Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Environment International 29 (2003) 429–435

ENVIRONMENT INTERNATIONAL

www.elsevier.com/locate/envint

# Preliminary measurements of aromatic VOCs in public transportation modes in Guangzhou, China

L.Y. Chan[a,*], W.L. Lau[a], X.M. Wang[b], J.H. Tang[b]

[a] *Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Hong Kong, China*

[b] *State Key Laboratory of Organic Geochemistry, The Chinese Academy of Sciences, Wushan, Guangzhou, China*

Received 18 August 2002

## Abstract

This study examined the exposure level of aromatic volatile organic compounds (VOCs) in public transportation modes in Guangzhou, China. A total of 40 VOC samples were conducted in four popular public commuting modes (subway, taxis, non-air-conditioned buses and air-conditioned buses) while traversing in urban areas of Guangzhou. Traffic-related VOCs (benzene, toluene, ethylbenzene, m/*p*-xylene and *o*-xylene) were collected on adsorbent tubes and analyzed by thermal desorption (TD) and gas chromatography/mass-selective detector (GC/MSD) technique. The results indicate that commuter exposure to VOCs is greatly influenced by the choice of public transport. For the benzene measured, the mean exposure level in taxis (33.6 $\mu g/m^3$) was the highest and was followed by air-conditioned buses (13.5 $\mu g/m^3$) and non-air-conditioned buses (11.3 $\mu g/m^3$). The exposure level in the subway (7.6 $\mu g/m^3$) is clearly lower than that in roadway transports. The inter-microenvironment variations of other target compounds were similar to that of benzene. The target VOCs were well correlated to each other in all the measured transports. The concentration profile of the measured transport was also investigated and was found to be similar to each other. Based on the experiment results, the average B/T/E/X found in this study was about (1.0/4.3/0.7/1.4). In this study, the VOC levels measured in evening peak hours were only slightly higher than those in afternoon non-peak hours. This is due to the insignificant change of traffic volume on the measured routes between these two set times. The out-dated vehicle emission controls and slow-moving traffic conditions may be the major reasons leading elevated in-vehicle exposure level in some public commuting journeys.

*Keywords:* Public transportation modes; VOC; Benzene; Traffic; Exposure

## 1. Introduction

Recently, there was an increasing concern of commuter exposure to volatile organic compounds (VOCs) in daily commuting trips. The commuting microenvironment has widely been recognized as an important sector that can cause elevated personal exposure to many VOCs. Exposure to VOCs, particularly those classified by the United States Environmental Protection Agency (USEPA) as known or suspected carcinogens, can cause adverse health effects because of their toxicity and potential health hazards. For instance, benzene is a carcinogenic compound and is closely linked to the induction of leukemia. The presence of some VOCs in the ambient air is also associated with the deterioration of air quality due to the formation of photochemical smog and tropospheric ozone.

In the past, most of the published in-vehicle air pollution studies tended to focus on the exposure of private vehicle user. Only few oversea studies examined the exposure level in public transportation modes. Duffy and Nelson (1997) investigated the benzene level in the cabin of moving motor vehicles and buses in Sydney, Australia. The results revealed that the concentration measured inside buses were about 50% of the in-vehicle average determined for newer catalyst-equipped cars. In Taegu, Korea, Jo and Yu (2001) reported that taxi drivers were exposed to higher aromatic compound levels than bus drivers during their daily work time. The concentration difference might be due to differences in vehicle height, vehicle cabin volume, smoking status and driving parameters. In Paris, France, Dor et al. (1995) stated that the mono-aromatic hydrocarbons (MAHs) inside vehicles come essentially from the exhaust of neighbouring vehicles, which penetrate the cabin either naturally

---

[*] Corresponding author. Tel.: +852-2766-6026; fax: +852-2334-6389.
*E-mail address:* celychan@polyu.edu.hk (L.Y. Chan).

0160-4120/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0160-4120(02)00189-7

or by ventilation. And the exposure level of MAHs inside car is two to three times greater than that recorded with other means of transportation, including subway and bus.

