

# Roadside air quality and implications for control measures: A case study of Hong Kong

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**Abstract:** Traffic related air pollution is one of major environmental issues in densely populated urban areas including Hong Kong. A series of control measures has been implemented by Hong Kong government to cut traffic related air pollutants, including retrofitting the Euro II and Euro III buses with selective catalytic reduction (SCR) devices to lower nitrogen dioxide (NO<sub>2</sub>) emissions. In order to reveal the real-life roadside air quality and evaluate the effectiveness of the control measures, this study first analyzed the recent six-year data regarding concentrations of pollutants typically associated with traffic recorded in two governmental roadside monitoring stations and second conducted on-site measurements of concentration of pollutants at pedestrian level near five selected roads. Given that there is a possibility of ammonia leakage as a secondary pollutant from SCR devices, a special attention was paid to the measurements of ammonia level in bus stations and along roadsides. Important influencing factors, such as traffic intensity, street configuration and season, were analyzed. Control measures implemented by the government are effective to decrease the traffic emissions. In 2014, only NO<sub>2</sub> cannot achieve the annual air quality objective of Hong Kong. However, it is important to find that particulate matters, rather than NO<sub>2</sub>, pose potentially a short-term exposure risk to passengers and pedestrians. Based on the findings of this study, specific control measures are suggested, which are intended to further improve the roadside air quality.

**Keywords:** Roadside air quality, traffic related pollutants, urban environment, air pollution, on-site measurement

## 1. Introduction

### 1.1 Background

Air pollution is one of the major environmental issues today. Exposure to air pollution is closely associated with increased human morbidity and mortality (Brunekreef and Holgate, 2002; EEA, 2014). The recent WHO report (WHO, 2014) regarding global burden of disease indicates that exposure to ambient air pollution caused 3.7 million deaths worldwide in 2012, including 936,000 in South East Asian regions. Among others, traffic exhausts have long been recognized as one of the major sources of air pollution in urban areas (Pfeffer, 1994; Clark and Ko, 1996; Zhang et al., 1999; Colville et al., 2001; Wang and Xie, 2009; Ai and Mak, 2015). The main traffic related pollutants include nitrogen oxides (NO<sub>x</sub>), particulate matters (PMs), carbon monoxide (CO), Sulphur dioxide (SO<sub>2</sub>) and ozone

(O<sub>3</sub>) (Vardoulakis et al., 2003; Thorpe and Harrison, 2008). Owing to increased traffic emissions and/or adverse dispersion conditions, traffic related pollutants can accumulate to reach very high concentrations at street level in comparison with background concentrations (Spadaro and Rabl, 2001; Gietl et al., 2010; Weijers et al., 2004; Zwack et al., 2011; Zhao et al., 2004; Ai and Mak, 2015), which could also make their incursion into the indoor environments through infiltration and ventilation (Ai and Mak, 2014, 2016). Therefore, efforts that are devoted to cut the traffic related pollutants and thus to improve the street-level air quality are of great significance.

Source control is always the most effective method. Since 1999, a wide range of measures (HKEPD, 2015a, Ning et al., 2012) have been implemented in Hong Kong to control traffic emissions, such as retrofitting franchised buses and pre-Euro diesel commercial vehicles with particulate reduction devices, retrofitting Liquefied Petroleum Gas (LPG) and petrol vehicles with catalytic converters to reduce NO<sub>x</sub> emissions, assigning low-emission franchised buses to low-emission zones (HKLC, 2015), tightening the fuel and emission design standards of new vehicles, and introducing LPG vehicles to replace the light buses and diesel taxis. The Environmental Protection Department of Hong Kong (HKEPD) reported that, from 1999 to 2014, the roadside concentrations of respirable suspended particulates (RSP), SO<sub>2</sub> and NO<sub>x</sub> have decreased by 45%, 67% and 45%, respectively. However, the level of NO<sub>2</sub> has increased by 3% from 1999 to 2014 (HKEPD, 2015b).

In order to tackle the roadside NO<sub>2</sub> problem, the Hong Kong government has adopted specific control measures. As one of important measures, the government subsidizes franchised bus companies for retrofitting their Euro II and Euro III buses with selective catalytic reduction (SCR) devices (HKEPD, 2013, 2015a). SCR devices use a metallic or ceramic wash-coated catalyzed substrate, or a homogeneously extruded catalyst and a chemical reductant to convert NO<sub>x</sub> into benign nitrogen gas and water in oxygen-rich exhaust streams (Shelef, 1995; HKEPD, 2013). In Hong Kong, SCR systems are installed in a few models of franchised buses and heavy duty vehicles. According to the trial test of HKEPD (2012), SCR technology is effective in reducing NO<sub>x</sub> emission, the average NO<sub>x</sub> emission reduction efficiency ranged from 66% to 86%. However, some mechanical problems have been detected during the trial test (HKEPD, 2012), such as blockage of exhaust pipe due to crystallization of urea (a reductant), exhaust gas leakage and urea leakage resulting in the thermal lagging material being burnt. Owing to mechanical problems, there is a risk of ammonia leakage from SCR devices, which would cause secondary roadside air pollution. It is necessary to examine the ammonia concentrations along roadsides and at bus stations, where there are buses with SCR devices passing through.

## 1.2 Objectives

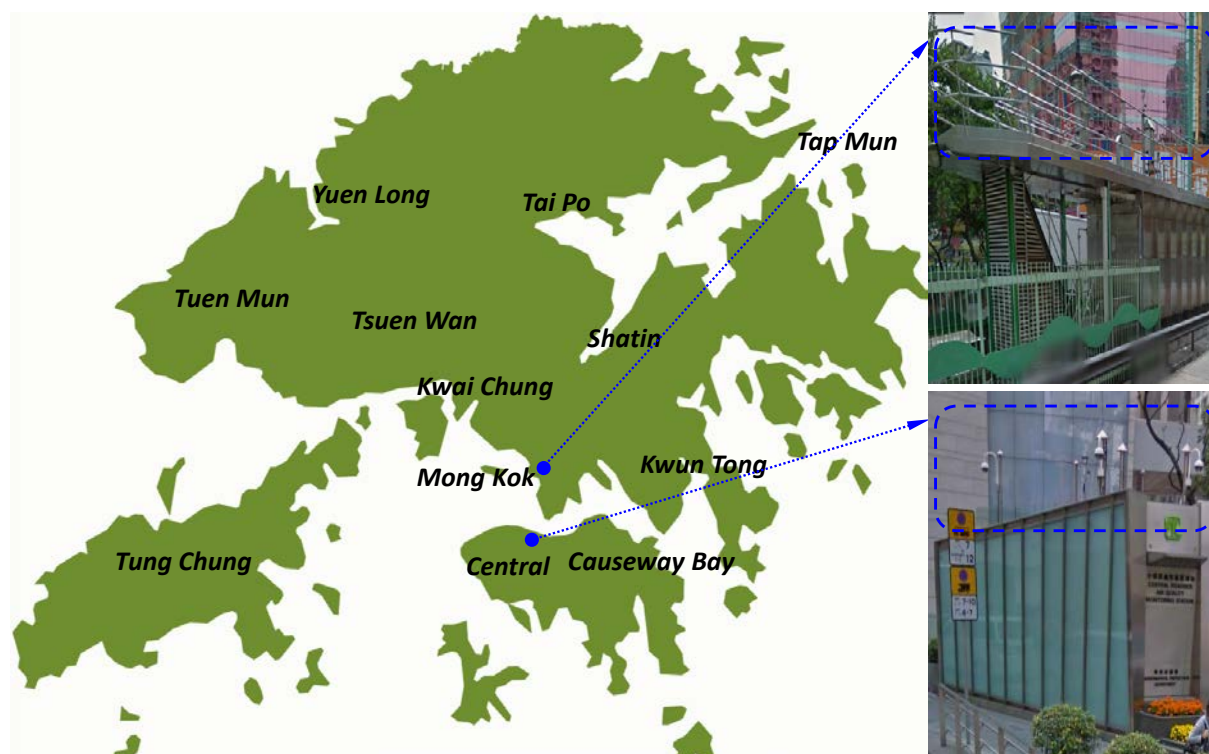
Although the HKEPD has reported the achievement of air pollution control in terms of the concentration decrease of major pollutants, detailed analyses of the evolution of roadside pollutant concentrations have not been made. In addition, the roadside air quality in comparison with the air quality objectives of Hong Kong (HKEPD, 2015c) was still unclear. Therefore, this study analyzed the roadside concentrations of pollutants typically associated with traffic during the period from 2009 to 2014, which were retrieved from two governmental monitoring stations in Mong Kok and Central districts (HKEPD, 2015d). The yearly and seasonally variation of the concentrations of pollutants typically associated with traffic were analyzed. In particular, the yearly averaged concentrations of pollutants were compared with the air quality objectives of Hong Kong, which thus can verify the effectiveness of the control measures and identify areas where further measures should be

