



PERGAMON



Atmospheric Environment 36 (2002) 5831–5840

ATMOSPHERIC
ENVIRONMENT

www.elsevier.com/locate/atmosenv

Exposure level of carbon monoxide and respirable suspended particulate in public transportation modes while commuting in urban area of Guangzhou, China

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Received 27 April 2002; accepted 15 August 2002

Abstract

This study examined commuter exposure to respirable suspended particulate (PM₁₀ and PM_{2.5}) and carbon monoxide (CO) in public transportation modes in Guangzhou, China. During the sampling period, a total of 80 CO, 80 PM₁₀ and 56 PM_{2.5} samples were conducted in four popular commuting modes (subway, air-conditioned bus, non-air-conditioned bus and taxi) while running in typical urban routes. The results show that the PM₁₀ as well as CO level is greatly influenced by the mode of transport. The highest mean PM₁₀ and CO level was obtained in a non-air-conditioned bus (203 µg m⁻³) and in an air-conditioned taxi (28.7 ppm), respectively. Noticeably, the exposure levels in subway are lower than those in the roadway transports. The ventilation condition of the transport is also a crucial factor affecting the in-vehicle level. There was statistically significant difference of PM₁₀ ($p < 0.01$) and CO ($p < 0.01$) level in taxi and PM₁₀ ($p < 0.01$) level in bus between natural and mechanical ventilation. In this study, the effect of driving time has minor impact on the in-vehicle level. The exposure levels were only slightly lower in afternoon non-peak hour than in evening peak hour. This is related to the fact that the road traffic in the selected urban routes is dominated by the extensive use of public transports, which provide service at regular intervals regardless of the time of day. The PM_{2.5} inter-microenvironment variation is similar to the pattern of PM₁₀. The PM_{2.5} to PM₁₀ ratio in the transports was high, ranging from 76% to 83%. The poor vehicle emission controls, poor vehicle maintenance, plus the slow moving traffic condition with frequent stops are believed to be the major causes of high in-vehicle levels in some public commuting trips.

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Keywords: Public transportation modes; PM₁₀; PM_{2.5}; CO; Commuter exposure

1. Introduction

Guangzhou is an economically developed city in south China. It situates at the north of the Pearl River delta and is the capital of the province of Guangdong. The city has an area of about 7434 km² and a population of 7.0 million. Its overall economic power is the third

among all China's cities and just after Shanghai and Beijing. In the year 2000, the gross domestic product (GDP) value of Guangzhou reached 238.3 billion Yuan, which is nearly 7.5 times more than that in 1990. The average annual growth rates of the total GDP value and the GDP value per capita were more than 20% over the last decade (Guangzhou Statistical Bureau (GZSB), 1999, 2001). However, serious air pollution is the adverse side effect of rapid development in Guangzhou. Similar to most metropolitan cities, vehicle emission is the major source of air pollution. Recent studies had

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shown that traffic-related air pollutants such as PM_{10} and CO in urban sites of Guangzhou were frequently exceeded the health-protecting guidelines as stated in the Chinese National Air Quality Standard (Fu et al., 2001; Qian et al., 2001; Wei et al., 1999; Zhang et al., 1999). This standard recommends an hourly CO limit of 10 ppm and daily PM_{10} limit of $150 \mu\text{g m}^{-3}$. Exposure to these pollutants can cause adverse health effects. They are also linked to higher mortality rate, heart disease and respiratory illness (Ghosh et al., 1996; Hong Kong Environmental Protection Department (HKEPD), 2000).

In year 2000, there were 1,340,548 licensed motor vehicles and 5020 km of paved public road in Guangzhou. More than two-third of the vehicle fleet is motorcycle. Private car ownership is relatively low. Recently, a survey on the Guangzhou inhabitant trips (Deng et al., 2000) reported that the daily commuting trips were mainly conducted in four different transportation modes: walking (41.9%), cycling (21.4%), public transportation (18.2%) and motorcycle (10.4%). Less than 1% of the commuters travelled by private car. Although the above data implied that the majority of daily commutes in Guangzhou were based on walking and cycling, public transportation modes were the most popular used motorized mean of transportation. They accounted for about half of the total motorized vehicle trips. Everyday, more than 5 million passenger journeys are made on the public transport system. In addition, the number of public transportation trips was increasing rapidly since the early 1990s. Taking bus as an example, the average daily passengers' trips in year 2000 was 4.24 million, which is about 2.2 times more than that in 1990 (Guangzhou Statistical Bureau (GZSB), 2001). Considering the severity of the local air pollution problem, the commuters in Guangzhou are presumably exposed to high level of traffic-related pollutants due to strong vehicular emissions. As there is an increasing concern of in-vehicle air pollution, the primary interest of this study is to investigate the exposure level of respirable suspended particulate (PM_{10} and $PM_{2.5}$) and carbon monoxide (CO) in four major public transportation modes while commuting in the urban area of Guangzhou. These experimental results may be useful to the local authorities for reviewing air quality management as well as transport management.

