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Authors

Guo, H
Zou, SC
Tsai, WY
[et al.](#)

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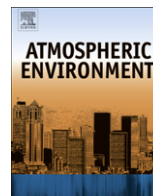
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Emission characteristics of nonmethane hydrocarbons from private cars and taxis at different driving speeds in Hong Kong

H. Guo^{a,*}, S.C. Zou^{a,b}, W.Y. Tsai^a, L.Y. Chan^a, D.R. Blake^c

^a Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong

^b School of Marine Sciences, Sun Yat-sen University, Guangzhou, China

^c Department of Chemistry, University of California at Irvine, CA, USA

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ABSTRACT

Vehicular emissions are the major sources of a number of air pollutants including nonmethane hydrocarbons (NMHCs) in urban area. The emission composition and emission factors of NMHCs from vehicles are currently lacking in Hong Kong. In this study, speciation and emission factors of NMHCs emitted from gasoline-fuelled private cars and liquefied petroleum gas (LPG)-fuelled taxis at different driving speeds were constructed using a chassis dynamometer. Large variations in the contributions of individual NMHC species to total emission were observed for different private cars at different driving speeds. The variations of individual NMHC emissions were relatively smaller for taxis due to their relatively homogeneous year of manufacture and mileages. Incomplete combustion products like ethane, ethene and propene were the major component of both types of vehicles, while unburned fuel component was also abundant in the exhausts of private cars and taxis (i.e. *i*-pentane and toluene for private car, and propane and butanes for taxi). Emission factors of major NMHCs emitted from private cars and taxis were estimated. High emission factors of ethane, *n*-butane, *i/n*-pentanes, methylpentanes, trimethylpentanes, ethene, propene, *i*-butene, benzene, toluene and xylenes were found for private cars, whereas propane and *i/n*-butanes had the highest values for taxis. By evaluating the effect of vehicular emissions on the ozone formation potential (OFP), it was found that the contributions of olefinic and aromatic hydrocarbons to OFP were higher than that from paraffinic hydrocarbons for private car, whereas the contributions of propane and *i/n*-butanes were the highest for taxis. The total OFP value was higher at lower speeds ($\leq 50 \text{ km h}^{-1}$) for private cars while a minimum value at driving speed of 100 km h^{-1} was found for taxis. At the steady driving speeds, the total contribution of NMHCs emitted from LPG-fuelled taxis to the OFP was much lower than that from gasoline-fuelled private cars. However, at idling state, the contribution of NMHCs from LPG-fuelled vehicles to OFP was comparable to that from gasoline-fuelled vehicles. The findings obtained in this study can be used to mitigate the air pollution caused by vehicles in highly dense urban areas.

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1. Introduction

Vehicular exhaust emissions are the major sources of a number of air pollutants including nonmethane hydrocarbons (NMHCs) in urban area (e.g. Mugica et al., 2001; HKEPD, 2005; Liu et al., 2008). Once released to the atmosphere, most NMHCs react rapidly with hydroxyl radicals and nitrogen oxides under the sunlight to form ozone, secondary volatile organic compounds (VOCs) such as peroxyacetylnitrate (PAN), and other oxidants (Carter, 1994). Thus, the abundance and speciation of VOCs emitted from vehicles significantly affect the atmospheric chemistry. Moreover, many VOCs

emitted from vehicular exhaust are toxic and some are well known carcinogens, such as benzene and formaldehyde (USEPA, 1998, 2002). In addition, the secondary VOCs, ozone and OH radical generated in the photochemical reaction are often more hazardous to human health and environmental quality (Burnett et al., 1994; Han and Naeher, 2006). Hence, understanding source profiles and emissions of VOCs from vehicles is critical to identify effective strategies for reducing VOC levels in the urban atmosphere.

The degree of VOC emissions from vehicles is closely related to vehicular driving modes. The driving modes usually compose idling, acceleration, cruising, and deceleration. As the VOC emission factors and rates from these different driving modes are different, the overall emission of a vehicle should be determined by deriving the total emission estimates under different circumstances. Many studies have been carried out on the correlations between vehicular driving

* Corresponding author. Tel.: +852 3400 3962; fax: +852 2334 6389.
E-mail address: ceguohai@polyu.edu.hk (H. Guo).

modes and the emissions of air pollutants i.e. carbon monoxide (CO), nitrogen oxides (NO_x), particulates and total hydrocarbons (THC) (e.g. Tsai et al., 2003; Kado et al., 2005; Morawska et al., 2005; Chan et al., 2007; Kim Oanh et al., 2008; Livingston et al., 2009; Chang et al., 2009). For instance, Ntziachristos and Samaras (2000) found that CO and THC emissions from catalyst passenger cars in European countries consistently decreased with the increase of speed at low speeds, and then increased again at higher speeds, with the minimum emissions at 80 km h⁻¹. Ericsson (2001) performed on-road emission testing and concluded that fuel consumption and emissions of THC and NO_x can be minimized at driving speed between 50 km h⁻¹ and 70 km h⁻¹. Chan et al. (2004, 2007) used on-road remote sensing technique and chassis dynamometer to measure emissions from petrol, diesel and liquefied petroleum gas (LPG) vehicles in Hong Kong. Strong correlations between the average emission factors and vehicle speeds were found. Emission factors of CO, THC and NO_x decreased rapidly with instantaneous vehicle speed up to 40 km h⁻¹–55 km h⁻¹, and then increased slightly. Another study by Chan and Ning (2005) showed that the emission factor of CO and THC from diesel vehicles in Hong Kong decreased rapidly with instantaneous vehicle speed up to 60 km h⁻¹, the emission factors kept decreasing slightly beyond 60 km h⁻¹. These previous studies mainly focused on the total HC emission, though the speciation of NMHC emissions from vehicle exhaust may be more important to human health and air quality, and more useful for NMHC emission estimates from vehicles.

