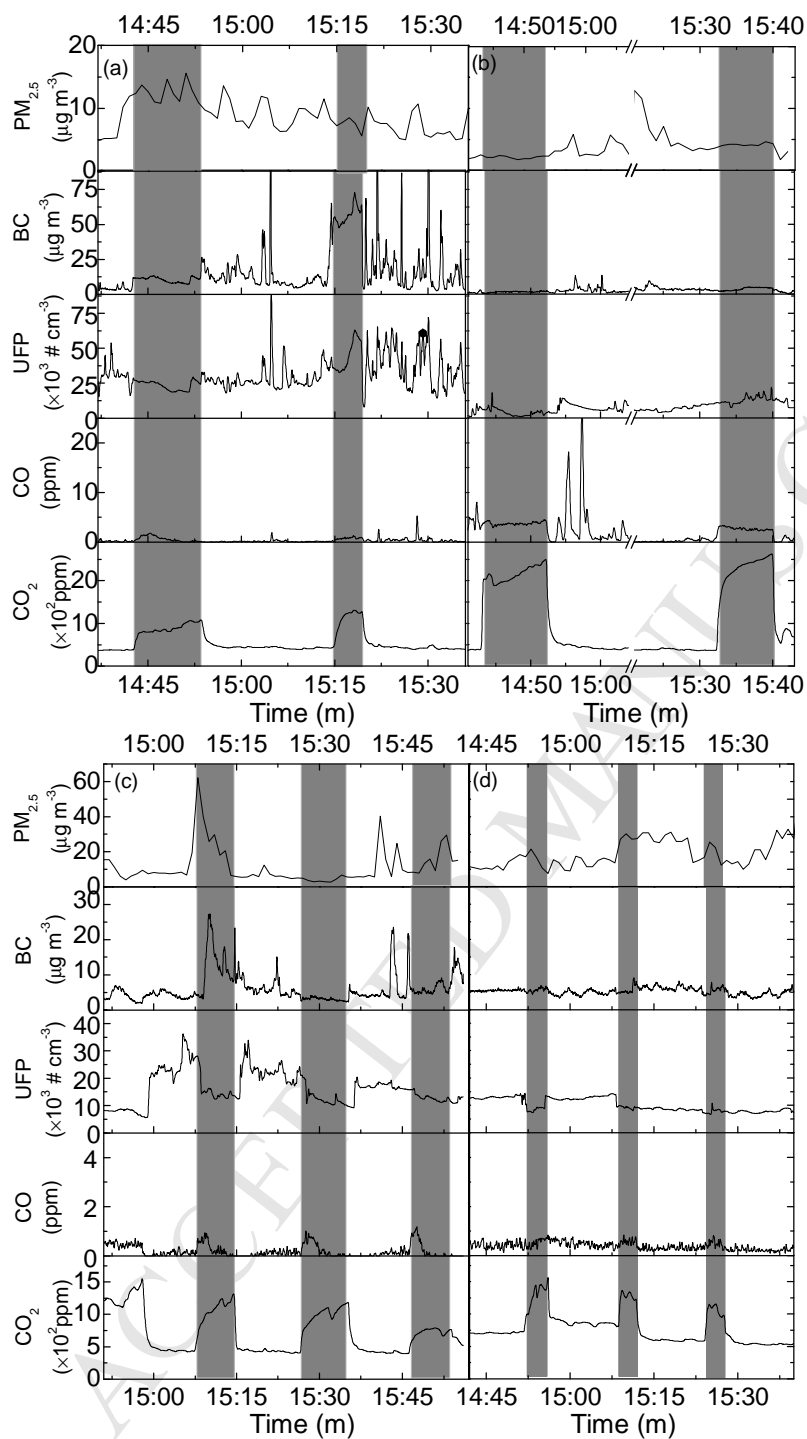


Figure 6 Typical time series of pollutant concentrations while travelling by different transport systems. (a) Diesel Bus; (b) LPG Bus; (c) MTR AG Platform; (d) MTR UG Platform

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

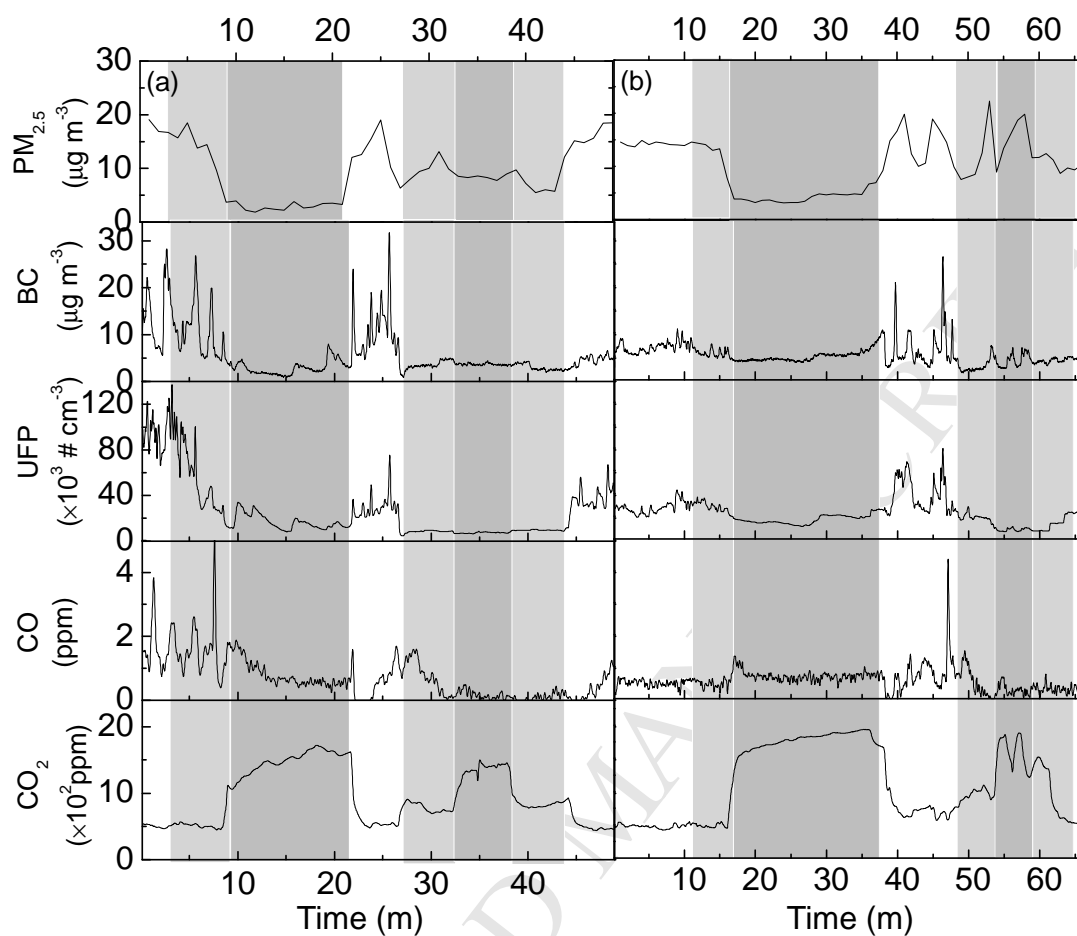


Figure 7 Comparison of integrated exposure to pollutants by diesel bus and by MTR. (a) From Mongkok (MK) to Tsim Sha Tsui (TST); (b) From Sheung Wan (SW) to Causeway Bay (CB)

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

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