implemented.

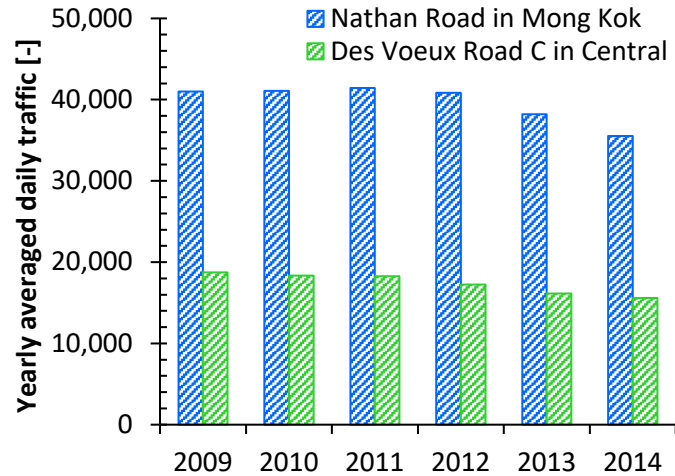
Given that the governmental monitoring stations were located above the pedestrian level (HKEPD, 2015e), specifically at a height of 3–4.5 m, on-site measurements at a height of 1.5 m above the ground were conducted in this study to (a) reveal the pedestrian-level roadside air quality and (b) evaluate the short-term exposure risk of passengers and pedestrians who normally do not stay for a long time along roadsides. Considering that concentrations of some pollutants could attenuate vertically along height (Weber et al., 2006; Vakeva et al., 1999; Chan and Kwok, 2000), the pedestrian-level measurements may reveal some new information. On-site measurements were conducted from winter 2012 to summer 2013 at five major roads and five busy bus stations in Hong Kong. Among the five roads, two roads were categorized as busy roads in low-emission zones (HKLC, 2015) and three as normal traffic roads. In order to determine whether there was any leakage of ammonia as secondary pollutant from SCR devices, the levels of ammonia along roadsides and at the bus stations were measured when (and after) a bus with SCR systems was passing (and passed) through. In addition, at the five roads, roadside concentrations of pollutants typically associated with traffic including NO<sub>2</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, CO, SO<sub>2</sub> and O<sub>3</sub> were measured. Together with these pollutants, environmental parameters including air temperature, relative humidity and wind speed as well as general weather condition were also recorded for analyses.

## 2. Roadside concentrations retrieved from HKEPD

The hourly data recorded at two governmental roadside monitoring stations in Mong Kok and Central, from 2009 to 2014, was retrieved from HKEPD (2015d) for analysis. Figure 1 illustrates the locations of the two roadside monitoring stations. Note that Mong Kok and Central are two of the most densely populated districts in Hong Kong. Concentrations of pollutants typically associated with traffic including NO<sub>2</sub>, PM<sub>10</sub>, PM<sub>2.5</sub>, CO, SO<sub>2</sub> and O<sub>3</sub> were recorded hourly at both Stations, except for O<sub>3</sub> at both stations before 2011 and PM<sub>2.5</sub> at Mong Kok before 2011.

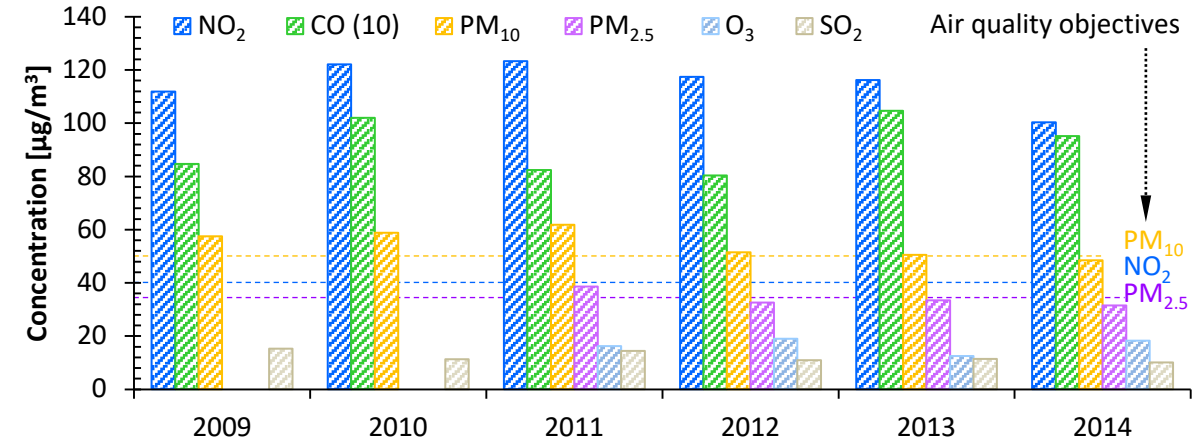


**Figure 1** Locations of roadside monitoring stations in Mong Kok and Central, where the sensors for pollutants monitoring are marked with blue boxes.



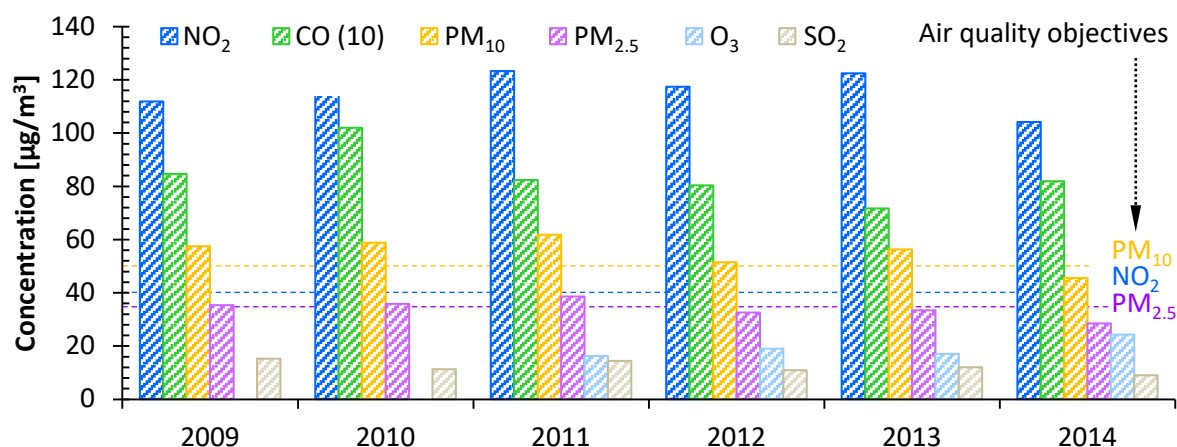
**Figure 2** Yearly averaged daily traffic intensity at the two roads in Mong Kok and Central where the roadside monitoring stations are located.