Guangzhou is a fast growing and economically developed city in South China. The city has an area of about 7500 km$^2$ and a population of about 7.0 million. Its overall economic power is the third among all China's cities and just after Shanghai and Beijing. In year 2000, the gross domestic product (GDP) value of Guangzhou reached 238.3 billion Yuan. The average annual growth rates of the total GDP value as well as the GDP value per capita increased more than 20% over the last decade (GZSB, 1999, 2001). However, as a consequence of rapid development and urbanization in Guangzhou, traffic-related air pollution was found to be one of the major environmental problems. Recent studies had reported that traffic-related pollutants such as $PM_{2.5}$, $PM_{10}$, CO and $NO_x$ in the urban sites of Guangzhou frequently exceeded the Chinese National Air Quality Standard (Wei et al., 1999; Zhang et al., 1999). There were 1,340,548 licensed motor vehicles and 5020 km of public road in the whole territory in the end of 2000. Similar to most metropolitan cities in Asia, public transportation modes are greatly utilized and is a major component in the composition of daily commuting trips in Guangzhou (Deng et al., 2000). Everyday, more than 5 million passenger journeys are made on the public transportation system. The number of public transportation trips has increased sharply and continuously since the early 1990s. Most commuters are required to spend 1–2 h in their daily commutes. As there is limited information on in-vehicle VOC exposure data in the study area, the primary aim of this study is to compare the exposure levels of benzene, toluene, ethylbenzene, m/*p*-xylene and *o*-xylene in four popular public transportation modes while commuting in the urban area of Guangzhou. The target compounds are strongly associated with vehicle use and are commonly known as vehicle emission markers (Chan et al., 1991).

## 2. Field study design

Four popular public transportation modes, which are subway, taxis, non-air-conditioned buses and air-conditioned buses, were selected in this study for aromatic VOCs measurement. These four commuting modes together served more than 85% of the total public transportation journeys in year 2000. Buses are the cheapest and the most abundant mode of transport. There are about 300 bus routes in the urban area of Guangzhou. They provide convenient access to every corner of the city. Most of the buses are diesel fuelled. In air-conditioned buses, the windows are closed and air conditioning system is used throughout the year. Taxis provide a supplementary service to other major transportation modes. They operate throughout Guangzhou, 24 h/day. In the year 2000, there were about 15,620 taxis. Nearly all of them are gasoline fuelled. Air conditioning systems are installed in all taxis. The ventilation condition of taxis was fixed with windows closed, air-conditioning on and fresh air vent closed in this study. This was the most typical and common setting in Guangzhou taxis during the sampling period. 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 south-eastern part of the city while Line 2 is under construction and not yet finished. Underground electrified trains provide fast and safe commutes to the citizens. Centralized air conditioning system is adopted in trains.

As there is no co-located route for all selected roadway transports, two independent bus-service routes, Route 1

Table 1
Features of the sampling routes

| Transport | Route | Average journey time (min) | Average vehicle speed (km/h) | Characteristics of route |
|---|---|---|---|---|
| (1) Subway | (Line 1) Guangzhou East Station – Xilang | 30 | 37.0 | Runs within the inner Guangzhou City. Running mostly on its own 18.5 km underground track. |
| (2) Non-A/C bus[a] | (Route 1) Guangzhou East Station – Youth Park | 55 | 15.6 | A 14.3-km main road with six to eight driving lanes.<br>Crosses busy commercial areas, shopping districts and residential areas.<br>Heavy traffic flow, stop-and-go traffic and many parts of the route are in street canyon configuration. |
| (3) A/C bus[b] | (Route 2) Guangzhou East Station – Jichunlu | 51 | 16.1 | A 13.7-km main road with six to eight driving lanes.<br>The features of this route are similar to Route 1. |
| (4) Taxi | (Route 1 or 2) | 32 or 31 | 26.8 or 26.5 | Same as above |

[a] Non-A/C bus = non-air-conditioned bus.

[b] A/C bus = air-conditioned bus.

(14.3 km) and Route 2 (13.7 km), both connecting the eastern and western parts of the city were selected for non-air-conditioned bus and air-conditioned bus measurements, respectively. While taxis trips were traversed on Route 1 on Monday, Wednesday and Friday and on Route 2 on Tuesday and Thursday. The features of the sampling routes are summarized in Table 1 and the location of the routes is shown in Fig. 1. These two routes are located close to each other and are similar in length, traffic density, street configuration and traffic composition. Hence, they can provide a good comparison among different roadway transports. The selected routes are six to eight lanes (dual direction) on average and traverse busy central commercial areas, shopping districts and residential areas. Adding to that, high traffic density, low vehicle speed and stop-and-go traffic were frequently observed on these routes. However, traffic congestion was only occasionally found during the sampling period. The air samples in the subway were collected on Line 1, which is closed to the routes of roadway transport.