Few studies were conducted on the speciation of NMHCs from vehicle exhaust (e.g. Bailey et al., 1990; Tsai et al., 2003; Kado et al., 2005; Kim Oanh et al., 2008). Bailey et al. (1990) analyzed 16 NMHCs in the emissions from vehicles fuelled by leaded gasoline in UK, and noted a variation in the proportion of components over the speed range. Tsai et al. (2003) investigated the emissions of NMHCs from motorcycles engine exhaust on a dynamometer in Taiwan. Forty-eight NMHC species were measured and the concentration distribution at different driving modes was similar. Kim Oanh et al. (2008) studied vehicle emission factors of two VOCs i.e. toluene and xylenes in a busy street of Bangkok and found that their emission factors at daytime did not vary much but were substantially reduced at nighttime. Six VOC species including 1,3-butadiene, benzene, toluene, ethylbenzene, xylenes and styrene emitted from vehicles were monitored in California (Kado et al., 2005). The study showed that compressed natural gas (CNG)-fuelled vehicle had the highest emissions of 1,3-butadiene and benzene.

There are a number of methods currently used to determine the emissions from motor vehicles. Each method would introduce certain uncertainty in emission factors. The most common methods for determination of vehicle emission factors are chassis dynamometer (e.g. Durbin et al., 2002; Jayaratne et al., 2009), on-road measurements with on-board emission measurement system (e.g. Morawska et al., 2005; Zavala et al., 2009), and cross-road (remote sensing) measurements (e.g. Schifter et al., 2003; Chan et al., 2007). The chassis dynamometer testing system directly measures pollutant emissions from vehicles placed on a dynamometer and the on-road measurement system uses on-board equipments to monitor vehicular emissions, whereas the cross-road remote sensing measurements provide indirect estimation through measurements of pollutant concentrations in the close vicinity to a road link.

As vehicle emissions are generally affected by many factors such as fuel type, emission standards, emission control technology, fleet size, average speed, model year, deterioration rates, driving cycles and ambient meteorological conditions, and a large amount of data are required in order to establish a vehicle emission inventory, it is difficult to develop an accurate vehicle emission inventory for a large city like Hong Kong. The chassis dynamometer testing used

in this study is a traditional and most commonly used method, which requires a well-equipped laboratory and is based on simulated driving cycles. This method is essentially designed to establish uniform emission standards for regulatory purposes and for testing of new technologies. It does not necessarily reflect the real on-road driving conditions and the level of maintenance of the actual fleet (Palmgren et al., 1999; Kim Oanh et al., 2008). It is also expensive and time consuming with low vehicle through output. As such, it is not surprising that the vehicle emissions have large variations and are dependent on individual vehicles. In this study, due to high cost on NMHC emission test from vehicles, the vehicles investigated may not be a statistically based sub-sample of the current Hong Kong fleet. However, the emission factors obtained in this study can be cross-checked by using more than one method and/or compared with previous studies to gain more confidence in the results. They can also be used as a reference data to estimate gasoline- and LPG-fuelled vehicle emissions in different driving modes and to illustrate the relationship between driving speed and vehicle emission.

The aim of this study is therefore to investigate the exhaust emissions of NMHCs from different fuel types of on-road representative vehicles including gasoline- and LPG-fuelled vehicles for urban driving conditions ranging from idling to 100 km h⁻¹ using the chassis dynamometer. The emission profiles at different driving speeds of the tested vehicles are compared and the emission factors of major NMHC species from gasoline-fuelled and LPG-fuelled vehicles are estimated. The effect of vehicle emissions on ozone formation potential is discussed.

2. Methodology

2.1. Vehicle selection

In this study, six gasoline-fuelled private cars and four LPG-fuelled taxis were examined. The 10 vehicles were recruited from several sources including private owners, taxi companies and the university campus. These cars were selected as far as possible to cover the most common fleet of light vehicles in Hong Kong in terms of age and mileage. The specifications of the typically selected on-road vehicles are listed in Table 1. As the LPG taxis were initially introduced into Hong Kong in 2000, the vehicles tested had a relatively small variation on the age and all taxis in Hong Kong were made by the same manufacturer. The ages of taxis measured were 1–3 years when this study was conducted.

2.2. Chassis dynamometer testing system

Different fuel types of the selected on-road vehicles were tested for idling state and different steady-state driving conditions ranging from 25 to 100 km h⁻¹ (USEPA, 2003), using a chassis dynamometer testing system (ESP Precision Dynamometer Model PD-250),

Table 1
Specifications of the tested on-road vehicles.