In the past, the published commuter exposure studies tended to focus on the exposure in private car, which is the prime commuting mode in developed countries. In China, the situation is different as public transportation modes are mostly used by commuters in place of private cars. Only few overseas studies examined the exposure level in public transportation modes, in particular, in developing China. For carbon monoxide exposure, Chan and Liu (2001) investigated the in-vehicle CO level in bus, light bus and taxi traversing major

commuting routes in Hong Kong. They found that CO level in taxi was the highest. In Mexico City, Fernandez-Bremauntz and Ashmore (1995) mentioned that the differences in CO concentrations found between different transport modes were due to the differences in vehicle height and lane of travel. In Paris, Dor et al. (1995) revealed that the CO exposure level inside automobile was 2–3 times greater than that recorded in other means of transportation, including bus, subway and walking. For particulate exposure, Gee and Raper (1999) revealed that the PM_4 level measured by the cyclists were much lower than the levels inside buses. Praml and Schierl (2000) investigated the PM_{10} exposure in buses and trams in Munich, Germany. They reported that the particulate concentrations in vehicles depend on the external sources including outdoor concentration and road traffic. In London, Adams et al. (2001) measured the $PM_{2.5}$ level in the bus, underground rail system, bicycle and car. They stated that the exposure of vehicle occupants is clearly affected by the variety of vehicle types, interior sources of particulate and the ventilation condition of the vehicle.

2. Field study design

Four popular public transportation modes, including subway, air-conditioned bus, non-air-conditioned bus and taxi, were selected in this study for particulate and carbon monoxide measurement. These four commuting modes together served more than 85% of the total public transportation journeys in the year 2000. Bus is the cheapest and the most abundant mode of transport. There are about 300 bus routes in the urban area of Guangzhou. It provides convenient access to every corner of the city. Most of the buses are diesel fuelled. Only a few percent of them are LPG fuelled. In air-conditioned bus, the windows are fixed and the air conditioning system is used throughout the year. Taxi provides the supplementary service to other major transports. It operates throughout Guangzhou, 24 h a day. In year 2000, there were about 15620 taxis. Nearly all of them are gasoline fuelled. Air conditioning system is installed in all the taxis. However, the ventilation setting of the taxis can change with the seasons. The subway system is an urban underground railway network traversing the inner city. Line 1 is 18.5 km in length and connects the Guangzhou East Station and the southeastern part of the city while Line 2 is under construction and not yet finished. Underground electrified train provides fast and safe commutes to the citizens. Centralized air conditioning system is adopted in train.

As there is no co-located route for all selected roadway transports, two independent bus-service routes, Route 1 (14.3 km) and Route 2 (13.7 km), both

Table 1
Features of the selected routes

Transport	Route	Length (km)	Average journey time (min)	Characteristics of route
(1) Subway	(Line 1) Guangzhou East Station—Xilang	18.5	30	Traverse within the inner Guangzhou city. Running mostly on its own underground track.
(2) Non-A/C bus ^a	(Route 1) Guangzhou East Station—Youth Park	14.3	53	Traverse busy commercial areas, shopping districts and residential areas. A 6–8 lane access road with heavy traffic flow, stop-and-go traffic and many parts of the route in street canyon configuration.
(3) A/C bus ^b	(Route 2) Guangzhou East Station—Jichunlu	13.7	49	Similar to Route 1
(4) Taxi	(Route 1 or 2)	14.3 or 13.7	32 or 30	Same as above

^a Non-A/C bus—Non-air-conditioned bus.

^b A/C bus—Air-conditioned bus.