The yearly averaged daily traffic intensity at the two roads in Mong Kok and Central is presented in Figure 2. It shows that the traffic intensity at Mong Kok was nearly two times of that at Central. In addition, the yearly averaged traffic intensity at each road was relatively stable from 2009 to 2012, which decreased since 2013. On average, the percentage decreases of traffic intensity from 2009 to 2014 are 13.3% and 16.8% at the roads in Mong Kok and Central, respectively. Figures 3 and 4 present the yearly averaged concentrations of the six pollutants from 2009 to 2014 in Mong Kok and Central, respectively. The roadside concentrations of pollutants in Mong Kok were very close to those in Central. The combined analysis of traffic intensity and air quality data indicates that the large difference in yearly averaged traffic intensity between Mong Kok and Central did not produce a same degree of difference in pollutant concentrations. This inconsistency between traffic intensity and air quality suggests that the yearly averaged traffic intensity cannot be used alone to indicate the long-term air quality, as the atmospheric flow and turbulence would migrate and homogenize the local traffic emissions.



**Figure 3** Yearly averaged roadside concentrations of pollutants typically associated with traffic in

Mong Kok from 2009 to 2014, where the air quality objectives for NO<sub>2</sub>, PM<sub>10</sub> and PM<sub>2.5</sub> are also plotted.



**Figure 4** Yearly averaged roadside concentrations of pollutants typically associated with traffic in Central from 2009 to 2014, where the air quality objectives for NO<sub>2</sub>, PM<sub>10</sub> and PM<sub>2.5</sub> are also plotted.

The results presented in Figures 3 and 4 reveal generally a tendency of decrease in concentration level of the six pollutants over these years, except for CO and O<sub>3</sub>, which showed a fluctuation in yearly averaged concentration. Taking Central as an example, the SO<sub>2</sub>, PM<sub>10</sub>, PM<sub>2.5</sub> and NO<sub>2</sub> levels have been decreased from 2009 to 2014 by 41%, 21%, 20% and 7%, respectively. Parallel with the decrease of traffic intensity, such decreases of pollutant concentrations indicate that the measures implemented by the Hong Kong government in recent years (HKEPD, 2015a, 2015b) are effective to control the traffic emissions and improve roadside air quality.

Table 1 presents the air quality objectives of Hong Kong (HKEPD, 2015c). The annual objectives for pollutants NO<sub>2</sub>, PM<sub>10</sub> and PM<sub>2.5</sub> were also plotted in Figures 3 and 4 for convenient comparison. Comparison of the yearly averaged roadside concentrations with Hong Kong air quality objectives leads to the following findings. First, although there are no annual objectives for pollutants CO, SO<sub>2</sub> and O<sub>3</sub>, it is safe to estimate, from the 24-hour or 8-hour objectives, that yearly averaged concentrations of these three pollutants were well below the related objectives. Second, concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> met the objectives in both districts in 2014, although they were more or less higher than the safe limits before 2014. Third, the yearly averaged concentration of NO<sub>2</sub> in both districts exceeded largely the safe limit.

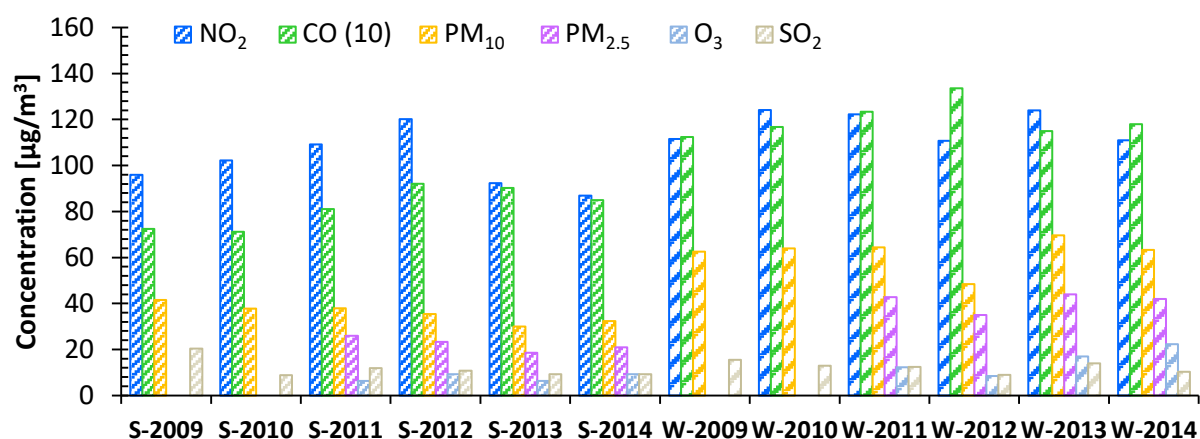
In summary, yearly averaged concentrations of PM<sub>10</sub>, PM<sub>2.5</sub>, CO, SO<sub>2</sub>, and O<sub>3</sub> in 2014 have achieved the air quality objectives of Hong Kong, whereas NO<sub>2</sub> was significantly higher than the related objective. One reason for the high concentration of NO<sub>2</sub> is that the control measures such as retrofitting Euro II and III franchised buses with SCR systems in reducing NO<sub>2</sub> level was in progress, and there were still many Euro II and III franchised buses without SCR systems. Another reason is there were other types of vehicles producing NO<sub>2</sub>, but no control measures were implemented. It is implied that, apart from current control measures, more effective measures in tackling NO<sub>2</sub> emission are still needed.

**Table 1** Air quality objectives of Hong Kong (HKEPD, 2015c).

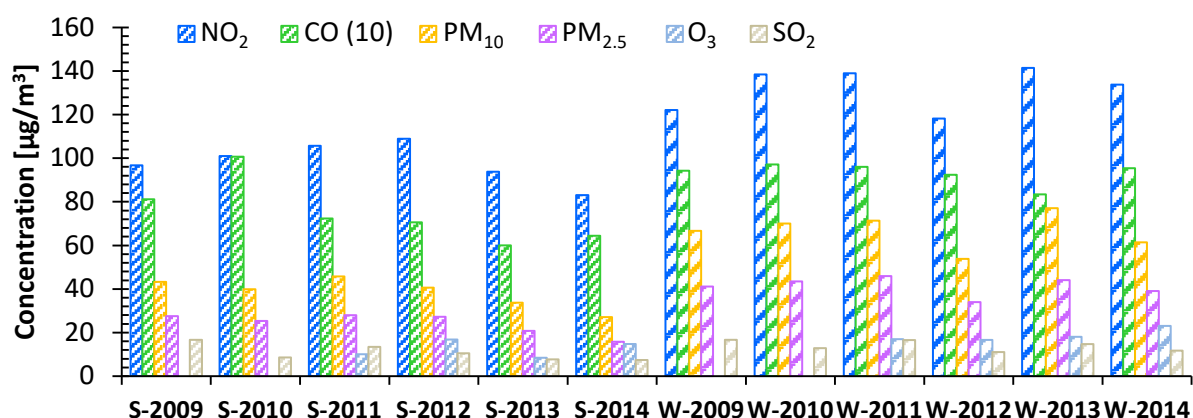
Pollutants	Time-averaged concentration [µg/m³]				
	10 minutes	1 hour	8 hours	24 hours	Annual

