In-cabin exposure levels of carbon monoxide, carbon dioxide and airborne particulate matter in air-conditioned buses of Hong Kong

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Short title: CO, CO_2 and PM_{10} in bus cabins

Abstract

Bus cabin air quality has not been incessantly monitored in Hong Kong. This study investigates the in-cabin exposure levels of CO, CO_2 and PM_{10} for running buses in Hong Kong that are equipped with Euro II, III and IV engines. A representative urban-suburban bus route was chosen and there were no significantly different in-cabin CO levels reported among engine types and between rush and non-rush hours. However, in-cabin CO level was found significantly associated with ambient/roadside CO level; the former was altogether higher than the latter due to the bus' own exhaust. Regarding in-cabin PM_{10} concentration, the engine type played a major role. The outcome demonstrates that new buses (i.e. Euro IV) generally provide a better in-cabin environment for commuters. Therefore, implementation of an air filtration upgrade, together with a routine filter cleaning schedule, is an effective measure to ameliorate bus cabin air quality. This study also provides useful information for further investigation into the causal relationship between health risks and long-term air pollution exposure in local bus cabins.

Key Words

Bus travelling, carbon dioxide, carbon monoxide, exposure, particulate matter.

Introduction

Hong Kong is a densely populated city with a well-developed bus network. In 2007, local franchised buses served a total of 4 million commuters (34.4% of the total traveller population) daily [1]. A survey of activity patterns in enclosed transit showed that a Hong Kong resident would spend an average of 1.09 hours in a bus cabin on weekdays and 1.14 hours on weekends [2]. To ensure public health, bus cabin air quality should be incessantly monitored and improved.

Airborne particulate matter (PM) is believed to be associated with increased morbidity and mortality [3,4]. Studies in the European Union (EU) in 2000 reported an increased risk of emergency hospital admissions for cardiovascular and respiratory diseases due to short-term PM exposure and an estimate of about 350,000 premature deaths due to long-term PM exposure [5]. Mass concentration of particles with an aerodynamic diameter smaller than 10 μm (PM_{10}) is a common monitoring parameter for air quality. The short-term (24-hour) and long-term (1-year) exposure limits for PM_{10} specified in various guidelines are summarized in Table 1 [4,6-8]. In Hong Kong, the indoor air quality (IAQ) of a bus cabin is classified according to the 24-hour weighted average [7]. The average PM_{10} levels estimated for bus, taxi, subway, ferry and tram were 137.5, 95, 78, 85 and 117.4 μg m^{-3} respectively, indicating a higher PM_{10} exposure inside a bus cabin [2]. Other pilot studies showed that the average PM_{10} exposure concentrations in Hong Kong bus cabins were from 109 to 265 μg m^{-3} [9,10], and the hourly estimate of exposure for an average bus passenger was 95 μg m^{-3} - a value comparatively higher than the average roadside PM_{10} level of 77 μg m^{-3} [2,11]. Table 2 exhibits the in-cabin PM_{10} exposure averages for buses running in other cities. The average measured on Taiwan highways (60 μg m^{-3}) was the lowest among all cities while the averages recorded in Guangzhou (128 μg m^{-3}) and Munich (110-165 μg m^{-3}) were comparable [12-14]. A much higher exposure level was found in Mexico City (212 μg m^{-3}) [15].

Studies revealed that a bus' own exhaust can infiltrate into the bus cabin in different ways [16,17]. As carbon monoxide (CO), a toxic by-product of incomplete combustion, was the dominant automobile exhaust emission pollutant found in Hong Kong, it was the combustion gas chosen for investigation in this study [18,19]. Table 1 shows the in-cabin CO exposure guidelines for buses [7]. The recommended 8-hour and 1-hour exposure limits in Hong Kong are 9 and 25 ppm respectively. According to previous local studies, the in-cabin CO levels were 10.2 ppm among taxis, 2.6-3 ppm among public buses, and 0.5-2 ppm amid subways, ferries and trams [2,9]. The city bus in-cabin CO exposure averages from various countries are presented in Table 2 for comparison: high concentrations (9.4 to 41.1 ppm) were recorded in Athens and Mexico City [20-21]; the averages of Guangzhou and Taipei were comparable (8.9 ppm vs. 8.6 ppm) [12,13]; and those measured in Milan (3.8 ppm) and Paris (4.0 ppm) were relatively low [22,23].

The Hong Kong government adopted the European emission standards for diesel engines in 1994 and all new buses are required to meet the Euro IV emission standards since 2006 [24]. At the end of 2007, about 90% of the 5,900 local franchised buses were in compliance with the standards [25]. Although a Euro IV diesel vehicle emits about 95% less PM_{10} than a pre-Euro vehicle manufactured before 1995, cabin air quality in running buses has not been continuously monitored and insufficient information is available for the review of policy regarding urban bus renewal in this region. This study investigates the in-cabin exposure levels of CO, CO_2 and PM_{10} for running buses in Hong Kong that are equipped with Euro II, III and IV engines.