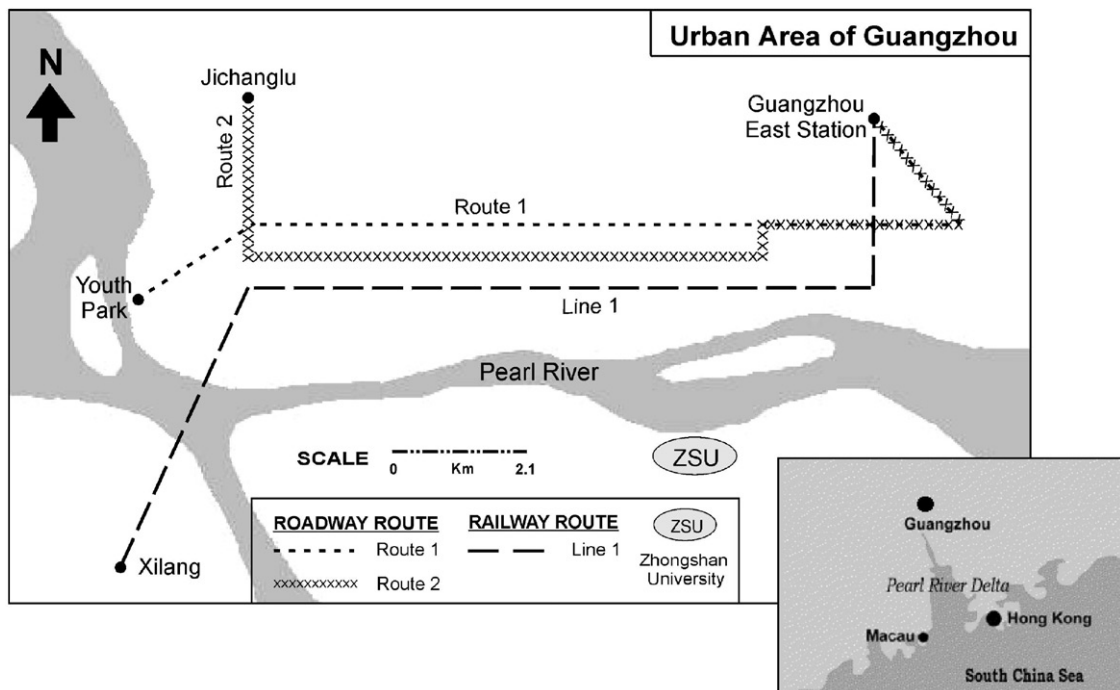


Fig. 1. Location of the sampling routes.

connecting the eastern and western parts of the city were selected for non-air-conditioned bus and air-conditioned bus, respectively. Taxi also traversed on Route 1 on Monday, Wednesday and Friday and on Route 2 on Tuesday and Thursday. The features of the measured routes are summarized in Table 1 and the location of the

sampling routes is shown in Fig. 1. These two routes are located close to each other and similar in length, traffic density, street configuration and traffic composition. Hence, they can provide a good comparison among different roadway transports. The selected routes traverse busy central commercial areas, shopping

districts and residential areas. The roads on these routes are 6–8 lanes (dual direction) on average and several sections of the routes are in street canyon configuration. Adding to that, high traffic density, low vehicle speed and stop-and-go traffic were frequently observed in these routes especially on the lane near curbside. However, severe traffic congestion was only occasionally found during the sampling period. The air samples in subway were collected on Line 1, which is closed to the routes of roadway transports.

Field sampling was conducted in 5-consecutive weekdays (Monday–Friday) in May and December 2001. In each sampling day, the PM_{10} and CO level of all selected commuting modes were measured in both afternoon non-peak hours (14:00–16:30) and evening peak hours (17:00–19:30). In some trips, $PM_{2.5}$ levels were also monitored concurrently with PM_{10} levels. As to examine the real exposure level of the public transport users, all the air samples were collected under the normal service of the transports. Our staff travelled as passengers during sampling. No instruction was given to the drivers regarding the driving behaviours. In this study, the measured taxis were randomly hired at the origin without any selection criteria. The ventilation condition of taxi was fixed as windows closed, air-conditioning on and fresh air vent closed in May and window opened and air-conditioning off in December. And these settings are typical and commonly found in Guangzhou taxis in the corresponding months. In each survey trips, information such as sampling time, travelling route, traffic condition, number of passenger and weather condition was recorded by our sampling team staff. The average driving speed of the measured transports was simply derived from the length and travelling time of the route.

3. Sampling method and quality assurance

Considering the short sampling duration in the commuting microenvironments, DustTrak (TSI Model 8520) portable aerosol monitors were used to measure PM_{10} and $PM_{2.5}$ level in this study. It is a real-time laser photometer instrumentation for the determination of aerosol mass concentration, thus capable of measuring short-term exposure level and concentration profile during daily commuting trips. The measurement is performed using a light scattering technique. Different impactors are available for the inlet of DustTrak allowing measurements of PM_{10} and $PM_{2.5}$. The data logging interval was set at 30 s. Zero checking of the monitor was performed by attaching a HEPA filter to the sampling inlet before each survey trip. DustTrak was pre-calibrated against Arizona Test Dust (ISO 12103-1) in the manufacture company (TSI). This test dust has a wide size distribution covering the entire detected size

range of the DustTrak. Directly applying the monitor into commuting microenvironment is inappropriate. Therefore, a secondary calibration for measuring traffic-related particulate was done to obtain more accurate mass concentration data. All the sampling results from DustTrak were calibrated against gravimetric samplers (Greasby Anderson High Volume air sampler for PM_{10} and R&P Partisol 2000 air sampler for $PM_{2.5}$). The correlation investigation was conducted at the boundary site of the Zhongshan University, where is close to a main street with high traffic flow. The particulate levels were measured concurrently by PM_{10} -DustTrak sampler, PM_{10} -Hi-Vol sampler, $PM_{2.5}$ -DustTrak sampler and $PM_{2.5}$ -Partisol sampler over a 24-h period. The specific conversion equations, Eqs. (1) and (2), were constructed by using 24-h averaged concentrations.