In this preliminary study, microenvironmental monitoring was performed intensively in a five-consecutive day period (Monday through Friday) in May 2001. During the sampling period, a total of 40 VOC samples were successfully collected and analyzed. On each sampling day, the VOC samples in all selected commuting modes were collected in both afternoon non-rush hours (14:00–16:30) and evening rush hours (17:00–19:30). All the VOC samples were collected at respiratory level of the passengers. With an aim to have a better understanding of the real VOC exposure level of the public transport users, all the air samples were collected during normal service of the transport. Our staff travelled as passengers during sampling. No driving instruction was given to the drivers. In this study, the measured taxis were randomly hired at the origin without any selection criteria. All the surveyed taxis were gasoline-fuelled and the buses were diesel-fuelled. Smoking in public transportation modes was strictly prohibited. And no commuter violated this regulation during sampling under our surveillance. On each survey trip, some useful information, such as sampling time, travelling route, traffic condition, number of passengers and weather condition, were clearly recorded.

## 3. Sampling method and quality assurance

In-vehicle VOC samples were collected by stainless steel adsorbent tubes (Tekmar, Part No. 14-1677-203). The adsorption tubes has length of 7 in. and internal diameter of 0.25 in., and were packed with Tenax TA and Carbosieve S-III. Before sampling, all the adsorbent tubes were conditioned at 225 °C at constant helium flow of 40 ml/min for 2 h. The tubes were then stored properly in protective glass cartridges provided by the manufacturer. During sampling, the adsorbent tube was connected to a portable low-flow sampling pump (SKC). The flow rate of the pump was adjusted to about 0.15 l/min. The volume of air sample collected ranged from 4.0 to 9.0 l, depending on the journey time of the trip. The sampling pump was calibrated by a flow meter (Gilian, Gilibrator flow calibrator) before and after each sample collection. The average of these two flow

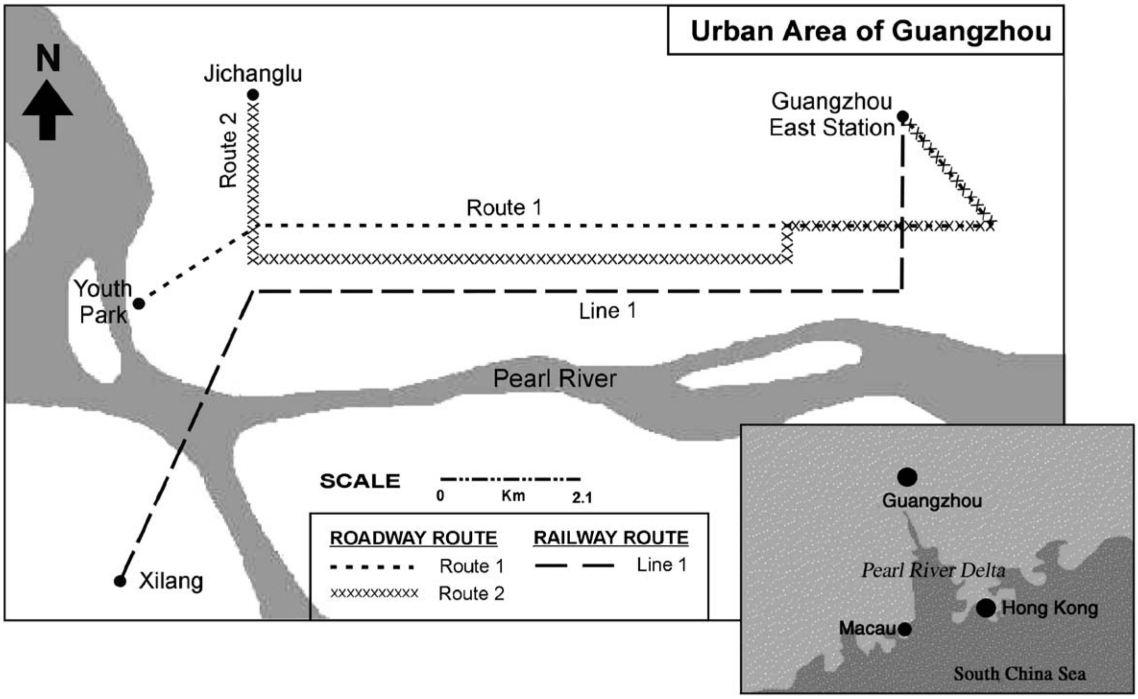

Fig. 1. Location of the sampling routes.

rates was used as the sample flow rate in all concentration calculations. In this study, no final flow rate shifted more than 10% from the initial flow rate. The sampled tubes were sent back to laboratory and stored in a refrigerator at − 20 °C. All the VOC samples were analyzed within 3 days after sampling.