	Fuel	Year of manufacture	Engine cylinder capacity (cc)	Mileage (km)
Private car 1	Gasoline	1992	2960	112,650
Private car 2	Gasoline	1994	2199	63,367
Private car 3	Gasoline	2003	2354	13,233
Private car 4	Gasoline	2002	2362	23,191
Private car 5	Gasoline	1999	1498	86,375
Private car 6	Gasoline	1997	2199	120,299
Taxi 1	LPG	2003	1998	342,866
Taxi 2	LPG	2004	1998	157,480
Taxi 3	LPG	2002	1998	543,378
Taxi 4	LPG	2002	1998	352,986

following the standard test procedures established in European Emission Regulation 70/220/EEC and its amendments (EU, 1970). The dynamometer was located in a certified independent testing laboratory approved by the Vehicle Certification Agency (VCA) of the United Kingdom and the Hong Kong Environmental Protection Department for testing gas emissions of motor vehicles and motorcycles. To ensure the reliability and repeatability of the measured data, each dynamometer test was first allowed to run at the required constant driving speed for several minutes until the steady-state values had been achieved. Five steady-state speeds i.e. idling, 25, 50, 70 and 100 km h⁻¹ were chosen for sample collection. These speeds cover most driving profiles in Hong Kong. The idling state in front of traffic lights is represented by “0 km h⁻¹” samples and cruising mode on urban busy roads is represented by “25 km h⁻¹” samples, while smooth driving on most urban roads in Hong Kong is represented by “50 km h⁻¹”, and driving on highway are represented by “70 km h⁻¹” and “100 km h⁻¹” samples. Since the focus was on the steady driving modes, the acceleration and deceleration modes were not tested in this study. It should be noted that the transient cycles, characterized by abrupt acceleration and deceleration, are important driving processes and usually induce the highest emissions of VOCs. As the VOC mixing ratios were very high and the variations of the measurements were large for acceleration and deceleration modes, we failed to complete the tests on the transient operation. Therefore, the emission factors obtained in this study do not include the entire driving patterns in Hong Kong, which could lead to underestimation of VOC emissions from motor vehicles. The transient cycles shall be supplemented in future study.

2.3. Gas sampling and analysis

The exhaust gaseous emissions (i.e. CO, CO₂, NO_x, HC and O₂) from the tested vehicles were measured using an automated instrument (AutoLogic, WI, USA), while the VOC samples were collected directly from the tailpipe of vehicles by using evacuated 2-L stainless steel canisters. Details of the characteristics of the canisters, their cleaning and pre-conditioning procedures are described in Colman et al. (2001). During sampling the canister valve was slightly opened, allowing about 1 min for the collection of “integrated” samples. After sampling, the filled canisters were shipped to the laboratory of the University of California at Irvine for chemical analysis within two weeks of being collected.

All canisters were analyzed for methane and NMHCs including 22 saturated hydrocarbons, 15 unsaturated hydrocarbons and 14 aromatic hydrocarbons. The analytical system used to analyze NMHCs involved the cryogenic pre-concentration of highly-concentrated 2–5 cm³ of air sample in a stainless steel tube filled with glass beads (1/8” diameter) and immersed in liquid nitrogen (–196 °C). A mass flow controller with a maximum allowed flow of 500 mL min⁻¹ controlled the trapping process. The trace gases were revolatilized using a hot water bath and then reproducibly split into five streams directed to different column-detector combinations.

Three different detectors, including quadrupole mass spectrometry detectors (MSD; for unambiguous compound identification and selected ion monitoring), flame ionization detector (FID; sensitive to hydrocarbons), and electron capture detectors (ECD; sensitive to halogenated hydrocarbon), were employed. The first column-detector combination (abbreviated as “DB5ms/MSD”) was a DB-5ms column (J&W; 60 m × 0.25 mm i.d. × 0.5 μm film thickness) output to the HP 5973 MSD. The second combination (“DB1/FID”) was a DB-1 column (J&W; 60 m × 0.32 mm i.d. × 1 μm film thickness) output to the FID. The third combination (“PLOT-DB1/FID”) was a PLOT column (J&W GS-Alumina; 30 m × 0.53 mm i.d. × 1.5 μm film thickness) connected in series to a DB-1 column (J&W; 5 m × 0.53 mm i.d. × 1.5 μm film thickness) and output to the FID. The fourth

combination (“Restek1701/ECD”) was a RESTEK 1701 column (60 m × 0.25 mm i.d. × 0.50 μm film thickness) which was output to the ECD. The fifth combination (“DB5-Restek1701/ECD”) was a DB-5 (J&W; 30 m × 0.25 mm i.d. × 1 μm film thickness) column connected in series to a RESTEK 1701 column (5 m × 0.25 mm i.d. × 0.5 μm film thickness) and output to the ECD. The DB5ms/MS, DB1/FID, PLOT-DB1/FID, Restek1701/ECD, and DB5-Restek1701/ECD combinations received 10.1, 15.1, 60.8, 7.2 and 6.8% of the sample flow, respectively. Additional analytical details are given by Simpson et al. (2000) and Colman et al. (2001).

2.4. Quality assurance and quality control

Before sampling, all canisters were cleaned at least five times by repeatedly filling and evacuating humidified pure nitrogen gas. The cleaned canisters were checked to ensure that all the target compounds were not found or were under the method detection limit. In addition, duplicate samples were regularly collected to check the precision and reliability of the sampling and analytical methods.

