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Atmospheric Environment 36 (2002) 255–264

ATMOSPHERIC ENVIRONMENT

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# Carbon monoxide levels measured in major commuting corridors covering different landuse and roadway microenvironments in Hong Kong

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Received 1 December 2000; accepted 1 August 2001

**Abstract**

Vehicle exhaust is the major source of pollutant in modern cities. About half of Hong Kong residents are living in suburban or rural areas. They need to traverse through tunnels, highways, urban street canyons and other road conditions in different landuse areas when they traverse to work in urban centres or new towns. Also, there is increasing traffic, especially trucks across the border between Hong Kong and mainland China via several border highways. This study helps us in assessing the exposure level of suburban and cross border commuters. Carbon monoxide (CO) is used as a tracer for traffic emission. An experimental vehicle traversing major commuting corridors were used to measure CO levels in different landuse and roadway microenvironments including tunnels and highways. The air samples were taken simultaneously at the outside and inside of a travelling vehicle. Result indicates that the pattern of fluctuation of the out-vehicle and in-vehicle CO level vary with different landuse areas. The variation pattern of in-vehicle CO level is closely related to that of out-vehicle level. The effects of the out-vehicle CO concentration on the in-vehicle CO concentration under different roadway conditions in various landuse categories are examined. There is an indication that external air pollutants penetrated into the in-vehicle compartment through car body cracks, ventilation system. From our observation, the exhaust of a nearby petrol vehicle contributed significantly to the in-vehicle CO level. The use of low standard of diesel fuel from Shenzhen in mainland China leads to higher CO level near border area. 

*Keywords:* CO; Exposure; Vehicle exhaust; Tunnel; Highway

## 1. Introduction

Motor vehicle emission is the major source of air pollution in many metropolitan cities and in particular, Hong Kong. There is much concern about the air pollution at street level. Previous studies showed that the levels of pollutants inside a vehicle are higher than those measured at fixed sites (Brice and Roesler, 1966; Chan et al., 1991, 1993; Petersen and Allen, 1982; Jo and Park, 1999). Chan et al. (2000) reported that the respirable suspended particulate (RSP) ($PM_{10}$) concentrations in roadside microenvironments are significantly higher than those in the nearby fixed rooftop monitoring stations. They pointed out that the fixed rooftop measurements do not reflect the real human exposure level at street level microenvironment. People spend considerable time in walking and commuting every day. They are exposed to high traffic-related air pollution.

Hong Kong is a well developed city with high traffic volume. The total number of licensed vehicles exceeded 500,000 in 1998 and it has increased over 45% in the past decade (Transport Department, 1999). This vehicle

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1352-2310/02/$ - see front matter 
PII: S1352-2310(01)00414-9

growth contributes to elevated level of air pollutants in street microenvironment. Hong Kong's air quality is deteriorating. There are 14 air monitoring stations in Hong Kong and three out of them monitor roadside air quality. Although the ambient and roadside carbon monoxide (CO) levels were within Hong Kong air quality objectives (HKAQO), the overall CO levels has increased 27% since 1996. The annual levels of nitrogen dioxide ($NO_2$) and respirable suspended particulates measured in all three roadside air monitoring stations violated the annual HKAQO in 1999. The annual average levels of $NO_2$ and RSP in roadside stations are 94 and 82 $\mu g/m^3$, respectively. These two levels are 17.5% and 49% higher than the relevant annual HKAQO, respectively (permissible limit: 80 $\mu g/m^3$ for $NO_2$ and 55 $\mu g/m^3$ for RSP). The annual $NO_2$ and RSP levels in roadside have increased about 35% (24 $\mu g/m^3$) and 39% (23 $\mu g/m^3$), respectively, since 1991 (Environmental Protection Department, 2000). This reflects the seriousness of the air pollution in street microenvironment.

There is a strong spatial variation of RSP and VOCs in Hong Kong (Chan et al., 2001a, b). This relates to differences in topography, traffic vehicle type, traffic condition and street configuration. There is limited study on the air quality in different roadways covering different landuse districts in Hong Kong. The air pollutant levels at street level in new town and rural area are not measured by the government as all the three HKEPD roadside monitoring stations are in urban area. About half of Hong Kong residents are living in new towns and rural area. They have to spend longer commuting time to work and school. Chan et al. (1999) has characterised the concentrations of gaseous pollutants in different public transportation modes. CO, being an unreactive gas, has found to be a useful tracer of traffic air pollution. The correlations between CO and other gaseous pollutants were not identified. However, it was found that the higher the CO concentration, the higher are the concentrations of other pollutants. In other studies, researchers found that there is a high correlation between CO and VOCs in automobile cabins in Paris ($r = 0.77-0.81$) and Amsterdam ($r = 0.73-0.76$) (Dor et al., 1995; Van Wijnen et al., 1995). CO is chosen in this study as it can be regarded as a useful tracer for other traffic-related air pollutants such as particulate and VOCs.