NO <sub>2</sub>	-	200	-	-	40
PM <sub>10</sub>	-	-	-	100	50
PM <sub>2.5</sub>	-	-	-	75	35
CO	-	30,000	10,000	-	-
SO <sub>2</sub>	500	-	-	125	-
O <sub>3</sub>	-	-	160	-	-

Seasonally averaged results in summer and winter are presented in Figures 5 and 6. As expected, the concentrations of pollutants were mostly higher in winter than in summer. Taking Central in 2014 as an example, the seasonally averaged concentration of NO<sub>2</sub>, CO, PM<sub>10</sub>, PM<sub>2.5</sub>, O<sub>3</sub> and SO<sub>2</sub> in winter was higher than that in summer by 61%, 48%, 127%, 149%, 57% and 59%, respectively. Similar seasonal variation of pollutant concentration in other cities was also reported, such as in Stockholm, Sweden (Aalto et al., 2005), Germany, Spain, Helsinki, Finland (Hussein et al., 2004), Rome, Barcelona, Italy and India (Saksena and Uma, 2008). The detailed analyses of the reasons for the occurrence of this seasonal pattern in pollutant concentration are provided in Section 4.2.3.



**Figure 5** Seasonally averaged concentrations of roadside pollutants in Mong Kok in winter and summer from 2009 to 2014; S represents summer and W winter.



**Figure 6** Seasonally averaged concentrations of roadside pollutants in Central in winter and summer from 2009 to 2014; S represents summer and W winter.

### 3. On-site measurements: methodology

This section describes in detail the measurement method including the sampling locations, data collection and instrumentation.

Considering geographical location and traffic condition (namely, types of vehicles and traffic intensity), five roads in Hong Kong were selected to conduct on-site measurements of concentration of pollutants typically associated with traffic at pedestrian level along roadsides. The five roads are Nathan Road in Mong Kok, Hong Chong Road in Hung Hom, Des Voeux Road C in Central, Kwun Tong Road in Kwun Tong and Yue Man Square in Kwun Tong (see Table 2 and Figure 7). In order to improve roadside air quality, the Hong Kong government set up low-emission zones in Mong Kok and Central in 2011 and encouraged franchised bus companies to deploy low-emission buses to ply those routes passing the low-emission zones (HKLC, 2015). Among the five roads, Nathan Road and Des Voeux Road C were located in low-emission zones, while other three roads were outside low-emission zones and thus called normal traffic road in this study.

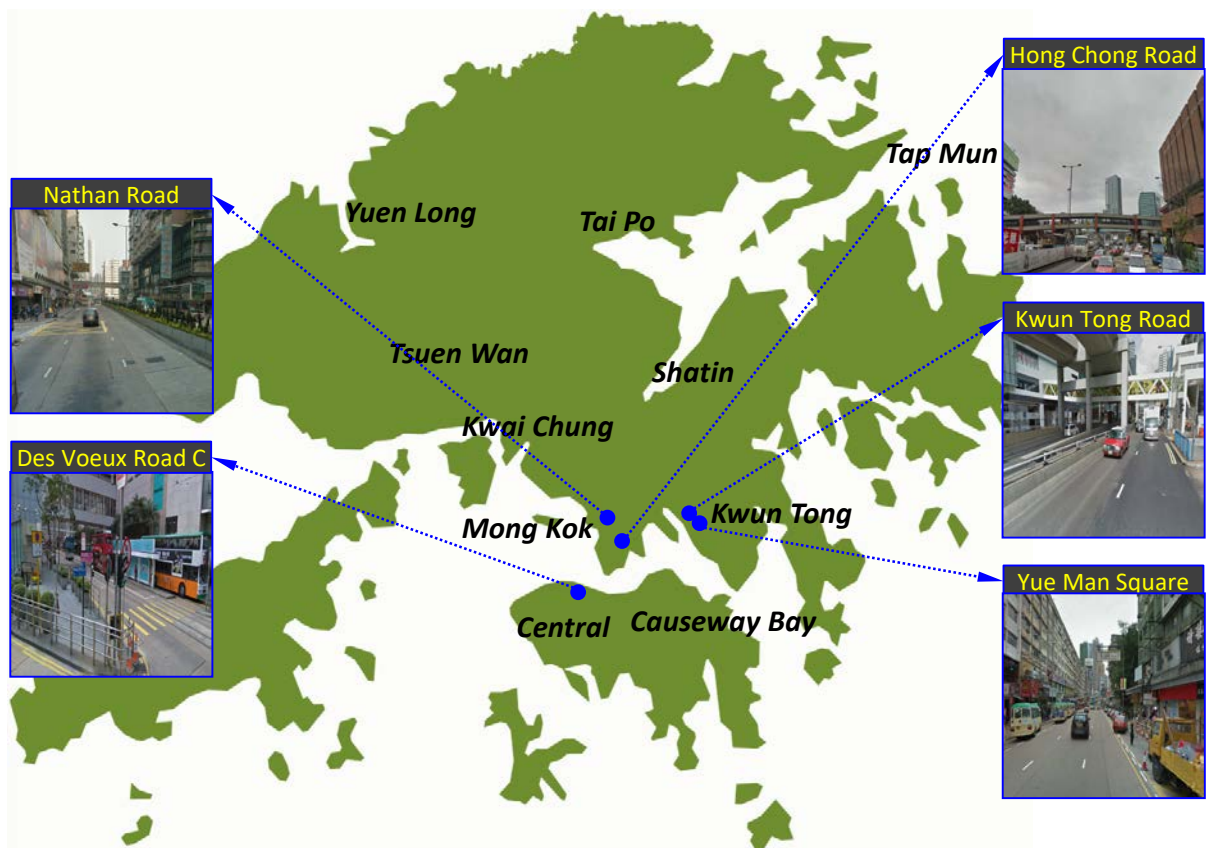
**Table 2** Details of the five roads where on-site measurements were conducted; building height indicates the average height of buildings on both sides of a road; aspect ratio (the ratio of building height to road width, Oke, 1987), which is an important parameter characterizing a street configuration.

Location	Road width	Yearly averaged daily traffic (HKTD, 2014)	Building density	Building height	Aspect ratio
Nathan Road in Mong Kok (Low-emission zone)	30 m	38,220	High	80 m	2.7
Hong Chong Road in Hung Hom (Normal traffic road)	60 m	114,400	Low	40 m	0.67
Des Voeux Road C in Central (Low-emission zone)	30 m	16,140	High	80 m	2.7
Kwun Tong Road in Kwun Tong (Normal traffic road)	50 m	22,450	Moderate	40 m	0.8
Yue Man Square in Kwun Tong (Normal traffic road)	25 m	2,450	Moderate	34 m	1.4

On-site measurements were conducted in an 8-month period from November 2012 to June 2013, which covers both winter and summer. The time period for measurements was divided into different time slots including morning, afternoon and evening to investigate the emission characteristics. It is expected that heavy traffic occurs always in the early morning during 7:00 a.m. – 9:00 a.m. and in the evening during 5:00 p.m. – 7:00 p.m. The results obtained during these rush hours were particularly analyzed. The traffic volume and composition during measurements were estimated by conducting manual counts. In addition, the environmental parameters including air temperature and relative humidity, wind speed and wind direction were recorded along with the measurements of pollutants. Weather condition, such as sunny, rainy or cloudy day, during measurements was also recorded for analyzing its possible influence on pollutant level. The sampling interval of all measurements was 1 minute. Note that all measured results were processed in 1 hour non-overlapping data sets for analysis.