The quantification of target VOCs was accomplished using multi-point external calibration curves. The calibration curves were updated every day and were prepared using 1000 ppbv standard calibration gases (TO-14 gases, Spectra Gases Inc.) at five different diluted concentrations plus humidified zero air (0–40 ppbv). The standard gases were analyzed in the same way as the vehicle emission samples.

The measurement precision, accuracy and detection limits of NMHCs varied compound by compound and were periodically quantified for each species during the sampling period. Detailed procedures are described in Simpson et al. (2000) and Colman et al. (2001). Briefly, the detection limit was 100 pptv for most NMHCs in the vehicle exhaust. The accuracy of the measurements was 5% for NMHCs, whereas the measurement precision was 0.5–5%.

2.5. Data analysis

The emission factors of various pollutants are usually obtained by measuring the exhaust concentrations, the volume of the exhaust, and the total running mileage in one test cycle. In this study, the concentrations of air pollutants emitted from vehicle exhaust were measured using the methods described in Section 2.3. Since the actual exhaust volumes in various driving modes were not directly measured, we used the mean rotating speed of the engine, volume of the cylinder, and the running time in that driving mode to derive the emission factors. The emission factors of air pollutants were calculated using the equations developed by Tsai et al. (2003):

$$V = rtV_{\text{motor}} \times 10^{-6}F \quad (1)$$

$$m = CV_N \times 10^{-3} \quad (2)$$

$$EF = m/L \quad (3)$$

where V is the exhaust gas volume of a specific driving mode (m³), r is the rotating speed of the engine (rpm), t is the total time in that driving mode (minute), V_{motor} is the total volume of the engine cylinders (cc), and F is the correction factor of the engine type, which is unity for a 2-stroke engine and is 0.5 for a 4-stroke engine. The parameter m is the exhaust amount of the pollutant (mg) in a specific driving mode, C the concentration of the pollutant (mg m⁻³), V_N the normalized value of V by temperature and pressure correction (m³), L is the running mileage during the test procedure (km). Although it cannot present the actual exhaust

volume, it could be used as reference data to estimate VOC emissions of private cars in different driving modes.

2.6. Photochemical reactivity

It is well known that VOCs are significant precursors of O₃ formation (Guo et al., 2004). Individual compound has different characteristic photochemical reactivity. In order to calculate the O₃-forming potential of the vehicular emissions, the speciated emission factors for each vehicle type were multiplied by the maximum incremental reactivity (MIR) scale developed by Carter (1994). The MIR is in units of grams of O₃ per gram of organic compound and therefore is simply multiplied by the emission factors (grams of organic compound per km driven), to yield reactivity-adjusted emission rates in units of O₃ per km.

3. Results and discussion

3.1. Speed-dependent NMHC exhaust emission characteristics

3.1.1. Gasoline-fuelled private car

Table 2 presents the weight percent contribution of individual NMHCs to the total emission at different driving speeds for gasoline-fuelled private cars. The ranges of the measured concentrations of individual NMHCs are also given in the table. The individual weight percentage was calculated by normalizing individual weight concentration (mg m⁻³) to total weight concentration. It was found that alkanes were the major NMHCs emitted from gasoline-fuelled vehicles, followed by aromatics and alkenes. The weight percentage of alkanes ranged from 40 to 63%, whereas the percentages of alkenes and aromatics were between 6 and 12%, and from 19 to 32%, respectively. Further inspection indicated that with the increase of driving speed, the emissions of alkanes had a slight increasing trend, and the emissions of aromatics showed a decreasing pattern. For individual NMHCs, it can be seen that the dominant species emitted from private cars were ethane, *n*-butane, *i*-pentane, *n*-pentane, 2,2,4-trimethylpentane, ethene, benzene, toluene, *m/p*-xylene and 1,2,4-Trimethylbenzene among the driving speed ranges. The emissions of different species showed different relationships with the driving speeds. For instance, the emission of ethane increased from 3.1 to 20.8% when the driving speed changed from idling state up to 100 km h⁻¹, whereas the weight percentage of pentanes remained unchanged with the increase of driving speeds (see Table 2). On the other hand, high percentage of toluene was found at low driving speeds i.e. ≤50 km h⁻¹ and it slightly decreased at high driving speeds. It is noteworthy that large variations in weight contribution of most NMHC species were generally observed at low driving speeds i.e. idling and 25 km h⁻¹, whereas the contribution of most species became relatively stable when the driving speeds were above 50 km h⁻¹. For example, the coefficient of variations (CV) of *i*-pentane were 80% at idling state and 48% at 25 km h⁻¹, while the CV values decreased ranging from 22% at 100 km h⁻¹ to 25% at 50 and 70 km h⁻¹. The CV values of benzene were 93% at idling state and 80% at 25 km h⁻¹, but they decreased to 52% at 50 km h⁻¹ and 34% at 100 km h⁻¹. Statistical 2-tail *t*-test was conducted for each NMHC species among different driving speeds. No significant differences in the weight percent contribution ($p > 0.05$) were found for each species except ethane, whose contribution was significantly higher at higher driving speeds (70 and 100 km h⁻¹) than that at idling state ($p < 0.01$), indicating that more ethane was produced while the car was driven at high speed. The large variations in NMHC contribution observed in this study are in line with other study. Flandrin et al. (2001) tested 25 passenger cars in France using chassis dynamometer and found strong variations in the NMHC composition for a catalyst vehicle under different driving conditions. It is noteworthy

that the relationship between driving speed and emission contribution of NMHC species is associated with many other factors such as year of manufacture, engine cylinder capacity, net weight, rated power, maximum torque and so on. Hence, substantial vehicle emission tests are necessary to formulate effective control strategy on NMHC emissions.