For PM_{10} ($r = 0.89$ and $n = 12$):

$$\begin{aligned} \text{Hi-Vol } (\mu\text{g m}^{-3}) \\ = 0.498\text{DustTrak } (\mu\text{g m}^{-3}) - 2.9. \end{aligned} \quad (1)$$

For $PM_{2.5}$ ($r = 0.92$ and $n = 12$):

$$\begin{aligned} \text{Partisol } (\mu\text{g m}^{-3}) \\ = 0.450\text{DustTrak } (\mu\text{g m}^{-3}) - 1.8. \end{aligned} \quad (2)$$

Recently, Yanosky et al. (2002) reported on a comparison of the DustTrak with the Federal Reference Method (FRM) for $PM_{2.5}$ measurement. They found that DustTrak can provide precise measurements and the proportional bias in the DustTrak levels can be corrected using the slope and intercept from the regression analysis between DustTrak and FRM. In order to more facilitate comparisons with other studies, all the particulate results conducted in this study were converted to high volume sampler and Partisol sampler scale accordingly. It is important to point out that the adjusted PM level greatly depended on the result of the conversion equations. Accordingly, this may limit the extent to which the data can be considered as absolute, although it does not affect the measurement precision.

Portable CO monitors (Interscan Co., Model 4148) were used to measure CO level in this study. It is a real-time electrochemical-sensing voltametric device. The data were displayed and recorded by a portable data logger (Metrosonics, Model dl-714). The data was logged every 30s in all the trips. Zero gas and span gas (25 ppm) calibrations were performed before each sampling trip.

Q-Trak (TSI Model 8550) portable IAQ monitors were also used to measure the CO_2 level for checking the ventilation status in all measured taxis. Although this method cannot measure the exact air exchange rate, it is used to obtain a better understanding of the vehicle interior air movement with respect to the transport of the internal and the external pollutant sources. The

Q-Trak was calibrated with standard CO₂ gas (2000 ppm) just before each sampling period.

All the air samples were collected at respiratory level and the sampling location was selected to ensure free of any obstruction. Before the start of sampling, all the portable monitors were turned on to stabilize for several minutes. Duplicate samples of all measured parameters were collected regularly to check the precision and reliability of the selected monitors. These paired data were acquired by parallel running of the monitors (side-by-side monitoring) in each measured commuting microenvironment. The relative mean deviation of all duplicates was within 8%. Smoking inside public transportation modes was strictly prohibited. Additionally, no commuter violated this regulation during sampling under our surveillance.

4. Result and discussion

4.1. Inter-comparison of commuting microenvironments

In this study, a total of 80 PM₁₀ and 80 CO samples were collected in four different public transportation modes during the field study period. Table 2 summarizes the statistical results of these two pollutants in different transports. The results in taxis were tabulated separately by ventilation use in order to facilitate inter-comparison. The average PM₁₀ was found to be the highest in non-air-conditioned bus (203 µg m⁻³) and was followed by non-air-conditioned taxi (150 µg m⁻³). The average PM₁₀ level in air-conditioned commuting microenvironments are lower, ranged from 67 µg m⁻³ in subway to 128 µg m⁻³ in air-conditioned bus. For the CO level measured, the inter-microenvironment variation is quite different from that of the PM₁₀ measured. The highest average CO level was obtained in air-conditioned taxi (28.7 ppm). In non-air-conditioned taxi, air-conditioned bus and non-air-conditioned bus, the average CO level was 18.7, 8.9 and 8.2 ppm, respectively. The CO exposure level measured in subway (3.1 ppm) was the lowest. Several previous studies (Chan et al., 1999; Kingham et al., 1998; Fernandez-Bremauntz and

Ashmore, 1995) revealed that the commuter exposure to traffic-related pollutants is greatly influenced by the choice of commuting microenvironments. The results of the present study found similar features for respirable suspended particulate and carbon monoxide. In addition, we found that the inter-microenvironment variations were not the same for different pollutants measured.

The exposure level obtained in this study is substantially lower in railway transport than in roadway transports. The averaged PM₁₀ and CO levels in roadway transports was about 1.2–3.0 and 2.6–9.3 times higher than that in subway, respectively. Relatively low exposure level in subway could be attributed to the fact that commuting train run on its own underground track, which was located away from busy road or other traffic. Thus, the train was not directly influenced by the vehicular emission on the street. Adding to that, electrified trains are used and that helps to persistently maintain the underground tunnel air quality at satisfactory level under normal situation.