The analyses of VOC samples from adsorbent tubes were performed by thermal desorption (TD) and gas chromatography/mass-selective detector (GC/MSD) technique. The major components of the analytical system were a thermal desorption system (Tekmar AEROTrap 6000), a gas chromatography system and a mass selective detector (Hewlett-Packard, 5972 GC/MSD). A HP-VOC capillary column (30 m × 0.32 mm × 0.5 μm) was used with GC and pure helium gas was used as carrier gas. The oven temperature of the GC was initially held at 35 °C for 2 min. It was then raised to 250 °C at a rate of 8 °C/min and kept for 5 min finally. Each target compound was identified by its retention time and fragmentation pattern. The quantification of target VOCs was accomplished by using multi-point external standard curves. The analysis reports were checked for errors that may be caused by the shifts in retention time.

The calibration curves were prepared by using 1 ppmv standard gases (Scott Specialty, TO14 standard) at five different diluted concentrations plus zero air (0–50 ppbv). Five sets of duplicate VOC samples were collected to check the precision and reliability of the sampling and analyzing method. The relative mean deviation of all duplicates was within 12% for the target compounds. The method detection limit (MDL) of the VOCs was defined as the product of the standard deviation of seven replicate measurements at 1 ppbv and a Student's *t*-test value of 3.143 (99% confidence for seven replicates). The MDLs ranged from 0.42 to 0.96 μg/m$^3$ for all measured VOCs. Other common quality controls such as field blank check and breakthrough test were also included.

## 4. Result and discussion

### 4.1. Inter-comparison of commuting microenvironments

Table 2 summarizes the statistical results of the aromatic VOCs in different transports. None of the data obtained was below their corresponding detection limit. By considering the daily VOC levels in each commuting mode, there were no significant differences (CV < 50%) in VOC concentrations for the five-consecutive day measurements. Among the target aromatic VOCs, toluene and benzene were the two most abundant compounds in all surveyed trips. For the benzene measured, the mean exposure level in taxis (33.6 μg/m$^3$) was the highest and was followed by air-conditioned buses (13.5 μg/m$^3$) and non-air-conditioned buses (11.3 μg/m$^3$). The benzene exposure level in the subway (7.6 μg/m$^3$) was the lowest. The inter-microenvironment variations of other target aromatic compounds were similar to that of benzene. The taxi/air-conditioned bus/non-air-conditioned bus/subway ratio of the mean concentration was about 4.4/1.8/1.5/1.0 for benzene and 3.4/1.7/1.4/1.0 for total BTEX. The results of the present study indicate that the commuter exposure to aromatic VOCs greatly depended on the mode of transport. Our results were consistent with those from Kingham's et al. (1998), which reported that there were significant differences in benzene exposure between the modes of transport while commuting on a busy route in Huddersfield, UK.

Table 2
Statistical results of target VOCs in different transportation modes

| Compounds | *n* | In-vehicle concentration (μg/m$^3$) | | | |
|---|---|---|---|---|---|
| | | Median | Mean | Range | S.D. |
| *(A) Subway* | | | | | |
| Benzene | 10 | 7.0 | 7.6 | 4.1–13.2 | 4.3 |
| Toluene | 10 | 35.7 | 38.0 | 21.6–62.1 | 13.8 |
| Ethylbenzene | 10 | 5.8 | 5.6 | 2.9–6.9 | 1.9 |
| m/*p*-Xylene | 10 | 4.9 | 4.6 | 2.2–6.8 | 2.0 |
| *o*-Xylene | 10 | 5.4 | 4.7 | 2.2–5.9 | 1.6 |
| Total BTEX | 10 | 57.2 | 60.5 | | |
| *(B) Taxi* | | | | | |
| Benzene | 10 | 34.5 | 33.6 | 22.4–47.9 | 10.6 |
| Toluene | 10 | 123.4 | 108.5 | 68.2–141.9 | 30.6 |
| Ethylbenzene | 10 | 19.1 | 20.3 | 12.5–29.4 | 6.9 |
| m/*p*-Xylene | 10 | 26.3 | 26.0 | 15.7–35.3 | 8.4 |
| *o*-Xylene | 10 | 16.2 | 17.2 | 10.6–24.9 | 5.9 |
| Total BTEX | 10 | 217.3 | 205.6 | | |
| *(C) Non-air-conditioned bus* | | | | | |
| Benzene | 10 | 10.7 | 11.3 | 5.2–18.5 | 5.3 |
| Toluene | 10 | 48.5 | 48.9 | 23.1–75.3 | 17.8 |
| Ethylbenzene | 10 | 8.4 | 8.3 | 5.1–13.3 | 2.6 |
| m/*p*-Xylene | 10 | 9.8 | 10.6 | 7.4–15.3 | 2.8 |
| *o*-Xylene | 10 | 7.1 | 7.0 | 4.4–11.3 | 2.3 |
| Total BTEX | 10 | 83.5 | 86.1 | | |
| *(D) Air-conditioned bus* | | | | | |
| Benzene | 10 | 13.0 | 13.5 | 6.6–21.5 | 4.9 |
| Toluene | 10 | 55.9 | 63.6 | 28.6–86.6 | 18.4 |
| Ethylbenzene | 10 | 7.2 | 8.2 | 4.6–12.3 | 2.6 |
| m/*p*-Xylene | 10 | 9.3 | 10.5 | 6.3–14.8 | 3.0 |
| *o*-Xylene | 10 | 6.1 | 6.9 | 3.9–10.4 | 2.2 |
| Total BTEX | 10 | 93.6 | 102.7 | | |