Interestingly, ethane was found to be more abundant than ethene in gasoline combustion emissions in Hong Kong, especially at high driving speeds (see Table 2), opposite to the findings obtained in South China, Taiwan, the United States and Beijing, where ethane only accounted for a small fraction of the total NMHC emissions from gasoline-fuelled vehicles (Chang et al., 2001; Watson et al., 2001; Lu et al., 2003; Liu et al., 2008). In addition, the contributions of 1,3-butadiene and ethyne to the total vehicle emission at all tested driving speeds were negligible, different from findings of previous studies (Ye et al., 1998; Rudolph et al., 2002; Ho et al., 2009), suggesting that caution should be taken when we use 1,3-butadiene and ethyne as tracers of vehicle emissions.

3.1.2. LPG-fuelled taxi

Table 3 shows the emission profiles (in percent contribution by weight) of major NMHC species emitted from LPG-fuelled taxi at different driving speeds. The concentration ranges of individual NMHCs are also shown in the table. Different from exhaust emissions from gasoline-fuelled private cars, LPG emissions were mainly caused by low molecular weight alkanes namely C₂–C₄ hydrocarbons. Ethane, propane, *i*-butane and *n*-butane were the major component in the emission. Alkanes accounted for 74–94% of the total emissions, whereas alkenes and aromatics made minor contributions. The contribution of ethane, a product of incomplete combustion of fossil fuel, ranged from 7.5% at 100 km h⁻¹ to 11.4% at idling state, whereas the abundance of propane (24–37%), *i*-butane (16–20%) and *n*-butane (19–25%) in the emission was due to the leakage of unburned LPG to the exhaust stream, confirmed by the low percentage of ethane and high percentage of propane and butanes in the LPG fuel (Tsai et al., 2006). It is noteworthy that the contribution of alkanes decreased with the increase of driving speed (i.e. from 94% at idling state down to 74% at 100 km h⁻¹), reflecting the fact that the LPG fuel was more completely combusted at higher driving speeds. In contrast, the aromatic hydrocarbons showed an increasing trend with the increase of driving speed (i.e. 1.23% at idling state up to 6.87% at 100 km h⁻¹), suggesting that more complete combustion of LPG could more possibly result in the formation of large molecular weight hydrocarbons such as aromatics. The major species in LPG-fuelled vehicle emissions found in this study are similar to other studies (Chang et al., 2001; Lu et al., 2003; Ho et al., 2009; Lai et al., 2009). Propane was the most abundant species in the LPG-fuelled vehicle emission in all studies, but its contribution in Taiwan (>40%) and Beijing (~60%) was higher than that in Hong Kong (24–37%). One major difference in LPG vehicle emission among these studies was that the contribution of ethane in Hong Kong (8–14%) was much higher than that in Taiwan (1.6%), Beijing (4.1%) and Guangzhou (~2%), suggesting that differences in LPG fuel composition, engine type, and combustion conditions could lead to ethane variations in exhaust emissions. The results suggest that saturated hydrocarbons are usually the major species emitted from LPG-fuelled vehicles and the emissions of unsaturated hydrocarbons and aromatics increase at high driving speed. This is consistent with the observations in Guangzhou, South China, and in a tunnel study in Hong Kong (Lai et al., 2009; Ho et al., 2009).

It is noted that the variations of the contributions of major NMHC species i.e. C₂–C₄ alkanes for LPG-fuelled taxi (Table 3) were much smaller than those for gasoline-fuelled private car (Table 2). This is due to the fact that both the year of manufacture and the

Table 2
Species contributions (% by weight) at different driving speeds for private cars.