Measurements

The common bus models in Hong Kong are Euro II, III and IV air-conditioned double-deckers with fixed windows. Their cabin air temperature (T), relative humidity (RH) and airflow are automatically controlled for thermal comfort. To prevent outdoor particles from entering the bus cabin through fresh air intake, electrostatic filters are used in the Euro IV models.

Figure 1 illustrates the bus route between a suburban residential area Tuen Mun (TM) and an urban area Mongkok (MK) selected for the study. TM is a new town in the northwest of Hong Kong dominated by residential development with relatively less busy roads, while MK is a thickly populated and bustling commercial zone located in the heart of the city. The traffic in MK is very heavy as it is a focal point of many arterial transport routes in the city.

Travelling distance between the two bus terminals (i.e. TM and MK) was 32 km and PM_{10} levels in the bus cabin were monitored and recorded (DustTrak, TSI, USA) every 1 minute throughout the journey. The detection range of the aerosol monitor was 0.001 to 100 mg m^{-3} at an air flow rate of 1.7 L min^{-1}. It was noted that a lower PM_{10} concentration would be obtained on the upper deck and an earlier reported upper-to-lower-deck PM_{10} ratio was 0.84 [19]. However, all measurements, which were conducted on weekdays during bus service hours from 07:00 to 00:00 including two rush hour periods 07:00-10:00 and 16:00-19:00 [26], were taken on the upper deck at points as marked in Figure 2 to minimize disturbance to normal bus operations. Air samples were collected at a height of 1.45 m above the deck floor (i.e. the breathing level of passengers) and kept away from the bus main entrances, air inlets/outlets, and passengers. At the same time, T, RH, CO_2 and CO levels were measured (IAQ Meter, TSI, USA). All equipment used in the study was factory calibrated prior to the measurements. The resolutions for T, RH, CO_2 and CO were 0.1^{o}C, 0.1%, 1 ppm and 0.1 ppm respectively. In addition, data of hourly ambient/roadside PM_{10} and CO levels were obtained from the government air quality monitoring stations closest to the two bus terminals for comparison with the 10-minute averages of in-cabin PM_{10} and CO taken right after departure as well as before arrival.

Results and discussions

The measurement results of 52 commuter trips with groupings based on 2 travelling directions, 3 bus engine types and 2 measurement periods are summed up in Table 3. Normality was assumed for all parameters except CO_2 ($p \geq 0.9$, Shapiro-Wilk's test); and normal distributions could be assumed for the cabin air temperature from MK to TM, the in-cabin PM_{10} level from TM to MK, and the travelling times required for Euro III and in non-rush hours ($p \geq 0.9$, Shapiro-Wilk's test).

The average travelling time between the two terminals was 68 minutes (standard deviation SD=10 minutes). Except for travelling from MK to TM which would take 4 minutes longer on average ($p=0.05$, t-test), there was no significant travelling time difference for all subgroups ($p \geq 0.2$, t-test). Characterized by an average T of 22°C (SD=2.5°C) and RH of 47% (SD=9%), the cabin thermal conditions were acceptable to most Hong Kong residents [20,21] and within the ranges (T=20-28°C and RH=40-70%) recommended by the Hong Kong Environmental Protection Department (HKEPD) [17]. The cabin air temperature in newer buses (i.e. Euro IV) was reportedly lower ($p \leq 0.05$, t-test). Lower in-cabin temperatures were also detected in rush hours as compared with non-rush hours ($p \leq 0.05$, t-test) and that was expected for a better air diffusion performance during rush hours [27].

Table 4 summarizes the in-cabin and ambient/roadside CO and PM_{10} levels for Euro II, III and IV buses.

CO_2 levels

The overall average in-cabin CO_2 level was 1290 ppm (SD=491 ppm) and within the "comfortable" level according to the local guideline value - an hourly average exposure concentration of 2500 ppm [28]. Except for some differences between Euro III and Euro IV ($p=0.01$, t-test), there was no significant difference among the subgroups ($p>0.2$, t-test). This exposure level showed an improved bus ventilation performance as compared with an average of 1722 ppm measured in a previous study ($p<0.01$, t-test) [9]. However, it was still significantly higher than the average of 959 ppm found in a Taiwan study ($p<0.01$, t-test), where correlations were reported between the in-cabin CO_2 levels and the number of passengers [29].