The VOC exposure levels in railway transport (subway) were substantially lower than those in roadway transport (taxi and bus). The averaged benzene and total BTEX levels in roadway transport modes were 1.5 to 4.4 and 1.4 to 3.4 times higher than that in the subway, respectively. The in-vehicle air quality of the subway was less and indirectly influenced by vehicular emission on the street, since the train travelled on its own underground track, which is located away from busy street or other traffic. Hence, under normal situation, the quality of tunnel air, as well as in-train air, is better than roadway air.

The in-vehicle exposure levels in taxis were significantly higher than those in buses for the target VOCs. The concentration differences between buses and taxis could be explained by a combined effect of fuel type, driving lane and vehicle height. The in-vehicle BTEX levels in diesel-fuelled vehicles would primarily impacted by the penetration of roadway air into the cabin (Jo and Yu, 2001). For the gasoline-fuelled vehicles, due to the presence of target VOC sources in gasoline, the engine evaporative emissions and vehicle exhaust emissions from these vehicles are rich in target aromatic compounds. Hence, self-contamination is sometimes a crucial factor for their in-vehicle levels. As most of the measured taxis have a fairly old vehicle age (>6 year) and have high mileage, the elevated VOC levels found in these vehicles may be associated with the internal leakage of engine evaporative emissions and/or vehicle exhaust emissions through the structural faults and body cracks into the vehicle interior. The selection of driving lane on the road may also have a great influence on the in-vehicle levels. Taxis and other light duty gasoline vehicles such as private cars and motorcycles usually traverse in the middle lane of the road (fast lane) where the roadway air is more seriously contaminated by gasoline-related exhausts. On the contrary, buses usually traverse near the curbside of the road (slow lane) which is used extensively by other service buses, and hence, the roadway air mainly contains diesel-related pollutants. It is therefore, the in-taxi VOC levels would more easily be elevated by infiltration of the exhaust of the gasoline vehicles in front into the taxi interior especially during stop-and-go traffic or idling at traffic lights. Apart from this, the in-vehicle level may also be closely related to the vehicle height. Vehicle exhaust is generated near the road surface and the strength of pollutant source is higher there. Since the height of the taxi cabin is lower than that of the bus cabin, the bus commuters are comparatively less affected by vehicle exhaust than the taxi commuters.

The mean in-vehicle VOC levels in air-conditioned buses and non-air-condition buses were close for all target compounds except toluene. The higher toluene level in air-conditioned buses may be due to the emission from the internal casting and furniture of its interior, since some measured air-conditioned buses are fairly new. Toluene is a major constituent used as solvents in painting, surface coating, vanishing and many product makings (Chao and Chan, 2001). Regardless of the concentration difference of toluene, the closeness in BTEX levels in these two different ventilated buses infers that the window-closed and mechanical ventilation conditions in air-conditioned buses are ineffective to minimize the intrusion of roadway VOC sources. The traffic exhausts from neighbouring vehicles can penetrate the bus interior through the air vent during fresh air intaking from roadway air and through the doors during opening of doors at intermediate stops.