Eventually, a large number of 1-hour data sets during the 8-month measurement period were obtained. It must be pointed out that this data processing and analyzing method was motivated by the fact that most people, such as passengers and pedestrians, normally do not stay for a period being longer than 1 hour along roadsides with heavy traffic nearby. Therefore, the 1-hour results are important to indicate the short-term exposure risk of these people.



**Figure 7** Locations and views of the five roads where roadside measurements were conducted.



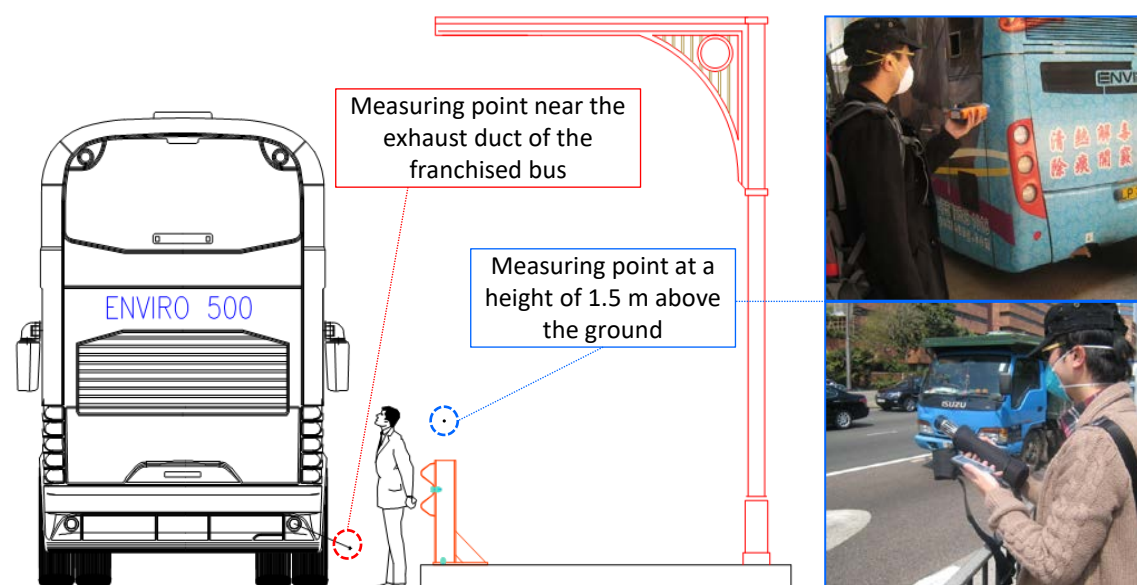
**Figure 8** Symbol indicating franchised bus with SCR devices.

Two types of measurement were conducted to investigate the leakage risk of ammonia from buses



with SCR devices (see Figure 8). First, five different routes of franchised bus with SCR devices were identified and measurements were conducted at the back of the franchised buses or their exhaust ducts near the waiting area of a bus station (see Figure 9). According to HKBRIC (2015), all the Euro IV or above franchised buses were installed with SCR devices, and some of their common routes were 1A, 112, 6C, 58X and 905. The Hung Hom Bus Terminal was one of bus stations where measurements of ammonia level were conducted. For each route of franchised bus, measurements were conducted for five times to improve the accuracy and reliability. Second, the measurements of ammonia level were conducted at pedestrian level along roadsides, specifically a height of 1.5 m above the ground (see Figure 9), to examine the exposure risk of passengers and pedestrians who were standing or walking along roadsides. The measurements were conducted at all the five roads (see Table 1). Considering that more franchised buses with SCR devices were encouraged to provide service in low-emission zones, it was interesting to compare ammonia levels at low-emission roads with those at normal roads.

Similar to the second type of measurement for ammonia, measurements for other pollutants including PM<sub>10</sub>, PM<sub>2.5</sub>, NO, NO<sub>2</sub>, SO<sub>2</sub>, CO and O<sub>3</sub> were conducted at pedestrian level along roadsides of the five roads (see Figure 9) to examine the roadside air quality and the exposure risk of passengers and pedestrians. The measured parameters, equipment, and their uncertainties and ranges are summarized in Table 3.



**Figure 9** Measuring points near the exhaust duct of a franchised bus and at pedestrian level along roadsides.

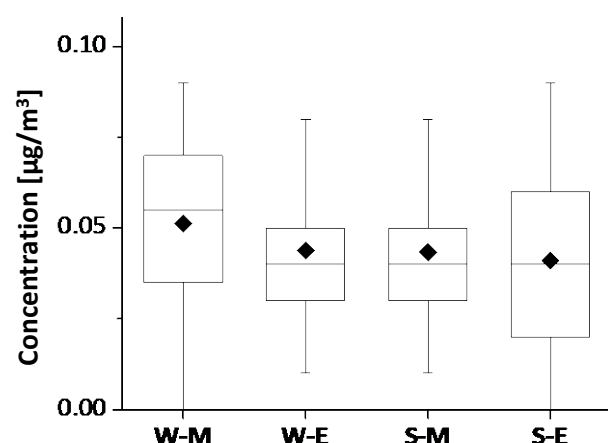
**Table 3** Summary of the parameters measured and the equipment used.

Parameters	Equipment	Uncertainty and range
Ammonia	Tetra Personal Multigas Monitor (Crowcon Detection Instruments Ltd., UK)	±5% of reading in a range of 0 to 100 ppm
PM <sub>2.5</sub> and PM <sub>10</sub>	TSI DustTrak™ 8520 (TSI Inc., USA)	±1% of reading in a range of 0.001 to 100 mg/m <sup>3</sup>

NO <sub>2</sub> , NO, SO <sub>2</sub> , CO and O <sub>3</sub>	GrayWolf DirectSense™ PPC Monitoring Kits (GrayWolf Sensing Solutions, LLC, USA)	A resolution of 0.1 ppm, 1 ppm, 0.2 ppm, 1 ppm and 0.02 ppm in a range of 0 to 20 ppm, 0 to 200 ppm, 0 to 20 ppm, 0 to 500 ppm and 0 to 1 ppm respectively for NO <sub>2</sub> , NO, SO <sub>2</sub> , CO and O <sub>3</sub>
Wind speed	Dantec 54N50 Low Velocity Flow Analyzer (Dantec Elektronik, Denmark)	±5% of reading in a range of 0 to 5m/s
Temperature and relative humidity	HT-3003 Humidity/Temperature Meter (Duncan Instruments Canada, Ltd., Canada)	A resolution of 0.1 °C and 0.1% in a range of 0 to 60 °C and 10 to 95% respectively for temperature and relative humidity

#### 4. On-site measurements: results and discussion

This section first presents and analyzes the results of ammonia measurements. Measured results of other pollutants are then presented and analyzed.



**Figure 10** Ammonia concentrations measured at Hung Hom bus terminal at different time periods; W-M represents wintertime morning, W-A wintertime evening, S-M summertime morning and S-A summertime evening; the box edges represent the 25<sup>th</sup> and 75<sup>th</sup> percentiles, the whiskers for the 1<sup>th</sup> and 99<sup>th</sup> percentiles, the lines in the boxes for median values, and the symbols (♦) for mean values.