## 2. Field work design

CO levels were monitored inside and outside an experimental van traversing major commuting corridors covering different landuse and roadway microenvironments. The survey was conducted from November 1998 to January 1999. This was winter when the highest pollutant concentration levels were measured in Hong Kong. Portable CO monitors installed inside a light vehicle van were used to measure the out- and in-vehicle CO levels while traversing different major commuting corridors. The vehicle is a 1998 Toyota diesel vehicle with a total mileage of 4000 km at the beginning of this study. It was driven over representative commuting routes covering different landuse roadway microenvironments.

All the windows and air vents were closed to minimise intrusion of pollutants. Air-conditioning system was turned on during sampling. This is a typical ventilation condition of a vehicle in Hong Kong. Traffic volume, location of the vehicle and the corresponding time were marked on field data sheets. The out-vehicle CO level was monitored by extending a Telfon tube through window of the vehicle. In order to eliminate the possible direct measurement of vehicle exhaust from surrounding vehicles, the out-vehicle sample was taken 1.5 m above ground level. The in-vehicle CO level was measured in the middle of the vehicle and at passengers' respiratory level.

The samples were collected at peak hours (08:00–10:00 and 17:00–19:00) and non-peak hours (10:00–12:00 and 14:00–17:00). The travelling routes are the major commuting corridors that represent characteristic commuting traffic in each district. A total of five tunnels, seven highways and various urban, suburban and rural roads within 20 districts were traversed. The microenvironment conditions and road characteristics of the above commuting corridors are described in Tables 1 and 2 and the routes are shown in Fig. 1. The average sampling time ranges from 2–4 min in vehicle tunnels, 10–20 min in highway and 15–20 min in rural and urban roads.

## 3. Measurement equipment and quality assurance

The CO concentration was measured by an electrochemical voltammetric sensing Interscan 4148 portable continuous CO monitor with a detection range of 0–50 ppm and the detection limit is 0.1 ppm. All CO levels were recorded in part per million (ppm). Readings were recorded every 15 s by a Metrosonics dl-714 portable data logger and the output was programmed to give half-minute averaged intervals. The monitor was turned on and allowed to stabilise for around 5 min before the start of each trip. It was calibrated by a standard CO span gas and zero air before and after each survey trip. The drift of the monitor was always less than 2% at the end of each sampling and the response time of the monitor is 20 s to 90% of final value.

In some trips, Tedlar sampling bags were used to collect air samples to supplement the portable CO monitor. Integrated samples were taken in different

Table 1
Microenvironment conditions and road characteristics of tunnels and highways

| Tunnel/highway | No. of sample | Microenvironment condition and road characteristics | AADT[a] |
|---|---|---|---|
| Lion Rock Tunnel | 10 | Dual two-lane, uni-direction, links urban area and new town, traverse a mountain | 95,200 |
| Cross Harbour Tunnel | 6 | Dual two-lane, immersed tube, uni-direction, links between two urban commercial areas, cross-harbour tunnel | 120,290 |
| Eastern Harbour Tunnel | 6 | Dual two-lane, immersed tube, uni-direction, links urban residential area and urban mixed residential/commercial area, cross-harbour tunnel | 70,360 |
| Cheung Tsing Tunnel | 6 | Dual three-lane, uni-direction, provides linkage between outlying island and suburban area, traverse a small hill in an island | 56,730 |
| Tai Lam Tunnel | 8 | Dual three-lane, uni-direction, a part of Route 3 (Country Park Section), locates within country park, links two new towns | 29,710 |
| Tolo Highway | 18 | Dual three-lane, locates along coastal line, adjacent to Tolo Harbour, links two new towns | 124,410 |
| Island Eastern Corridor | 8 | Dual three-lane, locates at elevated bridge or reclaimed land, links urban commercial centre and urban residential area, mainly petrol cars | 70,360 |
| North Lantau Express | 6 | Dual three-lane, locates at an outlying island, provides linkage between new town and rural area, commercial and residential buildings are absent | 25,960 |
| Tuen Mun Highway | 6 | Dual three-lane, gradient road, links two new town centres, mainly bus and goods vehicle | 95,354 |
| Yuen Long Highway | 6 | Dual three-lane, extension of Tuen Mun Highway, links new town and rural area, major route to the border in the west of Hong Kong, mainly heavy diesel goods vehicles | 66,750 |
| Fanling Highway | 6 | Dual two-lane, provides linkage between new town and rural area, major route to the border at the east of Hong Kong, mainly heavy diesel goods vehicles | 60,800 |
| Route 3 Country Park Section | 7 | Dual three-lane, links two new towns, locates within country park, mainly private car and goods vehicle, provides a faster route to the border in the middle of the New Territories | 29,710 |

[a] AADT—annual average daily traffic.

commuting microenvironments. The readings were compared with the average value obtained by the portable CO monitor. All the sampling bags were transported to the laboratory for analysis within 2 h and the samples were measured by a thermo electron (model 48) gas filter correlation CO ambient analyzer. The analyzer was calibrated with zero and standard span gas regularly.