### 4.2. BTEX ratios and correlations

The concentration profile and the inter-correlation of BTEX compounds were examined. The average BTEX ratios (B/T/E/X) in taxis, air-conditioned buses, non-air-conditioned buses and subway were (1.0/3.2/0.6/1.3), (1.0/4.7/0.6/1.3), (1.0/4.3/0.7 /1.6) and (1.0/5.0/0.7/1.2), respectively. The target aromatic compounds were highly correlated to each other in the measured transports, with correlation coefficient ($r$) ranging from 0.79 to 0.96 in taxis, from 0.80 to 0.96 in air-conditioned buses, from 0.76 to 0.94 in non-air-conditioned buses and from 0.42 to 0.85 in subway. For the roadway transports, the similarity in concentration profile and the well inter-correlation of the target compounds infer that the in-vehicle BTEX compounds are mainly from the same source(s) in each commuting mode. Emission from motor vehicles is expected to be the most possible common major source in the measured microenvironments. Adding to that, it is interesting to note that subway, with its travelling route located in underground track away from other traffic, has the concentration profile quite similar to that in the roadway transports. This may be attributable to the fact that traffic-related pollutants from street-level ambient air can enter the underground tunnel through air exchange (e.g. fresh air intake and infiltration of air), and eventually reach the train cabin.

### 4.3. The effect of commuting time of day

The VOC level differences between two commuting periods were examined by considering the non-peak-hour to peak-hour exposure ratio. As shown in Table 3, the mean ratio for all target compounds ranged from 0.95 to 1.16 in subway and 0.87 to 1.09 in taxi. In non-air-conditioned buses and air-conditioned buses, the ratio of the target compounds was slightly lower, ranged from 0.75 to 0.88 and from 0.78 to 0.84, respectively. In general, the exposure level was only slightly lower in non-peak-hour than in peak hour for the measured transports. This can be explained by the fact that traffic volume change on the selected routes between the two time periods was small. Within the urban area of Guangzhou, the roads are quite busy all the time. This phenomenon is confirmed by the closeness of vehicle speeds of all measured roadway transport. The driving speeds of the surveyed buses and taxis rarely deviated more than 5 km/h between afternoon and evening commutes when running on the same route. Therefore, the difference of vehicle emission strength on the measured routes between the two set times may not be so large. Other than the traffic volume, the concentration difference may also be sensitive to the change of meteorological conditions (e.g. mixing height, wind speed and ground temperature) and vehicle-to-vehicle variation (e.g. extent of self-contamination).

### 4.4. Comparisons with oversea studies

Table 4 compares the present study with several recent studies. To the best of our knowledge, there is no similar study carried out in Guangzhou or other cities of China in the past. In general, the in-vehicle VOC levels obtained in

Table 3
Mean in-vehicle VOC levels (μg/m$^3$) for non-peak hour and peak hour commutes

| Compounds | npk hr[a] | pk hr[b] | npk hr/pk hr[c] | npk hr | pk hr | npk hr/pk hr |
|---|---|---|---|---|---|---|
| | *(A) Subway* | | | *(B) Taxi* | | |
| Benzene | 7.4 | 7.8 | 0.95 | 33.2 | 34.0 | 0.98 |
| Toluene | 40.8 | 35.2 | 1.16 | 113.4 | 103.8 | 1.09 |
| Ethylbenzene | 5.8 | 5.3 | 1.09 | 19.1 | 21.5 | 0.89 |
| m/*p*-Xylene | 4.6 | 4.5 | 1.02 | 16.0 | 18.2 | 0.88 |
| *o*-Xylene | 4.9 | 4.5 | 1.09 | 24.3 | 27.8 | 0.87 |
| | *(C) Non-air-conditioned bus* | | | *(D) Air-conditioned bus* | | |
| Benzene | 10.6 | 12.0 | 0.88 | 11.8 | 15.1 | 0.78 |
| Toluene | 41.9 | 55.9 | 0.75 | 57.6 | 69.6 | 0.83 |
| Ethylbenzene | 7.2 | 9.3 | 0.77 | 7.2 | 9.1 | 0.79 |
| m/*p*-Xylene | 9.2 | 11.8 | 0.78 | 9.2 | 11.7 | 0.79 |
| *o*-Xylene | 6.3 | 7.8 | 0.81 | 6.4 | 7.6 | 0.84 |

[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 level ratio.

this study lay in the middle of the pollution range of these studies. Based on the benzene measurements, the in-bus level of the present study was close to the studies in Göteborg (Barrefors and Petersson, 1996) and Paris (Dor et al., 1995), but lower than the studies in Taegu (Jo and Yu, 2001; Jo and Park, 1999; Jo and Choi, 1996), Birmingham (Kim et al., 2001), Huddersfield (Kingham et al., 1998) and Sydney (Duffy and Nelson, 1997) and much lower than the Taipei study (Chan et al., 1994). For taxi commuters, the benzene exposure level in Guangzhou taxis was twice than that in the Birmingham (Leung and Harrison, 1999) study, but about 30% lower than the Korea (Jo and Yu, 2001) study. The in-train benzene level was either comparable to or lower than that in other studies (Kim et al., 2001; Kingham et al., 1998; Barrefors and Petersson, 1996). The differences between studies may be due to the inconsistency of field study designs, driving conditions, meteorological conditions and other related conditions (Jo and Park, 1999). Therefore, careful consideration is required for direct comparison between studies.