	Vehicle speed, km h ⁻¹									
	0 (n = 4)		25 (n = 4)		50 (n = 4)		70 (n = 4)		100 (n = 4)	
	Concentration (mg m ⁻³)	Weight percent (%)	Concentration (mg m ⁻³)	Weight percent (%)	Concentration (mg m ⁻³)	Weight percent (%)	Concentration (mg m ⁻³)	Weight percent (%)	Concentration (mg m ⁻³)	Weight percent (%)
<i>Alkane</i>										
Ethane	0.05–7.4 ^a	3.14 (50%) ^b	1.8–15.2	5.47 (44%)	2.3–19.8	5.96 (72%)	0.08–18.5	11.1 (87%)	2.1–54.4	20.8 (49%)
Propane	0.04–0.4	0.32 (121%)	0.08–0.7	0.40 (68%)	0.1–1.1	0.37 (28%)	0.01–1.2	0.48 (56%)	0.1–1.2	0.57 (34%)
<i>i</i> -Butane	0.02–1.2	0.70 (105%)	0.1–1.9	0.69 (41%)	0.06–2.1	0.60 (64%)	0.02–1.8	0.80 (49%)	0.07–0.9	0.44 (74%)
<i>n</i> -Butane	0.3–5.9	2.53 (70%)	0.6–6.5	2.12 (93%)	0.6–9.4	2.01 (42%)	0.05–4.2	2.63 (37%)	0.5–4.4	2.33 (45%)
<i>i</i> -Pentane	0.6–38.1	8.14 (80%)	3.2–42.9	13.0 (48%)	3.6–64.6	12.8 (25%)	0.2–31.6	12.7 (25%)	1.9–26.6	11.8 (22%)
<i>n</i> -Pentane	0.2–6.8	2.23 (54%)	0.8–7.6	2.71 (124%)	0.7–11.3	2.66 (59%)	0.06–8.9	2.64 (44%)	0.3–4.5	2.48 (45%)
<i>n</i> -Hexane	0.1–4.2	1.72 (53%)	0.7–5.3	3.04 (40%)	0.5–9.8	2.82 (39%)	0.08–10.8	2.40 (57%)	0.2–2.9	1.76 (32%)
<i>n</i> -Heptane	0.1–4.0	1.55 (61%)	0.5–6.0	3.03 (38%)	0.4–10.3	2.86 (39%)	0.08–14.9	2.52 (65%)	0.2–3.8	1.62 (34%)
<i>n</i> -Octane	0.05–0.8	0.52 (29%)	0.02–2.8	0.73 (89%)	0.1–4.0	0.44 (68%)	0.007–8.4	0.4 (125%)	0.07–1.7	0.35 (67%)
<i>n</i> -Nonane	0.04–0.4	0.30 (51%)	0.02–0.6	0.27 (50%)	0.06–2.1	0.25 (67%)	0.005–1.7	0.18 (80%)	0.03–0.4	0.19 (27%)
Decane	0.06–0.25	0.30 (72%)	0.01–0.4	0.18 (120%)	0.02–0.9	0.15 (126%)	0.006–0.7	0.10 (74%)	0.02–0.2	0.13 (42%)
2,2-Dimethylbutane	0–0.2	0.10 (68%)	0.1–0.6	0.23 (190%)	0.03–0.8	0.28 (128%)	0.003–0.8	0.13 (89%)	0.01–0.4	0.27 (84%)
2,3-Dimethylbutane	0.2–3.8	0.49 (100%)	0.2–2.0	1.38 (26%)	0.4–6.6	1.47 (30%)	0.007–3.2	1.09 (78%)	0.2–2.5	1.38 (49%)
2-Methylpentane	0.04–12.5	2.96 (65%)	0.6–14.6	4.36 (22%)	1.1–23.2	4.34 (24%)	0.09–12.8	4.05 (26%)	0.5–8.1	3.78 (32%)
3-Methylpentane	0.02–7.8	1.93 (64%)	0.5–8.9	2.91 (16%)	0.8–13.7	2.90 (20%)	0.07–8.1	2.95 (24%)	0.3–5.0	2.55 (33%)
2-Methylhexane	0.04–4.6	1.47 (58%)	0.1–5.4	1.73 (41%)	0.4–8.8	1.70 (32%)	0.07–5.4	1.52 (49%)	0.2–2.9	1.14 (15%)
3-Methylhexane	0.02–4.3	1.45 (51%)	0.1–5.0	1.68 (36%)	0.4–8.3	1.67 (31%)	0.06–5.4	1.45 (50%)	0.2–2.7	1.34 (20%)
2-Methylheptane	0.02–1.9	0.85 (46%)	0.03–2.4	0.79 (41%)	0.1–4.1	0.75 (45%)	0.02–3.1	0.67 (46%)	0.09–1.2	0.54 (21%)
3-Methylheptane	0.02–1.8	0.75 (45%)	0.03–2.3	0.72 (39%)	0.1–3.9	0.70 (40%)	0.02–2.8	0.66 (43%)	0.08–1.1	0.47 (20%)
2,3,4-Trimethylpentane	0.03–7.2	2.07 (80%)	0.09–8.1	2.06 (64%)	0.2–13.1	2.15 (51%)	0.06–3.6	2.08 (53%)	0.08–3.8	1.82 (50%)
2,4-Dimethylpentane	0.02–2.7	0.73 (79%)	0.05–3.3	0.74 (52%)	0.1–5.2	0.77 (30%)	0.03–1.6	0.74 (41%)	0.1–1.8	0.73 (37%)
2,2,4-Trimethylpentane	0.6–26.0	5.99 (91%)	0.5–29.7	5.51 (72%)	1.5–44.8	5.95 (58%)	0.2–15.1	5.94 (58%)	0.4–16.0	6.21 (48%)
SUM		40.25		53.78		53.53		57.17		62.68
<i>Alkyne</i>										
Ethyne	0.004–0.08	0.27 (104%)	0.003–0.07	0.02 (218%)	0.002–0.1	0.03 (214%)	0.006–0.2	0.2 (127%)	0.001–1.6	0.04 (169%)
<i>Alkene</i>										
Ethene	0.02–2.1	2.15 (130%)	0.06–8.3	1.62 (66%)	0.4–34.1	2.79 (78%)	0.06–20.4	5.37 (45%)	0.5–15.5	4.4 (53%)