The results obtained by the monitor and sampling bags are shown in Table 3. The two sets of the result were comparable. The maximum percentage difference between the two sampling methods is 11% but it is usually within $\pm 5\%$. The uncertainty levels of the two methods are within $\pm 2\%$. This shows that the portable CO monitors have good stability and they are suitable for air sampling in the commuting vehicle.

## 4. General characteristics of in- and out-vehicle CO levels

Fig. 2 shows the typical in-vehicle and out-vehicle CO variation profiles of the commuting vehicle. The concentration levels varied in different routes and roadway microenvironments but the profiles are typical. The variation of the in-vehicle CO concentration level is different from that of the out-vehicle level. The fluctuation of the in-vehicle level is far less than that of the out-vehicle level. There is a time lag between out-vehicle and in-vehicle CO level. The out-vehicle level leads the in-vehicle level and its fluctuation frequency and magnitude are higher. The spectrum of in-vehicle level is smoothed and yet the variation trend follows the out-vehicle level. The out-vehicle level rises to a peak and drops to a low level rapidly but the rise and fall of the in-vehicle levels are gradual.

As mentioned in introduction, there is a strong spatial variation of air pollutants and in this study we observe that the variation patterns of the in-vehicle and the out-vehicle CO levels are different in roadway microenvironments within different landuse areas. Therefore, we divided the 20 districts into three main categories: urban area, new town, and rural area. Each category can be further divided into industrial, commercial, residential or mixed commercial/residential area. Among different commuting microenvironments, the fluctuation of out-vehicle CO level in urban commercial area is the greatest

Table 2
Microenvironment and road conditions of each landuse

| Land-use type | No. of sample | District | Microenvironment characteristics |
|---|---|---|---|
| Urban mixed commercial/residential | 8 | Mongkok (MK) | Old developed districts, medium-rise buildings, large shopping centres, narrow streets, high traffic volume, high dense populated area, mainly bus, minibus and private car |
| | | Kowloon City (KLC) | |
| Urban residential | 16 | North Point (NP) | Old developed districts, close to sea, medium traffic flow, mainly tram, bus and minibus |
| | | Kennedy Town (KET) | |
| | | Siu Sai Wan (SSW) | Low traffic flow, housing estate, medium dense populated area, close to sea, low traffic flow |
| | | Aberdeen (AD) | |
| Urban commercial | 11 | Central (CT) | Narrow roads, high-rise commercial buildings, many shopping centres, high traffic flow, mainly bus, private car and taxi |
| | | Wan Chai (WC) | |
| | | Causeway Bay (CB) | |
| Rural | 4 | Stanley (SL) | Low densely populated area, 2–4 storeys buildings, recreation area, beaches, very low traffic flow |
| New Town mixed commercial/residential | 12 | Tuen Mun (TM) | High-rise residential buildings, medium traffic flow, shopping centres, rail station nearby, wider roads |
| | | Yuen Long (YL) | |
| | | Tsuen Wan (TW) | |
| New Town residential | 18 | Shatin (ST) | Low traffic flow, housing estate, high-rise residential buildings, wider roads, mainly bus and minibus |
| | | Sheung Shui (SS) | |
| | | Tai Po (TP) | |
| | | Tung Chung (TC) | New developed new town, many construction sites, low traffic flow |
| Industrial | 11 | Kwun Tong (KT) | Old developed area, narrow roads, medium-rise buildings, medium traffic flow, mainly goods vehicle |
| | | Kwai Chung (KC) | |
| | | Tai Po Industrial Estate (TPI) | Wide roads, low-rise buildings, close to sea, low traffic flow |

and the in-vehicle CO level in this microenvironment is higher than that in the other landuse category. The concentrations of both in-vehicle and out-vehicle CO levels in rural area are the lowest but the in-vehicle level is higher than the out-vehicle level. In residential area, there are a few sharp peaks of out-vehicle CO level and the variation of in-vehicle CO level is small. In highway, the in-vehicle CO level shows small variation when compared to the out-vehicle CO level. When the vehicle traversed tunnel, the out-vehicle CO level increased immediately but the in-vehicle CO level only caught up after seconds.

## 5. Out-vehicle CO levels in different landuse, tunnels and highways

Figs. 3 and 4 show the average out-vehicle CO level in different landuse, tunnel and highway microenvironments. The values were obtained by averaging the measured data in respective microenvironments. The data was divided into peak hour and non-peak hour.

The variations of out-vehicle CO levels in seven landuse categories are shown in Fig. 3. The highest average out-vehicle CO level was recorded in the urban commercial area with 3.2 ppm at peak hour and 2.3 ppm at non-peak hour. The second and the third highest level were measured in mixed commercial/residential areas in urban and new town, respectively. The out-vehicle CO level was the lowest at rural area and the average level was 1.1 ppm at peak hour and 1 ppm at non-peak hour.