### 4.5. Vehicle emission control and traffic condition

The vehicle emission controls and traffic conditions in Guangzhou were reviewed. In Guangzhou, the inferior engines and fuels used in the vehicles combined with the inadequate use of catalytic converters are believed to the causes of high in-vehicle VOC pollution in some commut-

Table 4
Comparisons with several oversea studies

| Study | Location | Transport | In-vehicle mean concentration (μg/m$^3$) | | | | |
|---|---|---|---|---|---|---|---|
| | | | Benzene | Toluene | Ethylbenzene | m/*p*-Xylene | *o*-Xylene |
| Current study | Guangzhou, China | Subway | 7.6 | 38.0 | 5.6 | 4.6 | 4.7 |
| | | Taxi | 33.6 | 108.5 | 20.3 | 26.0 | 17.2 |
| | | Non-A/C bus | 11.3 | 48.9 | 8.3 | 10.6 | 7.0 |
| | | A/C bus | 13.5 | 63.9 | 8.2 | 10.5 | 6.9 |
| Jo and Yu (2001) | Taegu, Korea | Taxi | 47.0 | 170.0 | 15.1 | 29.1 | 12.5 |
| | | Bus | 29.0 | 99.2 | 11.6 | 23.2 | 8.8 |
| Kim et al. (2001) | Birmingham, UK | Train | 24.3 | 64.9 | 5.6 | 18.0 | 5.0 |
| | | Bus | 20.2 | 69.3 | 8.0 | 27.9 | 8.6 |
| Leung and Harrison (1999) | Birmingham, UK | Taxi | 17.9 | 40.2 | | 118.2 | 20.4 |
| Jo and Park (1999) | Taegu, Korea | Bus | 21.3 | 84.1 | 12.5 | 28.8 | 25.6 |
| Kingham et al. (1998) | Huddersfield, UK | Train | 12.9 | | | | |
| | | Bus | 21.2 | | | | |
| Duffy and Nelson (1997) | Sydney, Australia | Non-A/C bus | 30.0 | | | | |
| | | A/C bus | 25.0 | | | | |
| Jo and Choi (1996) | Taegu, Korea | Bus | 20.2 | 76.0 | 6.9 | 23.1 | 16.6 |
| Barrefors and Petersson (1996) | Göteborg, Sweden | Bus | 15.6 | 36.3 | | | |
| | | Train | 8.1 | 15.6 | | | |
| Dor et al. (1995) | Paris, France | Bus | 11–13 | 80 | | | |
| Chan et al. (1994) | Taipei, Taiwan | A/C bus | 160 | 367 | 77 | 149 | 95 |

ing trips. Recently, Fu et al. (2001) studied the vehicular pollution in China and reported that the emission factor of hydrocarbons from light-duty gasoline vehicles in China was about five times higher than that in the United States. They also stated that Chinese gasoline was generally more evaporative than that from the US market. This would result in high evaporative running loss emission in gasoline vehicles. Unsatisfactory vehicle maintenance is another cause of concern. In year 1999, as many as 200,000 vehicles were examined at on-road emission inspection points, and more than one-third of them failed the emission test (GZYEC, 2000). In addition to vehicle emission controls, the slow-moving traffic pattern in Guangzhou would also adversely affects the in-vehicle air quality. Many vehicles in Guangzhou are congested in urban districts. Hence, they travel with low driving speed and frequent acceleration, deceleration and idling (Zhang et al., 1999). Under this undesirable driving cycle, the commuter exposure to VOCs is expected to be higher, as the vehicular source strength is stronger and the inter-vehicle distance is shorter.