Buses usually travel near the curbside of the road where stop-and-go traffic is relatively high. Since the bus routes were selected inside the centre of Guangzhou City, most of the bus stops along the routes served more than 10 other bus-serviced routes. The measured buses as well as other serviced buses usually required to queue up when approaching the bus stops even in afternoon non-peak hour. They are also required to halt several minutes at stops for passenger alighting and boarding. Because of the closeness of the buses, the emission from the front bus can easily penetrate into the bus behind it during idling at intermediate stops. Such impact was one of the possible causes of higher PM₁₀ level in bus. On the contrary, the taxis usually traverse in the middle lane of the road with faster running speed and lower traffic density. By comparing the vehicle speed of the roadway transports, taxi is found to run approximately two times faster than bus on the same route. In the middle lane of the road, the increased air turbulence due to the faster vehicle speed also helped to increase the dispersion of emission exhaust and lower the pollutant level. Additionally, the sampling staff reported that higher level of

Table 2
Statistical result of PM₁₀ and CO in different transportation modes

	CO (ppm)				PM ₁₀ (µg m ⁻³)			
	<i>n</i>	Mean	Range	SD	<i>n</i>	Mean	Range	SD
Subway	20	3.1	1.7–4.5	0.9	20	67	26–123	30
Non-A/C bus	20	8.2	5.3–11.4	1.4	20	203	99–374	84
A/C bus	20	8.9	6.3–14.5	2.6	20	128	65–235	61
Non-A/C taxi	10	18.7	11.9–29.8	5.4	10	150	94–212	38
A/C taxi	10	28.7	10.5–46.1	10.2	10	82	40–153	32

PM₁₀ was observed when the bus approaching to, idling at and leaving from the bus stops. Apart from the external PM₁₀ source due to the vehicle exhausts, the PM₁₀ level would also be affected by the presence of internal PM₁₀ source. In-vehicle PM₁₀ level is related to the re-suspension of dust from the vehicle's floor due to the passengers moving around or taking a seat (Praml and Schierl, 2000). Therefore, frequent passenger movement in bus, especially during passenger alighting or boarding at immediate stops would be another cause of higher internal PM₁₀ source than in taxi.

Based on the experimental results, the CO level was found to be obviously higher in taxi than in bus. Although the in-taxi CO concentration varied significantly with trips, a trip-average level of 30 ppm or above was frequently reached. For well-maintained vehicles, the majority of pollutants existed inside the vehicle are derived from the exhausts of the surrounding vehicles (Duffy and Nelson, 1997). Exceptionally high CO levels in taxi and significant concentration difference between taxi and bus inferred that the in-taxi CO levels were frequently and seriously contaminated by the presence of internal sources. The most possible internal CO source is leakage from the taxi itself. As most of the measured taxis have a fairly old vehicle age (> 6 year) and with high mileage, we suggest that the higher CO level found in these taxis is due to the leakage from the poor-maintained engines or exhaust systems into the taxi cabin. The effect of vehicle height and travel lane would also affect the difference of CO level between bus and taxi, but these influences seem to be outweighed by the effect of self-contamination.

4.2. Effect of ventilation

The in-vehicle PM₁₀ and CO level is greatly influenced by the ventilation condition of the transports. Since the results of Shapiro-Wilk test (normality test) showed that most data sets were normal distributed at confidence level of 95%, the concentration difference between air-conditioned and non-air-conditioned roadway transports was statistically tested by *t*-test. There was significant difference of in-vehicle PM₁₀ ($p < 0.01$) and CO ($p < 0.01$) level in taxi and PM₁₀ ($p < 0.01$) level in bus between these two different ventilated vehicles. The adoption of air-conditioning system in measured vehicles was found to be an effective way to minimize the particulate exposure. The closed window condition in the air-conditioned vehicles can separate the vehicle interior air from the roadway air, thus preventing direct entrance of tailpipe emissions from the neighbouring vehicles into their compartments through the windows. Moreover, although to a minor extent, part of the coarse sizes PM₁₀ might be filtered from the air stream by filter and/or deposited in the system during fresh air intaking or internal air recirculating in these vehicles. On the

contrary, with windows opened in non-air-conditioned vehicles, in-vehicle PM₁₀ level was easily increased by the penetration of vehicle exhausts into the vehicle compartment, especially during stop-and-go traffic in urban route.