In urban commercial areas, the high traffic volume is also the highest in this landuse and there is frequent congestion in the junctions and before traffic lights. Table 4 shows the traffic flow in different landuse categories. At peak hour, the traffic flow sometimes reaches 10,000 vehicles/h in urban commercial area. Street canyon effect is another reason for the high CO level recorded. In these areas, tall buildings occupy along both sides of the street and are closely packed. Vehicle exhaust is trapped within the streets. Dispersion of air pollutants is restricted. CO remains in the street instead of dispersing away. In urban mixed commercial/residential area, the traffic flow exceeds 1400 vehicle/h at peak hour and it is the second highest among the seven

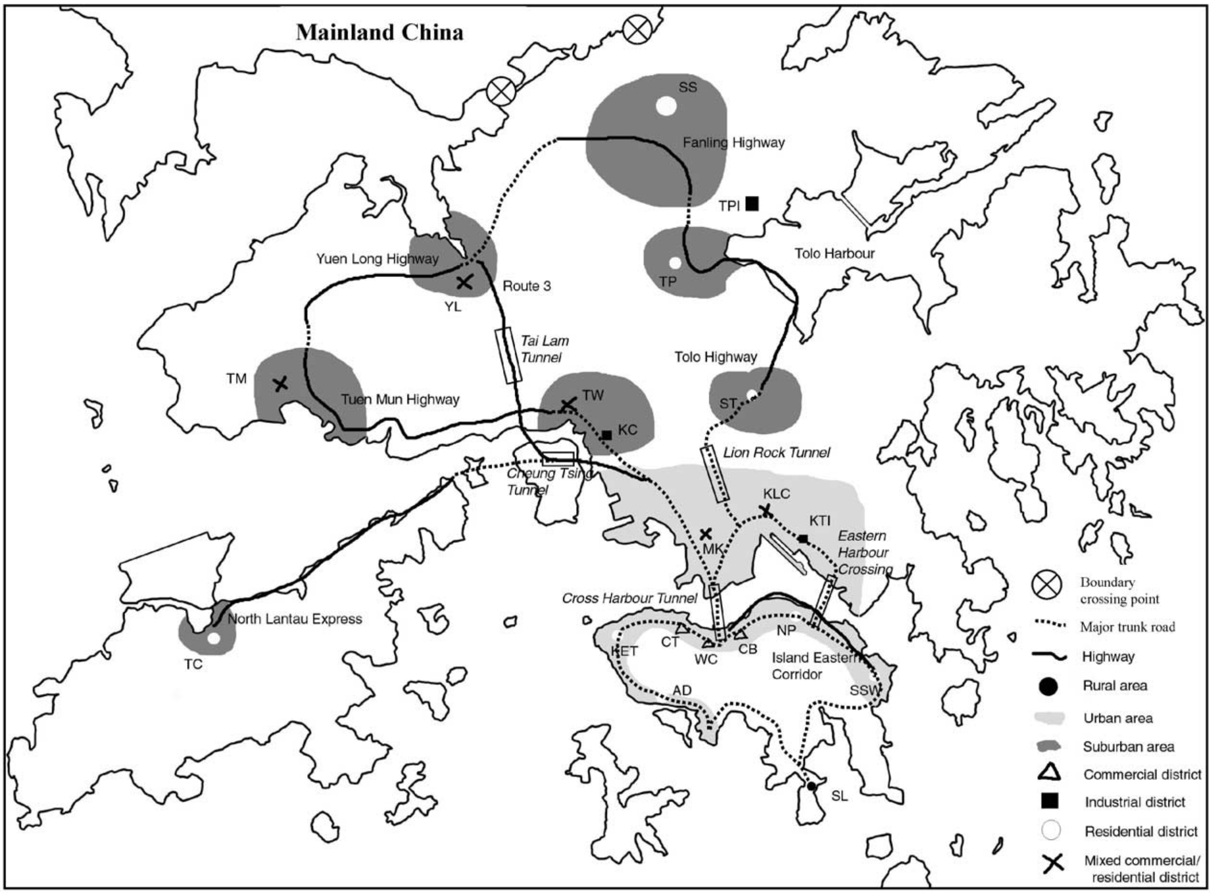


Fig. 1. Major commuting corridors in Hong Kong.