## 5. Conclusion

This study measured the exposure level of traffic-related aromatic VOCs in four major public transportation modes while driving in urban areas of Guangzhou. The in-vehicle level of VOCs is greatly influenced by the means of transportation. The mean VOC exposure levels in roadway transports were about several times higher than those in railway transport. Therefore, subway is highly recommended as a substitute for roadway transports. For roadway transport, taxi commuters were found to be exposed to higher VOC levels than bus commuters. Such differences may be closely related to fuel type, driving lane and vehicle height. The similar in concentration profile and the high inter-correlation of target VOCs suggest that vehicular emission is the major source of aromatic VOCs found in the measured commuting microenvironments. In this study, the influence of commuting time of day on in-vehicle level is minor. In general, the VOC levels from evening peak-hour commutes were only slightly higher than those in afternoon non-peak hour commutes. The results of this study indicate that Guangzhou commuters are sometimes exposed to high levels of VOCs during daily commutes. It is believed that the in-vehicle VOC pollution is closely associated with the inadequate vehicle emission control and slow-moving driving pattern. As this preliminary study was limited in its scope and only conducted in a 5-day period, the results are only indicative and are mainly in preparation for a more comprehensive study in the coming future.

## Acknowledgements

This project is supported by a grant from the Hong Kong Polytechnic University of the Hong Kong Special Administrative Region.

## References

Barrefors G, Petersson G. Exposure to volatile hydrocarbons in commuter trains and diesel buses. Environ Technol 1996;17:643–7.

Chan CC, Özkaynak H, Spengler JD, Sheldon L. Driver exposure to volatile organic compounds, CO, ozone, and $NO_2$ under different driving conditions. Environ Sci Technol 1991;25:964–72.

Chan CC, Lin SH, Her GR. Office worker's exposure to volatile organic compounds while commuting and working in Taipei City. Atmos Environ 1994;28:2351–9.

Chao CY, Chan GY. Quantification of indoor VOCs in twenty mechanically ventilated buildings in Hong Kong. Atmos Environ 2001;35:5895–913.

Deng MY, Li X, Lin XH. Counter measures of transportation development in Guangzhou based analysis on characteristic of the inhabitant trip. Econ Geogr 2000;20:109–14 [in Chinese, with English abstract].

Dor F, Moullec YL, Festy B. Exposure of city residents to carbon monoxide and monocyclic aromatic hydrocarbons during commuting trips in the Paris metropolitan area. J Air Waste Manage Assoc 1995;45:103–10.

Duffy BL, Nelson PF. Exposure to emissions of 1,3-butadiene and benzene in the cabins of moving motor vehicles and buses in Sydney, Australia. Atmos Environ 1997;31:3877–85.

Fu L, Hao J, He K, Li P. Assessment of vehicular pollution in China. J Air Waste Manage Assoc 2001;51:658–68.

Guangzhou Statistical Bureau (GZSB). Guangzhou Wu Shi Nian, 1949–1999. Beijing: China Statistical Press; 1999.

Guangzhou Statistical Bureau (GZSB). Statistical Yearbook of Guangzhou. Beijing: China Statistical Press; 2001.

Guangzhou Yearbook Editorial Committee (GZYEC). Guangzhou Yearbook 2001. Guangzhou: Guangzhou Yearbook Editorial Committee Press; 2001.

Jo WK, Choi SJ. Vehicle occupant's exposure to aromatic volatile organic compounds while commuting on an urban–suburban route in Korea. J Air Waste Manage Assoc 1996;46:749–54.

Jo WK, Park KH. Commuter exposure to volatile organic compounds under different driving conditions. Atmos Environ 1999;33:409–17.

Jo WK, Yu CH. Public bus and taxicab driver's exposure to aromatic worktime volatile organic compounds. Environ Res Sect (A) 2001;86:66–72.

Kim YM, Harrad S, Harrison RM. Concentrations and sources of VOCs in urban domestic and public microenvironments. Environ Sci Technol 2001;35:997–1004.

Kingham S, Meaton J, Sheard A, Lawernson O. Assessment of exposure to traffic-related fumes during the journey to work. Trans Res Part D, Transport Environ 1998;3:271–4.

Leung PL, Harrison RM. Roadside and in-vehicle concentrations of monoaromatic hydrocarbons. Atmos Environ 1999;33:191–204.

Wei F, Teng E, Wu E, Hu W, Wilson WE, Chapman RS, et al. Ambient concentrations and elemental compositions of $PM_{10}$ and $PM_{2.5}$ in four Chinese cities. Environ Sci Technol 1999;33:4188–93.

Zhang YH, Xie SD, Zeng LM, Wang HX, Yu KH, Zhu CJ, et al. Traffic emission and its impact on air quality in Guangzhou area. J Environ Sci 1999;11:355–60.