Quite different from PM₁₀, the CO level in air-conditioned taxi was significantly higher than that in non-air-conditioned taxi. It is a common practice for the taxi drivers to close the fresh air vent while using the air-conditioning system. The low air exchange rate combined with the presence of internal source enhanced the accumulation of CO level in air-conditioned taxi. The air exchange performance was indirectly examined by the measurement of CO₂ level in air-conditioned taxi. The data showed that the trip-averaged CO₂ level in air-conditioned taxi and non-air-conditioned taxi ranged from 3200 to 5000 ppm and 900 to 1600 ppm, respectively, for 3 occupants (including driver) in about 30-min journey. It is therefore, the air exchange in air-conditioned taxi relied on the penetration of external air through gaps, body cracks or structural faults into the taxi cabin is quite limited and insufficient to dilute the strong internal CO source. On the contrary, the CO level in non-air-conditioned taxi was relieved by the dilution effect of the roadway air through the windows, since the trip averaged CO level in the roadway air is far lower than the in-taxi level. The significant difference of in-taxi CO level between natural and mechanical ventilation strengthened the point that the in-taxi level was seriously influenced by the internal source. For the buses measured, there was no significant difference ($p > 0.05$) in average CO level between air-conditioned and non-air-conditioned bus. For the CO measurements in bus, the closeness in CO level in these two different ventilation types implied that the air-conditioning system used in the air-conditioned bus is ineffective to minimize the intrusion of external CO sources. The CO source from the emission of the neighbouring vehicles can penetrate the bus interior through the fresh air vent during fresh air intake and through the doors during opening of door at stops for passenger alighting and boarding. Also, the large volume space inside the bus helps to dilute any possible internal source. It is worthwhile to point out that the differences in pollutant levels between the two differently ventilated vehicles may also be influenced by the difference in route, even though the two measured roadway routes were carefully selected to have similar features.

4.3. Effect of commuting time of day

The PM₁₀ and CO level differences between two driving periods were examined by considering the non-peak-hour to peak-hour exposure ratio. As shown in Table 3, the mean ratio ranged from 0.81 to 1.11 for CO and 0.79 to 1.06 for PM₁₀. In general, the exposure level

Table 3
Mean in-vehicle concentration for the non-peak hour and peak hour commutes

Transport	<i>n</i>	npk hr ^a	pk hr ^b	npk hr/pk hr ^c		
				Mean	Range	SD
(a) CO (ppm)						
Subway	10	2.8	3.3	0.93	0.64–1.27	0.22
Non-A/C bus	10	7.6	8.8	0.86	0.66–1.16	0.15
A/C bus	10	8.8	9.0	0.98	0.70–1.73	0.36
Non-A/C taxi	5	19.8	17.9	1.11	0.70–1.58	0.39
A/C taxi	5	26.3	32.3	0.81	0.34–1.65	0.57
(b) PM ₁₀ (µg m ⁻³)						
Subway	10	74	60	0.82	0.50–1.11	0.16
Non-A/C bus	10	179	227	0.79	0.38–1.87	0.46
A/C bus	10	124	134	0.93	0.67–1.28	0.21
Non-A/C taxi	5	143	156	0.92	0.72–1.38	0.20
A/C taxi	5	84	79	1.06	0.36–2.10	0.72

^a npk hr—non-peak hour exposure level.

^b pk hr—peak hour exposure level.

^c npk hr/pk hr—non-peak hour to peak hour exposure ratio.

Table 4
Corresponding measurement of PM₁₀ and PM_{2.5}

Transport	<i>n</i>	PM ₁₀ (µg m ⁻³)		PM _{2.5} (µg m ⁻³)		PM _{2.5} /PM ₁₀ ^a	
		Mean	SD	Mean	SD	Mean	Range
Subway	14	55	14	44	11	0.79	0.74–0.85
Non-A/C bus	15	184	72	145	56	0.79	0.71–0.87
A/C bus	11	125	73	101	61	0.81	0.71–0.88
Non-A/C taxi	8	140	34	106	28	0.76	0.72–0.80
A/C taxi	8	88	33	73	30	0.83	0.68–0.90

^a PM_{2.5}/PM₁₀ = PM_{2.5} to PM₁₀ exposure ratio.

was only slightly lower in non-peak-hour than in peak-hour for both CO and PM₁₀. One possible explanation for this phenomenon was due the insignificant change of traffic volume from 14:00 to 20:00 on the selected routes. Within the urban area of Guangzhou, the roads are quite busy even during afternoon non-peak period. Moreover, although the selected routes comprised of different modes of transport, they were extensively used by the public transports which provide regular services in daytime regardless the time of day. This is confirmed by the closeness of driving speed of all measured roadway transports in these two time periods. The driving speed of bus and taxi was rarely found deviated more than 5 km h⁻¹ between afternoon and evening commute running on the same designated route. Other than this, the change of meteorological conditions (e.g. mixing height, wind speed and wind direction) and the vehicle-to-vehicle variation (e.g. extent of the influence

of internal pollutant source) may also have impact on the concentration difference.