Table 3
CO levels obtained by sampling bag and portable CO monitor

| Microenvironment | Tunnel | Highway | Roadside | In-vehicle |
|---|---|---|---|---|
| Portable CO monitor | 8.0 ppm | 1.5 ppm | 2.4 ppm | 1.9 ppm |
| Sampling bag | 8.6 ppm | 1.5 ppm | 2.5 ppm | 1.7 ppm |
| % difference[a] | −7.5% | 0 | −4.2% | 10.5% |
| Sample size | 10 | 10 | 10 | 10 |

[a] % diff = (portable monitor—sampling bag) * 100%/portable monitor.

landuse categories. The concentration levels in new town residential and industrial area are close. The traffic volume is relatively low in these areas (650–1010 vehicles/h at peak hour). In residential area, the building density is lower and there are more open spaces. The roads are wider than the urban and commercial categories. The dispersion of air pollutants is better. In industrial area, diesel vehicle is the major vehicle type. The CO level is the lowest in rural area because of very low traffic flow (550 vehicles/h at peak hour) and low-profile buildings. The small traffic volume variation leads to small concentration difference at peak and non-peak hour.

The average out-vehicle CO levels in various tunnel and highway microenvironments are shown in Fig. 4. Tunnels had the highest measured values while highways had the lowest measured values. Higher CO level was measured at peak hour inside the tunnels. Tunnel is enclosed with openings at both ends. The ventilation system usually does not provide sufficient fresh air into tunnel due to economic energy saving reasons. Also, the concentration of pollutants is confined by the tunnel and cannot be easily dispersed away. Hence, the CO concentration level in tunnel microenvironment is the highest. As the traffic volume increases, vehicle exhaust cumulates inside the tunnel and the concentration level increases gradually. This leads to higher measured CO level inside tunnels at peak hour. Those vehicle tunnels (the Lion Rock Tunnel, the Cross Harbour Tunnel and the Eastern Harbour Crossing) connecting urban area/

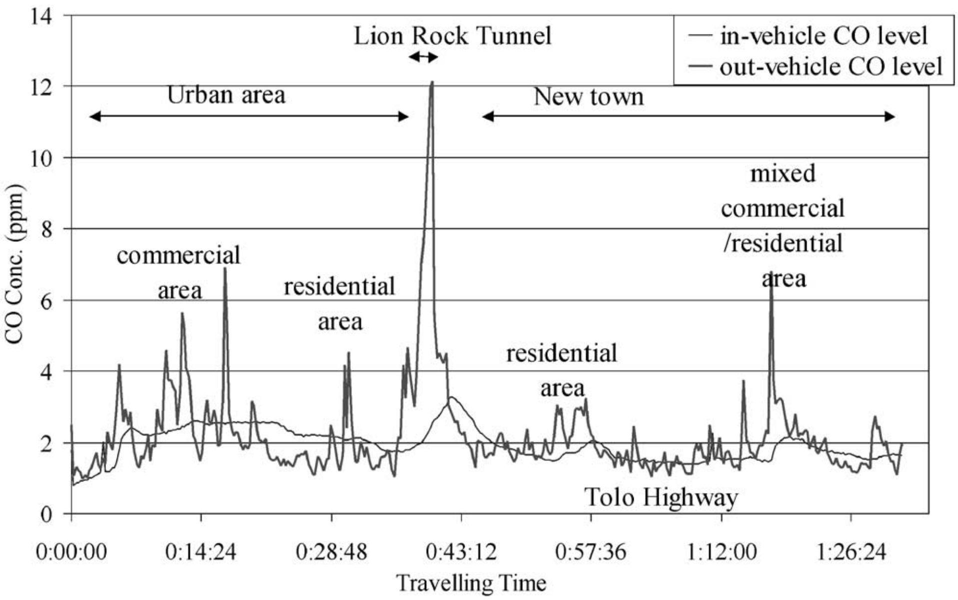


Fig. 2. CO level inside and outside a travelling vehicle.