#### 4.1 Ammonia

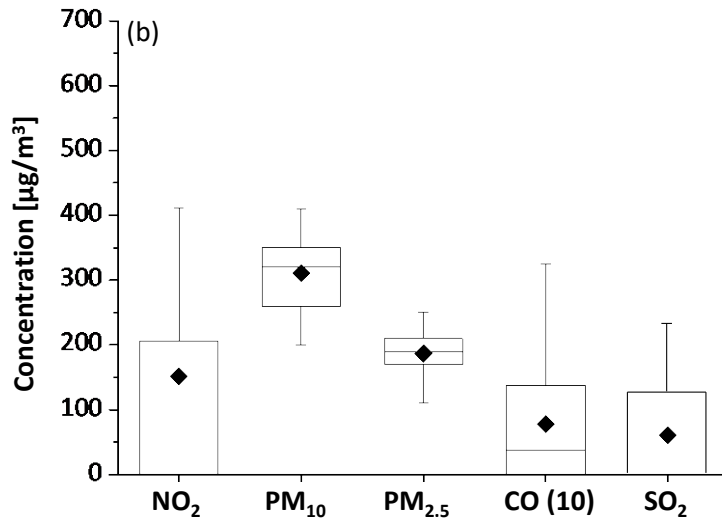
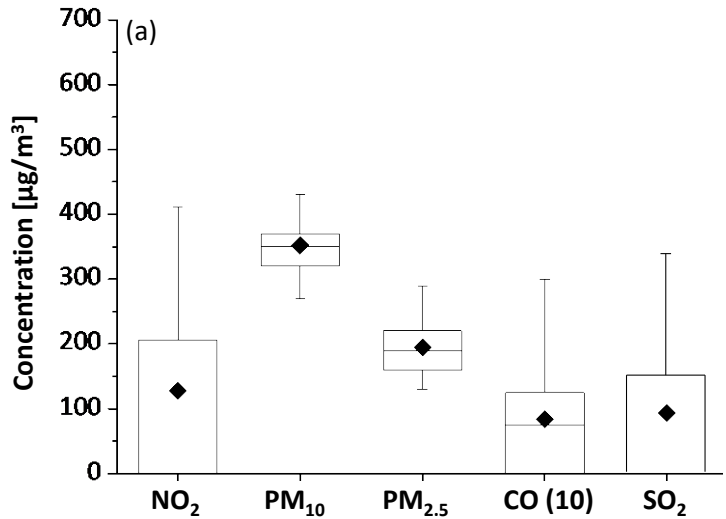
As described in Section 3, ammonia concentration was measured at bus stations and at roadside of the five roads. Figure 10 presents the ammonia concentrations measured at the Hung Hom bus terminal during both morning and evening rush hours. It can be seen that the ammonia levels were very low, all of which were less than 0.1 ppm. Note that a franchised bus with SCR devices passed through the bus terminal twice per hour. However, the ammonia levels did not increase perceptibly when a franchised bus with SCR devices was moving through the bus terminal. The ammonia levels at other bus stations and at the five roads were very close to these values obtained at the Hung Hom bus terminal. As a comparison, the ammonia level in a university gentlemen toilet was measured, which was in a range of 0.02 to 0.17 ppm. In general, such levels of ammonia are far less than the permissible exposure limit, namely 25 ppm (NIOSH, 1992). As ammonia leakage normally occurs due to mechanical problem, such low concentrations obtained from these measurements may indicate that

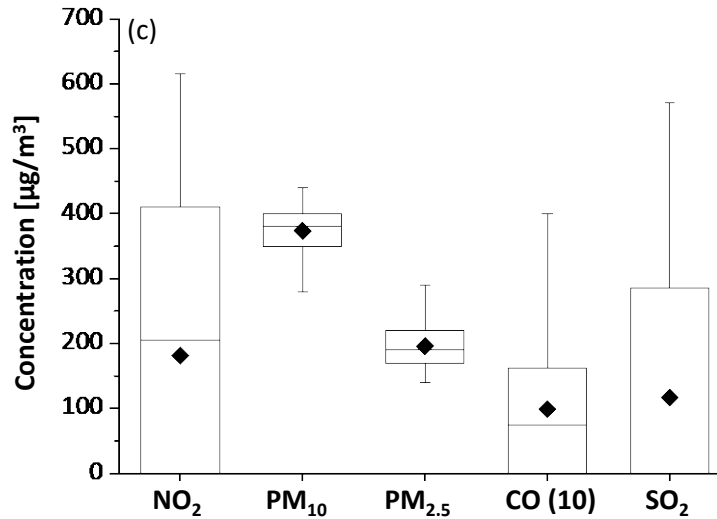
mechanical problems of SCR devices occur seldom in the franchised buses.

## 4.2 Other pollutants

### 4.2.1 General observations

As aforementioned in Section 3, a large number of 1-hour data sets were obtained, which were further classified into different time slots. Taking Kwun Tong Road in Kwun Tong as an example, Figure 11 presents box plots of pedestrian-level pollutant concentration during three time slots on a wintertime sunny day, where NO and O<sub>3</sub> are not presented. Zero level of NO was detected throughout the measurements, as NO can be easily transformed to NO<sub>2</sub>. O<sub>3</sub> was detected only in part of measurements. Even through it was detected; its levels were far less than the related air quality objective of Hong Kong. Concentrations of pollutants obtained at other roads showed a similar varying pattern among the three time slots. As shown in Figure 11, concentration of NO<sub>2</sub>, CO and SO<sub>2</sub> fluctuated highly over time, while PM<sub>10</sub> and PM<sub>2.5</sub> remained relatively stable concentrations. During the three time slots, the average concentration of most pollutants reached the highest value during evening rush hours, followed by morning rush hours and finally the noon period. In addition, it was observed that concentration of pollutants normally increased when franchised buses and trucks were passing through.





**Figure 11** Pedestrian-level concentrations of pollutants at Kwun Tong Road in Kwun Tong during different time slots on a specific sunny day in winter: (a) 8:30 a.m. – 9:30 a.m., (b) 11:30 a.m. – 12:30 p.m. and (c) 17:30 p.m. – 18:30 p.m.; the box edges represent the 25<sup>th</sup> and 75<sup>th</sup> percentiles, the whiskers for the 1<sup>th</sup> and 99<sup>th</sup> percentiles, the lines in the boxes for median values, and the symbols (♦) for mean values.

In general, pollutant concentrations obtained from the present measurements were mostly different from those obtained from HKEPD (see Section 2). This should be attributed mainly to two reasons. First, the vertical height of the two measurements is different. According to HKEPD (2015e), the measurement heights at roadside monitoring stations in Central and Mong Kok were 4.5 m and 3 m, respectively. However, the present measurements were conducted at pedestrian level, specifically at a height of 1.5 m (see Figure 9). Second, the data processing method is different. The present on-site measurements provide 1-hour averaged concentrations, whereas yearly or seasonally averaged concentrations obtained from HKEPD are presented in Section 2.

#### 4.2.2 Concentrations during evening rush hours

Cross comparison of 1-hour averaged concentrations at the five roads was made, which was based on a group of selected data recorded between 17:30 p.m. and 18:30 p.m. during evening rush hours under a similar weather condition. The results are presented in Table 4, which show that the concentrations of pollutants were mostly the highest at Hong Chong Road in Hung Hom, followed by Nathan Road in Mong Kok, Kwun Tong Road in Kwun Tong, Des Voeux Road C in Central, and finally Yue Man Square in Kwun Tong. The sequence in pollutant concentration is in consistence with that in traffic intensity (see Table 2), indicating the close relationship between roadside pollutant concentration and traffic intensity.

**Table 4** Measured average concentrations of pollutants at pedestrian level between 17:30 p.m. and 18:30 p.m. during evening rush hours; numbers in brackets represent standard deviations of concentrations obtained from different days.