Propene	0.02–1.3	0.63 (130%)	0.02–5.5	0.94 (85%)	0.2–27.3	2.03 (63%)	0.04–2.8	2.04 (40%)	0.3–9.5	2.18 (43%)
1-Butene	0–0.1	0.14 (95%)	0.002–0.6	0.12 (75%)	0.06–4.2	0.30 (69%)	0.008–0.4	0.27 (48%)	0.05–1.0	0.28 (42%)
<i>i</i> -Butene	0.001–1.8	1.53 (72%)	0.002–8.1	1.46 (95%)	0.5–21.4	3.47 (67%)	0.04–4.6	2.01 (36%)	0.5–6.1	2.75 (4%)
<i>trans</i> -2-Butene	0–0.3	0.23 (66%)	0.002–1.0	0.16 (82%)	0.05–4.2	0.33 (65%)	0.01–0.4	0.29 (32%)	0.05–0.8	0.28 (22%)
<i>cis</i> -2-Butene	0–0.2	0.16 (72%)	0.001–0.7	0.13 (78%)	0.03–3.2	0.26 (66%)	0.006–0.3	0.24 (29%)	0.03–0.7	0.19 (33%)
1,3-Butadiene	0–0.06	0.04 (24%)	0–0.4	0.03 (122%)	0.02–1.7	0.12 (94%)	0.001–0.3	0.14 (65%)	0.008–0.4	0.09 (60%)
1-Pentene	0.02–0.09	0.08 (87%)	0.003–0.3	0.08 (72%)	0.03–1.8	0.13 (48%)	0.005–0.2	0.10 (73%)	0.02–0.3	0.09 (74%)
Isoprene	0–0.05	0.01 (140%)	0–0.3	0.00	0–0.06	0.00	0–0.2	0.00	0.00	0.00
<i>trans</i> -2-Pentene	0.004–0.4	0.46 (69%)	0.01–1.0	0.25 (77%)	0.09–4.8	0.47 (44%)	0.02–0.9	0.28 (82%)	0.03–0.7	0.25 (63%)
<i>cis</i> -2-Pentene	0.002–0.2	0.16 (74%)	0.005–0.5	0.14 (70%)	0.05–2.5	0.22 (42%)	0.008–0.3	0.15 (70%)	0.02–0.4	0.12 (50%)
3-Methyl-1-butene	0–0.08	0.08 (87%)	0.002–0.2	0.07 (63%)	0.03–1.4	0.11 (45%)	0.004–0.2	0.09 (62%)	0.02–0.2	0.12 (56%)
2-Methyl-1-butene	0.001–0.4	0.35 (73%)	0.007–1.2	0.32 (68%)	0.08–4.4	0.43 (37%)	0.02–0.6	0.32 (60%)	0.05–0.8	0.30 (43%)
2-Methyl-2-butene	0.007–1.3	0.88 (55%)	0.01–3.0	0.58 (74%)	0.2–10.2	0.87 (49%)	0.03–1.1	0.76 (58%)	0.06–1.8	0.45 (46%)
SUM		6.89		5.89		11.53		12.04		11.49
<i>Aromatics</i>										
Benzene	0.02–7.2	2.69 (93%)	0.04–10.3	3.06 (80%)	0.4–20.6	3.32 (52%)	0.03–21.4	3.17 (66%)	0.9–12.1	5.3 (34%)
Toluene	0.1–14.6	10.09 (78%)	0.2–19.6	11.39 (53%)	1.9–81.0	13.57 (37%)	0.3–18.9	6.76 (64%)	1.5–22.3	10.7 (50%)
Ethylbenzene	0.009–0.8	1.06 (146%)	0.004–5.6	1.51 (83%)	0.2–6.6	1.10 (56%)	0.002–4.9	1.14 (64%)	0.1–2.6	0.95 (47%)
<i>m</i> -Xylene	0.02–1.6	1.39 (103%)	0.005–10.1	3.89 (76%)	0.2–7.9	1.23 (67%)	0.001–10.6	2.19 (72%)	0.1–6.0	0.89 (93%)
<i>p</i> -Xylene	0.01–1.0	0.97 (135%)	0.004–7.3	2.2 (86%)	0.1–5.2	0.91 (56%)	0.002–6.9	1.33 (70%)	0.06–3.4	0.57 (79%)
<i>o</i> -Xylene	0.01–0.9	0.87 (118%)	0.005–7.4	2.11 (87%)	0.2–4.7	0.87 (60%)	0.001–6.9	1.38 (72%)	0.06–3.2	0.58 (78%)
<i>i</i> -Propylbenzene	0.009–0.1	0.28 (80%)	0.01–0.3	0.10 (67%)	0.03–0.6	0.13 (55%)	0.004–0.1	0.09 (76%)	0.01–0.2	0.10 (65%)
<i>n</i> -Propylbenzene	0.02–0.3	0.67 (86%)	0.03–0.4	0.25 (79%)	0.05–1.3	0.28 (71%)	0.009–0.4	0.15 (64%)	0.03–0.3	0.21 (63%)
<i>m</i> -Ethyltoluene	0.07–1.2	3.22 (91%)	0.1–2.8	1.21 (83%)	0.3–8.2	1.47 (72%)	0.05–1.6	0.75 (62%)	0.2–2.2	1.13 (38%)
<i>p</i> -Ethyltoluene	0.04–0.6	1.44 (90%)	0.07–1.1	0.50 (86%)	0.1–3.1	0.55 (81%)	0.02–0.7	0.31 (67%)	0.06–0.8	0.42 (58%)
<i>o</i> -Ethyltoluene	0.03–0.4	1.19 (92%)	0.05–0.9	0.41 (82%)	0.1–2.7	0.52 (72%)	0.02–0.5	0.26 (68%)	0.06–0.7	0.37 (44%)
1,3,5-Trimethylbenzene	0.03–0.8	1.69 (84%)	0.07–1.7	0.67 (76%)	0.1–3.7	0.82 (72%)	0.02–1.2	0.50 (61%)	0.05–0.9	0.43 (46%)
1,2,4-Trimethylbenzene	0.09–2.3	5.41 (114%)	0.2–4.1	1.76 (99%)	0.3–10.3	2.01 (98%)	0.02–2.7	1.07 (73%)	0.2–2.9	1.43 (47%)
1,2,3-Trimethylbenzene	0.02–0.5	1.21 (161%)	0.06–0.8	0.41 (102%)	0.08–2.0	0.42 (105%)	0.01–0.8	0.2 (111%)	0.04–0.8	0.42 (71%)
SUM		32.18		29.48		27.2		19.32		23.5