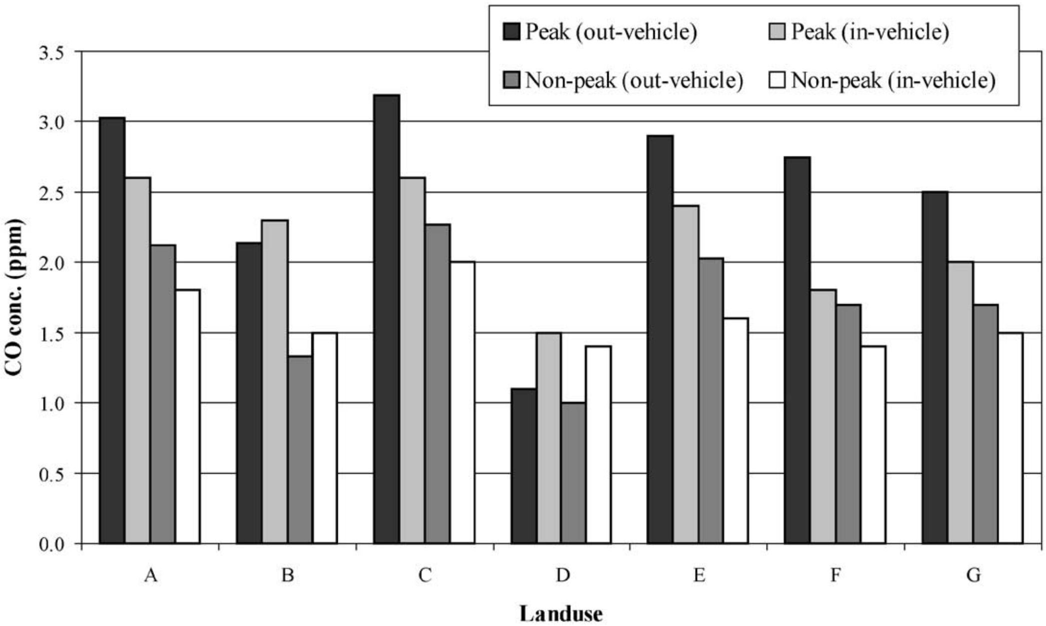


Fig. 3. Out-vehicle and in-vehicle CO level in different landuse areas. (A—urban mixed commercial/residential, B—urban residential, C—urban commercial, D—rural, E—new town mixed commercial/residential, F—new town residential, G—industrial.)

new town or urban areas had higher CO levels than those (Cheung Tsing Tunnel and Tai Lam Tunnel) connecting rural/new town or rural areas. The average CO levels in urban vehicle tunnels ranged from 7.6 to 8.5 ppm at peak hour and from 5.6 to 7.6 ppm at non-peak hour. The average CO levels in rural/new town vehicle tunnels were 2.9–3.0 ppm and 2.3–2.6 ppm at peak and non-peak hour, respectively. The main cause of the concentration variation is the difference in traffic volume.

In contrast, most highways are located at open areas. Dispersion of pollutant is always better and is strongly

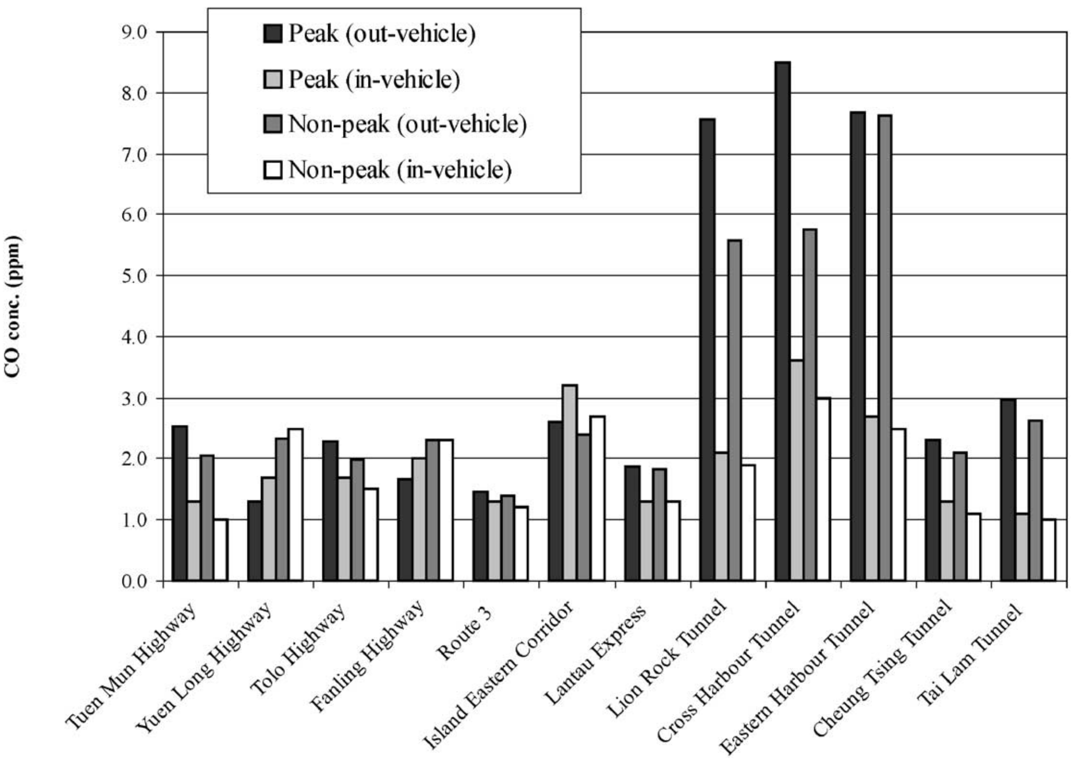


Fig. 4. Out-vehicle and in-vehicle CO levels in different tunnel and highways microenvironments.