4.4. Concurrent PM₁₀ and PM_{2.5} measurement

Table 4 presents the result of the concurrent PM₁₀ and PM_{2.5} measurements. The commuting microenvironment variation in PM_{2.5} was similar to the pattern of PM₁₀. The highest PM_{2.5} level (145 µg m⁻³) was also obtained in non-air-conditioned bus. The trip-averaged in-vehicle PM_{2.5} levels frequently exceeded 130 µg m⁻³ which is two times the USEPA PM_{2.5} daily standard of 65 µg m⁻³. Although such comparisons may not be so appropriate due to the inconsistency of the microenvironment measured and time-average adopted, the results tend to suggest that the PM_{2.5} exposure level during commuting in urban Guangzhou is fairly high. Qian et al. (2001) studied the long-term ambient air pollution

levels in urban districts of Guangzhou. They found that 79% of daily $PM_{2.5}$ air samples exceeded the USEPA standard of $65 \mu\text{g m}^{-3}$. In this study, the $PM_{2.5}$ to PM_{10} ratios in all measured transportation modes were high (76–83%). These ratios were close to those obtained in Wei et al.'s (1999) study, which found that the $PM_{2.5}$ to PM_{10} level was about 65% in the urban site of Guangzhou. As the commuting microenvironments are more close to traffic exhausts, the ratios obtained in our results are reasonably higher. The high in-vehicle $PM_{2.5}$ to PM_{10} ratios implicitly indicated that the in-vehicle air quality was greatly deteriorated by the influence of neighbouring vehicle exhausts. It is known that vehicle exhaust emitted from the vehicles, especially those diesel-fuelled, is the major source of fine particulate at street level of Guangzhou and other metropolitan cities. Although the ratio difference is not quite obvious, the $PM_{2.5}$ to PM_{10} ratios in air-conditioned vehicles (79–83%) were slightly higher than in non-air-conditioned vehicles (76–79%). One possible explanation is that air-conditioning system is capable of filtering part of the larger portion (2.5–10 μm) of PM_{10} , thus the portion of

$PM_{2.5}$ is relatively higher in the interior of the air-conditioned vehicles. However, further experiments are required to verify this assertion.

4.5. Comparisons with overseas studies

Table 5 compares the present study with several overseas studies. In general, except for extreme high CO level in the Mexico City (Fernandez-Bremauntz and Ashmore, 1995), the comparison results indicate that the exposure levels of PM_{10} , $PM_{2.5}$ and CO obtained in the present study lies at the upper pollution range. For particulate (PM_{10} and $PM_{2.5}$), the in-vehicle level in Guangzhou was several times higher than the studies in Hong Kong (Chan et al., 2002), London (Adams et al., 2001) and Birmingham (Pfeifer et al., 1999). The PM_{10} level in buses was comparable to Munich (Praml and Schierl, 2000). Similarly, the CO level in present study was also much higher than the studies in Hong Kong (Chan and Liu, 2001; Chan et al., 1999), Paris (Zagury et al., 2000; Dor et al., 1995) and Washington (Flachsbart et al., 1987). The CO exposure level of bus

Table 5
Comparison of in-vehicle concentration with other studies

Study	Location	Pollutant	Transportation mode	Averaged concentration
Current study	Guangzhou, China	PM_{10} ($PM_{2.5}$)	A/C bus	128 (106) $\mu\text{g m}^{-3}$
			Non-A/C bus	203 (145) $\mu\text{g m}^{-3}$
			Taxi	116 (90) $\mu\text{g m}^{-3}$
			Subway	67 (44) $\mu\text{g m}^{-3}$
Chan et al. (2002)	Hong Kong, China	PM_{10}	A/C bus	74 $\mu\text{g m}^{-3}$
			Non-A/C bus	112 $\mu\text{g m}^{-3}$
			Subway	44 $\mu\text{g m}^{-3}$
			Taxi	58 $\mu\text{g m}^{-3}$
Adams et al. (2001)	London, UK	$PM_{2.5}$	Bus	39 $\mu\text{g m}^{-3}$
Praml and Schierl (2000)	Munich, Germany	PM_{10}	Bus	110–165 $\mu\text{g m}^{-3}$
			Tram	161 $\mu\text{g m}^{-3}$
Pfeifer et al. (1999)	Birmingham, UK	$PM_{2.5}$	Taxi	33 $\mu\text{g m}^{-3}$
Current study	Guangzhou, China	CO	A/C bus	8.9 ppm
			Non-A/C bus	8.2 ppm
			Taxi	23.7 ppm
			Subway	3.1 ppm
Chan and Liu (2001)	Hong Kong, China	CO	Taxi	3.3 ppm
Zagury et al. (2000)	Paris, France	CO	Taxi	3.8 ppm
Chan et al. (1999)	Hong Kong, China	CO	Bus	1.9 ppm
			Tram	2.0 ppm
			Subway	1.5 ppm
Dor et al. (1995)	Paris, France	CO	Bus	4 ppm
			Subway	2 ppm
Fernandez-Bremauntz and Ashmore (1995)	Mexico City	CO	Bus	20.5–41.1 ppm
			Metro	16.8–26.5 ppm
Liu et al. (1994)	Taipei, Taiwan	CO	Bus	11.6 ppm
Flachsbart et al. (1987)	Washington, US	CO	Bus	4–8 ppm
			Train	2–5 ppm

commuter in Guangzhou was comparable to Taipei (Liu et al., 1994) and much lower than Mexico City (Fernandez-Bremauntz and Ashmore, 1995). Although, the differences between studies may be affected by the inconsistency of field study designs, driving conditions, meteorological conditions and other related conditions (Jo and Park, 1999), the results of the present study showed that public transportation commuters and drivers in Guangzhou were frequently exposed to elevated pollutant levels.