Location	NO <sub>2</sub> (µg/m <sup>3</sup> )	PM <sub>10</sub> (µg/m <sup>3</sup> )	PM <sub>2.5</sub> (µg/m <sup>3</sup> )	CO (µg/m <sup>3</sup> )	SO <sub>2</sub> (µg/m <sup>3</sup> )
Hong Chong Road in Hung Hom	216.3 (36.5)	408.9 (34.2)	207.3 (9.2)	1100.9 (158.8)	123.0 (24.3)

Nathan Road in Mong Kok	143.4 (25.1)	360.4 (38.0)	194.0 (27.5)	1011.1 (91.8)	93.7 (25.7)
Kwun Tong Road in Kwun Tong	158.2 (24.6)	327.0 (37.2)	182.6 (21.3)	1017.2 (151.0)	88.1 (30.8)
Des Voeux Road C in Central	142.7 (18.2)	335.0 (33.8)	179.4 (18.1)	870.9 (77.2)	86.2 (45.4)
Yue Man Square in Kwun Tong	55.5 (7.1)	115.4 (13.2)	48.4 (13.8)	606.6 (58.0)	25.8 (3.3)

Two main factors make the roadside pollutant concentration at Hong Chong Road in Hung Hom the highest among the five locations. The first factor is likely the highest traffic intensity (Kaur et al., 2007; Westerdahl et al., 2005; Tsai and Chen, 2004; Rakowska et al., 2014), as the roadside pollutants were produced by vehicles. The second is that there is a row of toll stations on the road for vehicles needing to cross the harbor tunnel, which slows down the vehicles' moving speed and causes traffic congestion (a common situation) on this road. To alleviate the traffic congestion near the Hung Hom Cross Harbor Tunnel, it is suggested to increase the vehicular toll for the Hung Hom Cross Harbor Tunnel and decrease that for other two cross harbor tunnels, namely the Eastern Cross Harbor Tunnel and the Western Cross Harbor Tunnel. At the Hong Chong Road, a previous measurement conducted by Lee et al. (2006) reports that the seasonally averaged PM<sub>2.5</sub> concentrations were around 54.1 µg/m<sup>3</sup> and 51.5 µg/m<sup>3</sup> in winter and spring, respectively, which are nearly one quarter of those measured during rush hours in the present study. The first reason for this discrepancy is that the traffic intensity and thus the emission rate was the highest during rush hours of a day (Chan et al., 2003; Cheng et al., 2015; Wang et al., 2002). Second, the present measurements were conducted near the road (see Figure 9), whereas their measurements at 1-2 meters away from the road.

Although Mong Kok and Central were set as the low-emission zones (HKLC, 2015), the measurements show that air pollutant levels at Nathan Road and Des Voeux Road C were still very high. This may imply that the traffic intensity was still the dominant factor determining the roadside concentrations of pollutants, while the existing policy for low-emission zones needs to be enhanced.

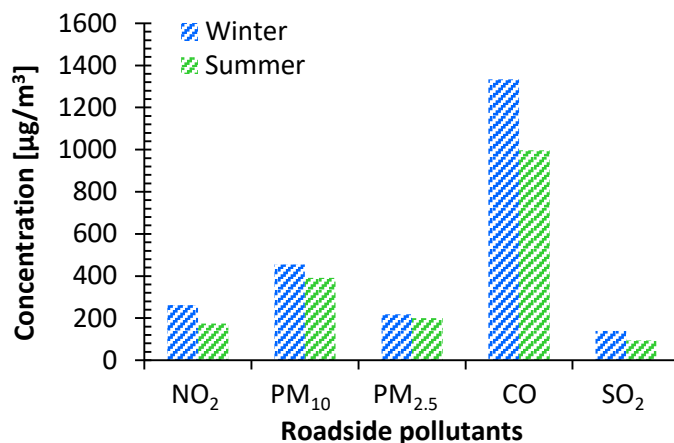
The pollutant level was much higher in Kwun Tong Road than in Yue Man Square. According to Table 2, the daily number of vehicles in Yue Man Square was only about 11% of that in Kwun Tong Road. It was observed that, for most of time, only mini buses and taxis serviced on Yue Man Square, whereas franchised buses and heavy duty vehicles seldom travelled on this road. In contrast, there were always a large number of vehicles travelling around the Kwun Tong Road. This again suggests that the roadside air quality is closely associated with the number of vehicle.

The width of a road normally determines the traffic intensity on the road, while the height of buildings on both sides of a road strongly influences the local microclimate above the road, including wind speed, air temperature and relative humidity. Therefore, street configuration characterized by the road width and building height should have a significant relationship with roadside concentrations of traffic related pollutants (Ai and Mak, 2015; Hunter et al., 1992; Liu et al., 2005). Among the five roads investigated in the present study, except for Hong Chong Road in Hung Hom, the other four roads were flanked by tall buildings. The term 'street canyon' is normally used to describe a situation where the street is flanked by buildings on both sides creating a canyon-like environment (Oke, 1987). When aspect ratio (see Table 2) of a street canyon is larger than 0.65–0.7, the atmospheric flow skims over the building tops. In this circumstance, penetration of wind into the street canyon is difficult and

highly dependent on the wind speed above the buildings (Nakamura and Oke, 1988; Longley et al., 2004; Eliasson et al., 2006). Such kinds of street canyons are generally characterized by low wind speed and high pollutant concentration (Liu et al., 2005; Kim and Baik, 2004; Qin and Kot, 1993; Vignati et al., 1996). As shown in Table 2, the aspect ratio of these roads was larger than 0.65-0.7, except that the Hong Chong Road in Hung Hom was just in this range. Cross examination of the effect of street configuration independently is almost impossible in the present study, as traffic intensities at the five roads were very different, which, however, is also a significant influencing factor.

#### 4.2.3 Seasonal variation

Figure 12 presents the average concentrations of pollutants at pedestrian level along roadsides at Hong Chong Road between 17:30 p.m. and 18:30 p.m. in winter and summer. For all five pollutants, the wintertime concentration was higher than the summertime concentration (see also Section 2), indicating that the seasonal pattern is an important influencing factor of local pollutant characteristics in urban environment. This seasonal pattern was also observed at other four roads. In general, the main reason for this pattern is the adverse meteorological conditions, including greater atmospheric stability, lower mixing layer height and lower temperature, in winter compared to in summer (Cheng et al., 2012). In addition, there are some specific reasons.



**Figure 12** Average concentrations of pollutants at pedestrian level along roadsides of Hong Chong Road in Hung Hom between 17:30 p.m. and 18:30 p.m. in winter and summer.

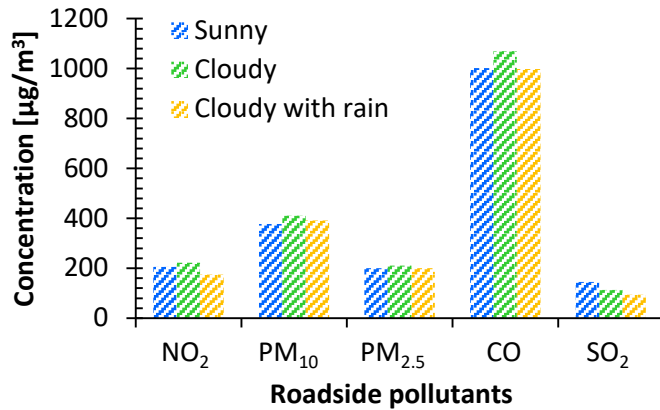
First, Hong Kong is affected by the Asian monsoon, where the prevailing wind direction in the two seasons is different (HKO, 2015a). In summer, the southwesterly marine wind is very helpful to accelerate the pollutants dilution. In contrast, the northeasterly wind in winter coming from interior Asia is accompanied by pollutants. Therefore, air quality in Hong Kong during winter is affected by both local and regional sources.