Table 4
Traffic volume in each landuse category[a]

| Landuse | AADT | Traffic flow at peak hour (vehicles/h) |
|---|---|---|
| Urban mixed commercial/residential | 24,400–53,030 | 1450–3100 |
| Urban residential | 8900–25,060 | 560–1640 |
| Urban commercial | 36,260–142,810 | 2700–10,010 |
| Rural | 9310–11,880 | 550–910 |
| New Town mixed commercial/residential | 11,380–16,030 | 680–1050 |
| New Town residential | 11,300–16,460 | 650–1010 |
| Industrial | 12,050–18,860 | 720–1370 |

[a] AADT—annual average daily traffic.

influenced by meteorological factors (such as wind speed and wind direction). Concentrations of pollutants are diluted. Hence, the average out-vehicle CO levels measured in highway were significantly lower than those measured inside vehicle tunnels. The CO concentration ranges from 1.4 to 2.6 ppm. The highest out-vehicle CO concentration was measured in the Island Eastern Corridor traversing urban districts while the lowest level was measured in Route 3 located in rural area. The average CO concentration measured at peak hour was higher than that at non-peak hour in all highways except Fanling highway and Yuen Long Highway. These two highways are frequently used by trucks. The use of relatively low standard diesel fuel from Shenzhen in mainland China and the large proportion of diesel vehicle on the roads are the cause of higher measured CO level at non-peak hour in Yuen Long Highway and Fanling Highway. Drivers prefer to use this fuel because its price is much cheaper. As a result, the emission level of the exhaust is greater. These two highways are the two major routes to Shenzhen across the Hong Kong border. Heavy duty diesel vehicles are the major vehicle type and they move slowly along the highways. Traffic congestion occurs easily as all the vehicles are required to queue up for Customs inspection at the border all day long. Vehicles still emit pollutants into the atmosphere while idling. In fact, the peak hour for these two highways is different from others. Hence, it appears that the usual peak hour concentration is lower than the usual non-peak hour concentration.

## 6. In-vehicle CO levels in different landuse, tunnel and highway

The in-vehicle CO variations in different landuse and roadway commuting microenvironments are shown in Figs. 3 and 4. The variation pattern is closely related to the out-vehicle level as described earlier. This demonstrates that the in-vehicle concentration is greatly influenced by the out-vehicle concentration. The highest concentration was recorded in urban commercial and urban mixed commercial/residential areas. The lowest in-vehicle level was measured in rural area. The average in-vehicle CO levels in tunnels ranged from 1.0 to 3.0 ppm at non-peak hour and from 1.1 to 3.6 ppm at peak hour. In general, the average in-vehicle CO level is 2–3 times lower than the out-vehicle CO level while traversing tunnel microenvironment. In highways, the in- and out-vehicle concentration levels are pretty close. The concentrations of in-vehicle CO level are 1.0–2.7 ppm and 1.3–3.2 ppm at peak and non-peak hour, respectively.

About half of Hong Kong residents are living in suburban or rural area. They need to go through tunnels or highways to commute to urban centre or other suburban area. The tunnel and highway data would be useful in assessing the exposure of a commuter. The in-vehicle CO level closely relates to the out-vehicle CO level. This shows the effect of penetration of emissions from neighbouring vehicles. This implies that the in-vehicle level is affected by the traffic volume and the dispersion of pollutants outside the vehicle. As all the windows and air vents are closed during sampling, this shows that the vehicle is not completely sealed especially for our light goods vehicle. The exchange of air mass takes place through the ventilation system and the leaks in the windows, doors and other part of the vehicle body. There is a time lag between the two levels. The time shift of the two levels is due to the air exchange rate. Ott et al. (1994) found that the air exchange rate was 0.22/min with window closed at vehicle speed of 20 mph. If the cracks and leaks do not exist, the in-vehicle CO level would rather keep constant. The temporal variation of the in-vehicle CO level indicates that the air exchange rate governs the air pollution level inside the vehicle compartment.

From our observation, the out- and in-vehicle CO levels jumped to a peak when a petrol vehicle passed the experimental vehicle but both levels did not rise significantly when a diesel vehicle passed the experimental vehicle. This implies that the sudden rise of the CO level is strongly influenced by the petrol-engine vehicle passing by. It agrees with the fact that the CO emission of a petrol vehicle is higher than that of a diesel vehicle. Clifford et al. (1997b) developed a 1 : 10 scale model to simulate the dispersion of vehicle exhaust in slow-moving traffic. The result showed that the pollution level measured on a vehicle model surface mainly comes from the car instantaneously in front of the vehicle. The model suggests that the pollution level received by a commuter may be strongly influenced by the exhaust produced from the car immediately in front. Our result is consistent with this study. For example, the petrol car is the major vehicle type in the Island Eastern Corridor. The out-vehicle CO level is relatively higher when compared with other highways and this leads to higher in-vehicle CO level.

The exposure levels of commuters are not only affected by the types of travelling routes, but also the time of the day. Result indicated that the commuter exposure level in peak hour is on average 40% higher than in non-peak hour. The measurement in peak hour is to assess the exposure level of a commuter travelling between home and office while the measurement in non-peak hour is to assess the exposure level of a commuter travelling between home and leisure places. The exposure levels of commuters are different at different time of a day. Commuters exposed to higher CO concentration while they commute to work.