4.6. Vehicle emission control and traffic condition

The poor air quality in the street level of Guangzhou is strongly associated with inadequate vehicle emission control and poor traffic condition. Similar to other urban cities, traffic emission has been identified as the main cause of air pollutant in the study area. In Guangzhou, the inferior engine and fuel used in the vehicles combined with the insufficient use of emission control technologies such as catalytic converter are the reasons leading to high in-vehicle as well as roadside pollutant levels. Recently, a study (Fu et al., 2001) concerning the vehicular pollution in China reported that the vehicular CO emission factor in China is 5–10 times higher than the levels in other developed countries. Also, the researchers stated that more than 80% of CO emission in Guangzhou was derived from motor vehicles. Adding to that, unsatisfactory vehicle maintenance is also a cause of concern. In year 1999, as many as 200 thousands vehicles were examined at 21 on-road emission inspection points, but only less than two-third of them passed the test (Guangzhou Yearbook Editorial Committee (GZYEC), 2000). Although a newly promulgated emission standard for light-duty vehicle has been implemented in Guangzhou in year 2000, the requirements are loose when compared with other metropolitan cities. This standard applied only on new vehicles and required control equipment only equivalent to the requirements of Euro 1 standard, that is similar to the control equipment installed on US 1989 cars (Wang et al., 2001). Besides that, the slow going traffic pattern in Guangzhou greatly affects the in-vehicle air quality. Many vehicles in Guangzhou travelled with low driving speed and frequent acceleration, deceleration and idling (Zhang et al., 1999). This phenomenon is attributed to the rapid increase of vehicle number over the last decade. The vehicle number and road length in the whole territory was 331,242 unit and 3547 km in year 1990 and 1,350,390 unit and 5021 km in year 2000, respectively. As the increase of road length is far below the increase of vehicle number, the traffic density was increasing and maintained at a very high level, in particular, in urban districts. Driving in low speed, stop-and-go traffic or frequent idling increased the commuter

exposure, since the emission source strength is higher and the inter-vehicle distance is lower.

5. Conclusion

The study has performed in-vehicle measurements on two health concerned pollutants, particulate and carbon monoxide, in four major public transportation modes while commuting in typical urban routes in Guangzhou. We have employed the DustTrak aerosol monitor with calibration adjustments for in-vehicle particulate measurement, with the limitation that the concentration values obtained are not absolute. The results of this study showed that the in-vehicle exposure level of particulate and carbon monoxide is greatly affected by the commuters' choice of commuting microenvironment. Lane of travel, use of air conditioning system and the presence of internal source were found to be the factors causing inter-microenvironment variations. The highest mean PM₁₀ and CO level was found in non-air-conditioned bus and air-conditioned taxi, respectively. In general, the average PM₁₀ and CO level in roadway transports was 1.2–3.0 and 2.6–9.3 times higher than that in subway, respectively. Hence, subway is highly recommended as a substitute for those roadway transports. The ventilation condition of the transport was also found to be an important factor affecting the in-vehicle level. The PM₁₀ level in bus and taxi can be lowered substantially by the use of air-conditioning system. However, lower CO level resulted in taxi under natural ventilation condition. In general, the influence of driving time is minor. The exposure levels resulted in evening peak-hour commutes were only slightly higher than those in afternoon non-peak hour commutes. The PM_{2.5} to PM₁₀ ratios obtained inside the measured microenvironments were high and implicitly implied that the in-vehicle air quality is strongly associated with the traffic emission. The in-vehicle exposure levels of the current study were higher than those measured in most overseas studies. The loose vehicle emission control requirements, poor vehicle maintenance, plus the slow moving traffic pattern with frequent stops in Guangzhou are the main reasons leading to elevated in-vehicle particulate and carbon monoxide exposure levels. Such consequences related to the increase of emission source strength and decrease of vehicle-to-vehicle distance. Therefore, control measures such as improvement of traffic management, better vehicle maintenance and the speeding up of vehicle emission control requirements to international standards should be concurrently promoted. Although the health impact of in-vehicle air pollution requires subsequent investigation in epidemiological studies, the results of this study indicate that Guangzhou commuters, especially professional drivers,

are frequently exposed to very high levels of particulate and carbon monoxide during daily commutes.

Acknowledgements

This project is supported by a grant from the Hong Kong Polytechnic University of the HKSAR. The authors would like to thank Mr. L.C. Wong and Miss B.F. Lee for assistance in sampling.

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