CO levels

The overall average in-cabin CO level of 2.3 ppm (SD=0.5 ppm) was not significantly different from the one (2.1 ppm) measured in a former study [9], but significantly lower than those (3.8-40 ppm) registered in other cities ($p<0.01$, t-test) [12-13,20-23]. It should be noted that vehicles in Hong Kong were running on lead-free or low lead gasoline instead of regular (leaded) petroleum [21]. As the study results of all in-cabin CO levels were much lower than the local guideline limits ($p \leq 0.01$, t-test), a satisfactory in-cabin environment in terms of CO concentration was assumed [7].

Based on Table 4, the in-cabin CO levels were significantly higher than the ambient/roadside levels measured by the monitoring stations ($p<0.0001$, pair t-test). This confirmed that in-cabin CO level was closely related to not only the emissions from neighbouring vehicles, but also the bus' own exhaust. During rush and non-rush hours, the ambient/roadside CO levels in MK (1.22 and 1.30 ppm) were about 0.2 and 0.4 ppm higher than those in TM (0.98 and 0.94 ppm) respectively ($p \leq 0.01$, t-test), while the corresponding in-cabin CO levels were 0.8 and 0.7 ppm higher ($p<0.05$, t-test). It was noted that congested traffic was expected in MK. Between rush and non-rush hours, the average in-cabin CO levels (2.2 and 2.4 ppm) did not vary significantly ($p>0.3$, t-test). This indicated the air quality concerning CO concentration was not improved in non-rush hours as considerable traffic still remained along the route.

Among different engine types, the in-cabin CO levels measured were not significantly different ($p>0.2$, t-test), except for Euro III/Euro IV in MK ($p<0.01$, t-test). The difference in the infiltration design (i.e. electrostatic filters in Euro IV) may be the reason. Figure 3 shows a significant linear relationship between the ambient/roadside and in-cabin CO levels with a slope of approximately unity and an intercept of 1.2 ppm ($R=0.44$, $p<0.01$, t-test). In other words, the in-cabin CO level was 1.2 ppm higher on average. Moreover, the average in-cabin CO level from MK to TM was 0.3 ppm higher than that from TM to MK ($p=0.02$, t-test). It was probably due to the longer travelling time from MK to TM.

PM_{10} levels

Again, the overall average in-cabin PM_{10} level found in this study, which was 169 µg m^{-3} (SD=96), was not significantly different from the results of some earlier studies carried out in Hong Kong ($p>0.05$, t-test) [2,9]. This PM_{10} level was comparatively high among all of the reference cities ($p<0.05$, t-test) [12-14,27], and it did not improve during non-rush hours ($p>0.4$, t-test). The ambient/roadside PM_{10} levels in MK were lower than those in TM because of the smoother flow of traffic in TM. There was no significant difference between the in-cabin PM_{10} levels from MK to TM and from TM to MK ($p>0.3$, t-test).

In-cabin PM_{10} level is affected by air infiltration, indoor mitigation, and resuspension of floor dust due to various passenger related activities (e.g. alighting, boarding and taking a seat). Proximate vehicle exhaust plays a major role in infiltration, especially when the buses are queuing up at a bus stop [30]. Despite the fact that there was no significant association between ambient/roadside and in-cabin PM_{10} levels on the whole according to Table 4 ($R=0.08$, $p>0.4$, t-test), associations between them were reported within the first 10 minutes after departure ($p \leq 0.05$). This latter result demonstrated that in-cabin PM_{10} level in the first 10 minutes after departure was dominated by the outdoor factors as PM_{10} contributions from the bus engine and moving passengers inside the cabin would become greater subsequently.

The absence of significant association between in-cabin CO_2 and PM_{10} levels ($R= -0.19$, $p>0.05$, t-test) in this study indicated that the background particulates in a district and dust resuspension due to passenger activities might have little contribution to in-cabin PM_{10} level. From Table 4, the significant differences in in-cabin PM_{10} levels among Euro II, III and IV buses revealed that engine type was the key affecting factor ($p<0.05$, t-test). Reportedly, a Euro IV model has a lower particulate emission level and a better filtration performance as compared with the older models such as Euro II and Euro III [31,32]. This study gave similar results.

Conclusion

This study chose a representative urban-suburban bus route to investigate the in-cabin exposure levels of CO, CO_2 and PM_{10} for running buses in Hong Kong that were equipped with Euro II, III and IV engines. There were no significantly different in-cabin CO levels reported among engine types and between rush and non-rush hours. However, in-cabin CO level was found significantly associated with ambient/roadside CO level; the former was altogether higher than the latter due to the bus' own exhaust. Regarding in-cabin PM_{10} concentration, the engine type played a major role. The outcome demonstrated that new buses (i.e. Euro IV) generally provided a better in-cabin environment for commuters. Therefore, implementation of an air filtration upgrade, together with a routine filter cleaning schedule, is an effective measure to ameliorate bus cabin air quality. The study also provides useful information for further investigation into the causal relationship between health risks and long-term air pollution exposure in local bus cabins.

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