Table 5 shows the comparison between our study, the local air quality guideline and a previous study in Hong Kong. All the CO levels obtained in this study are below Hong Kong air quality objectives (1-h average

Table 5
Comparison of the result with other transportation modes and air quality guideline in Hong Kong

| | CO conc. (ppm) | | |
|---|---|---|---|
| | Min | Avg | Max |
| Present study | | | |
| In-vehicle | 1.0 | 1.9 | 3.6 |
| Out-vehicle | 1.0 | 2.9 | 8.5 |
| Previous study (1999) (In-vehicle) | | | |
| Bus | 0.9 | 1.9 | 4.6 |
| Light bus | 1.3 | 2.4 | 3.9 |
| Tram | 1.4 | 2.0 | 3.5 |
| Railways | 0.8 | 1.5 | 2.2 |
| Ferry | 0.5 | 0.6 | 0.8 |
| Private car | 4.4 | 10.1 | 24.9 |
| HKAQO[a] (1 h) | — | 22.4 | — |

[a] HKAQO—Hong Kong air quality objective.

22.4 ppm). When compared with other transportation modes in Hong Kong (Chan et al., 1999), the overall average in-vehicle CO level in our light goods vehicle is close to those of bus and tram, less than those of that in light bus and private car, but higher than those of railway and ferry.

## 7. Ratio of in-vehicle and out-vehicle CO level

The average ratios of in- to out-vehicle CO level are calculated for various tunnels, highways and landuse commuting microenvironments. They were obtained by averaging the individual ratio in the respective commuting microenvironment. The ratios lay between 0.5 and 1.6 in different landuse category. The median ratios in urban residential, rural and industrial area are greater than one and that in the remaining landuse categories are less than one. All the ratios obtained inside the tunnels are below one and range from 0.4 to 0.7. The ratios obtained in highways show a different variation. The average ratios are always equal to or above one.

The in-vehicle CO level is greater than the out-vehicle CO level when the vehicle is in urban residential, rural district and in some highways. The ventilation condition was standardised in all trips and the in-vehicle level is a function of the out-vehicle level. This illustrates the effect of penetration of emissions from neighbouring vehicles and internal engine compartment. Vehicle exhaust intrudes into vehicle compartment through leaks, joints or ventilation system. Van Wijnen et al. (1995) obtained a similar result. The concentrations of pollutants inside cars are higher than that in outdoors. The author explained that it is the effect of vehicle exhaust of preceding car entering into vehicle compartment through ventilation system. As the ambient concentration of CO is low in these areas, the effect is particularly significant. Table 6 summarised the ratio obtained in other cities. The ratio lies between 0.6–1.1. Low ratio obtained in London was due to the out-vehicle sampling height. The sample was collected on the bumper at the front of the car. Fresh vehicle exhaust is collected directly at this height. This leads to higher out-vehicle CO level.

## 8. Conclusion

CO level was measured in major commuting corridors covering different landuse and roadway microenvironments. Our study shows that the in-vehicle CO level is greatly influenced by the out-vehicle level. About half of Hong Kong residents are living in suburban or rural area. These commuters are required to commute to work in urban centres or new towns through different landuse area via tunnels and highways. The fast development in

Table 6
Ratio of in-vehicle to out-vehicle obtained in other cities

| City | Type of vehicle | Ventilation mode | Commuting route type | Ratio | Ref. |
|---|---|---|---|---|---|
| London | Car | Closed windows and air-blowers | Various types of road, e.g. motorway, major access road | 0.6 | Colwill and Hickman, (1980) |
| Nottingham | Light van | Ventilation system control positions were not standardised but fan always switched to its slowest speed | Two busy routes, main arterial roads into city, congested city traffic to free-flowing traffic 80% freeway and 20% arterial | 0.7 | Clifford et al. (1997a) |
| Los Angeles | Car | (a) Closed windows and vents<br>(b) Open windows and vents | | (a) 0.9<br>(b) 0.9 | Petersen and Allen, (1982) |
| Raleigh | Car | Three modes: window and vent closed, window and air-conditioning closed with vent on, all closed except window | Three routes represent urban, highway and rural driving | 1.1 | Chan et al. (1991) |

new towns and increasing cross boundary activities between Hong Kong and mainland China leads to an increase in traffic volume along the major commuting corridors. The pollution level in these commuting microenvironment increase accordingly. Town planner must pay more attention to the commuting traffic problem. Also, the uses of low standard diesel fuel from Shenzhen in mainland China and by cross border vehicles leads to higher CO level near the border need to be tackled.

Result indicates that the pattern of fluctuation of the out-vehicle and in-vehicle CO level vary with different landuse. The variation pattern of in-vehicle CO level is closely related to that of out-vehicle level. This indicates that there is an internal leakage from engine compartment or exhaust emission from neighbouring vehicles, especially petrol vehicles. Vehicle engineer should improve the vehicle compartment design to minimise the intrusion of vehicle exhaust and drivers must preserve a frequent maintenance of the vehicles.

## Acknowledgements

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

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