Second, temperature difference between surfaces as well as between air and surfaces within a street canyon is higher in summer than in winter (Andreou and Axarli, 2012). The temperature difference induced buoyancy effect can drive airflow circulations inside a street canyon, which would increase the possibilities of flow exchange between the street canyon interior and the above atmosphere and thus enhances the pollutants dilution (Ai and Mak, 2015).

Third, in Hong Kong, rainy day is more likely to occur in summer (HKO, 2015b). Rain can wash away a part of air pollutants and clean the air. Figure 13 presents the average concentrations of



pollutants at Hong Chong Road in Hung Hom between 17:30 p.m. and 18:30 p.m. under sunny, cloudy and cloudy with rain conditions, when other conditions were approximately the same. It can be observed that rain can help to decrease the pollutants concentration, although the decreasing effect is not significant.



**Figure 13** Average concentrations of pollutants at pedestrian level along roadsides of Hong Chong Road in Hung Hom between 17:30 p.m. and 18:30 p.m. under different weather conditions.

#### 4.2.4 Comparison with air quality standard

As the measured results were split in 1-hour data, direct comparison with air quality objectives of Hong Kong (see Table 1) is only possible for pollutants NO<sub>2</sub> and CO, where their 1-hour safe limits are available. However, if the 1-hour averaged concentration of a specific pollutant during rush hours is less than the related 8-hour or 24-hour objectives, the concentration of this pollutant would certainly achieve the air quality objectives. Comparison of the pollutant concentrations in Table 4 with the air quality objectives in Table 1 indicates that, at all five roads, the pedestrian-level concentrations of pollutants NO<sub>2</sub>, CO and SO<sub>2</sub> met the air quality objectives, except for NO<sub>2</sub> at Hong Chong Road in Hung Hom. In addition, pedestrian-level concentrations of PM<sub>10</sub> and PM<sub>2.5</sub> at all roads, except for Yue Man Square in Kwun Tong, were much higher than the related 24-hour air objectives, which would exceed potentially the 1-hour objectives. The pedestrian-level air quality at Yue Man Square in Kwun Tong was the best among the five roads, which was most likely due to low traffic intensity (see Table 2).

Although the yearly averaged NO<sub>2</sub> concentration near road cannot meet the air quality objective (see Section 2), the 1-hour averaged value during rush hours achieved the objective for most roads. Considering that most people would not stay abidingly at a roadside for a period exceeding 1 hour, the roadside NO<sub>2</sub> concentration was generally safe for a normal passenger or pedestrian. For PM<sub>10</sub> and PM<sub>2.5</sub>, although the yearly averaged concentrations were closely equal to the annual objectives, the pedestrian-level measurements show that the 1-hour averaged concentrations during rush hours were very high, which would cause potentially short-term exposure risk for passengers and pedestrians. Overall, this study may suggest that both NO<sub>2</sub> and particulate matters should be paid special attention when formulating control measures of traffic emissions, as they could cause potentially long-term and short-term exposure risk for urban residents, respectively.

## 5. Discussion

This study first analyzed the six-year roadside air quality data to reveal the variation of air pollutant

concentration in the context of a series of control measures of traffic emissions being implemented by the Hong Kong government in these years. Short-term measurements were then performed to examine the short-term exposure of passengers and pedestrians. Overall, the decreasing trend of roadside concentration of major pollutants was revealed and specific suggestions on measures to further control roadside air pollution were made. However, it is important to discuss the limitations of this study and identify the areas for future studies.

This study was performed based on the assumption that the traffic emissions were the dominant pollutant sources of roadside air pollution in Hong Kong (see Introduction section). Although the traffic emissions are found and recognized as the main source of street-level air pollution by both the Hong Kong government (HKEPD, 2015b) and experts (e.g. Lee et al., 2006; Cheng et al., 2012, 2015), other pollutant sources, such as marine vessels, industry and power plants in both Hong Kong and the nearby Pearl River Delta region, could also influence the roadside air quality, which, however, are not analyzed in this study.

Air quality measurements alone are usually not sufficient to determine the contribution of traffic emissions to air pollution, while air quality measurements in combination with traffic inventory analyses should be very useful to indicate the association between traffic intensity and roadside air quality. However, this study (Section 2) shows that the yearly averaged traffic intensity and air quality data cannot reveal their association, as atmospheric flow and turbulence would migrate and homogenize the local pollutants for a yearly scale. It is believed that time series of air quality and traffic intensity data at a specific road during a sufficient period is important to reveal such an association, which, however, is not available in the present study.

In this study, all analyses regarding the association between traffic intensity and air quality were made between different roads, rather than at a specific road. Such a cross comparison between different roads should be acceptable, because of three reasons. First, traffic intensity was relatively stable at each road and was very different between different roads (see Figure 2 and Table 2). Second, same control measures of traffic emissions were implemented simultaneously at different roads. Third, the weather conditions at different roads during the same period can be considered as the same. However, such a comparison between different roads could be affected by the street configuration, such as the aspect ratio discussed in Section 4.2.2. Again, future studies should evaluate this association longitudinally using time series of air quality and traffic intensity data at a same road.

## **6. Summary and conclusions**

In order to investigate roadside air quality in Hong Kong, roadside concentrations of major pollutants typically associated with traffic, including PM<sub>10</sub>, PM<sub>2.5</sub>, NO<sub>2</sub>, SO<sub>2</sub>, O<sub>3</sub> and CO, obtained from roadside monitoring stations of HKEPD and from the present on-site measurements at pedestrian level along roadsides were analyzed.

With the efforts of the Hong Kong government, roadside concentrations of most pollutants typically associated with traffic decreased gradually over these years. Data from roadside monitoring stations shows that the concentrations of PM<sub>10</sub>, PM<sub>2.5</sub>, SO<sub>2</sub>, O<sub>3</sub> and CO in 2014 achieve the air quality objectives of Hong Kong, whereas the concentration of NO<sub>2</sub> still exceeds largely the annual objective, posing a long-term exposure risk to roadside workers. However, considering that most people do not stay along roadsides for a long time, the 1-hour averaged concentrations of pollutants are important to evaluate the short-term exposure risks of these people. The present measurements indicate that, at most roads, the concentration of NO<sub>2</sub> even during rush hours meets the 1-hour objective, whereas the

1 1-hour data for PM<sub>10</sub> and PM<sub>2.5</sub> exceeds potentially the safe limits, posting a short-term exposure risk  
2 to passengers and pedestrians. Overall, from the viewpoint of both long-term and short-term exposure  
3 risks, there is a need to further cut the traffic emissions of both NO<sub>2</sub> and particulate matters.

4 Based on the findings of the present study, the following suggestions are made to further decrease  
5 traffic induced air pollution in densely populated urban areas. First, considering the traffic intensity is  
6 likely the most essential factor influencing the pollutant concentrations, restricting the increasing rate  
7 of vehicles should be the primary measure to implement. Second, measures should be taken to  
8 decrease the occurrence of traffic congestion, which is equivalent to the effect of increased number of  
9 vehicles. Third, reduction of pollutant emissions for an individual vehicle may be achieved through (a)  
10 adopting cleaner fuels and (b) enhancing the infiltration and purification of its emission. For the latter,  
11 advanced infiltration and purification systems such as particulate infiltration system and SCR system  
12 should be developed. Fourth, wind in densely populated urban environment is increasingly stagnant.  
13 Reasonable urban development is important to enhance the penetration of wind into street canyons and  
14 then to accelerate pollutant dilution.

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