^a Minimum concentration–maximum concentration.

^b Median weight percent (Coefficient of Variation). The individual weight percentage was calculated by normalizing individual weight concentration (mg m⁻³) to total weight concentration.

mileage of LPG-fuelled taxis in Hong Kong had less variation than those of gasoline-fuelled private cars. In Hong Kong, over 95% of the taxis including the 4 LPG taxis tested in this study were made by the same manufacturer, with the same model and engine specification.

3.2. Speed-dependent emission factor of NMHCs

3.2.1. Gasoline-fuelled private car

On the basis of measured gaseous emission data from gasoline-fuelled vehicles on a chassis dynamometer, the mean emission

Table 3
Species contributions (% by weight) at different driving speeds for taxis.

	Vehicle speed, km h ⁻¹									
	0 (n = 4)		25 (n = 4)		50 (n = 4)		70 (n = 4)		100 (n = 4)	
	Concentration (mg m ⁻³)	Weight percent (%)	Concentration (mg m ⁻³)	Weight percent (%)	Concentration (mg m ⁻³)	Weight percent (%)	Concentration (mg m ⁻³)	Weight percent (%)	Concentration (mg m ⁻³)	Weight percent (%)
<i>Alkane</i>										
Ethane	0.2–9.4 ^a	11.4 (93%) ^b	0.2–4.2	11.0 (23%)	0.2–3.0	13.8 (35%)	0.4–3.3	13.1 (29%)	0.2–1.4	7.54 (67%)
Propane	0.5–40	35.3 (25%)	0.5–24.0	37.3 (31%)	0.2–9.2	36.3 (39%)	1.2–7.7	37.2 (33%)	0.5–2.8	24.0 (28%)
<i>i</i> -Butane	0.3–21.3	20.6 (48%)	0.2–11.8	19.8 (21%)	0.2–4.7	18.5 (30%)	0.8–2.8	16.0 (21%)	0.4–1.3	17.4 (26%)
<i>n</i> -Butane	0.3–26.9	24.9 (41%)	0.2–11.8	21.9 (18%)	0.2–5.4	20.1 (24%)	0.8–2.9	19.4 (15%)	0.5–1.6	20.0 (20%)
<i>i</i> -Pentane	0.03–0.8	0.73 (66%)	0.04–0.5	1.06 (109%)	0.02–0.2	1.71 (47%)	0.05–0.4	1.46 (62%)	0.03–0.2	1.63 (66%)
<i>n</i> -Pentane	0.007–0.1	0.10 (106%)	0.009–0.09	0.21 (129%)	0.006–0.05	0.46 (54%)	0.01–0.1	0.31 (70%)	0.01–0.05	0.48 (61%)
<i>n</i> -Hexane	0.005–0.04	0.08 (112%)	0.007–0.05	0.20 (130%)	0.009–0.03	0.35 (75%)	0.01–0.09	0.34 (65%)	0.01–0.05	0.53 (51%)
<i>n</i> -Heptane	0.004–0.03	0.07 (111%)	0.006–0.03	0.15 (126%)	0.007–0.03	0.25 (79%)	0.008–0.08	0.24 (70%)	0.01–0.05	0.38 (60%)
<i>n</i> -Octane	0.001–0.01	0.02 (111%)	0.001–0.003	0.03 (96%)	0–0.002	0.01 (138%)	0.001–0.004	0.02 (58%)	0.001–0.006	0.07 (62%)
<i>n</i> -Nonane	0–0.002	0.01 (90%)	0–0.004	0.01	0–0.002	0.03 (147%)	0–0.002	0.00	0.002–0.006	0.07 (59%)
Decane	0.001–0.003	0.01 (142%)	0.001–0.007	0.03 (126%)	0.001–0.004	0.04 (149%)	0.001–0.01	0.04 (118%)	0.002–0.007	0.11 (44%)
2,2-Dimethylbutane	0.001–0.005	0.01 (78%)	0–0.006	0.01 (151%)	0–0.004	0.03 (56%)	0.001–0.01	0.05 (82%)	0.002–0.01	0.08 (68%)
2,3-Dimethylbutane	0.001–0.005	0.03 (157%)	0.005–0.02	0.09 (100%)	0.002–0.01	0.09 (148%)	0.002–0.08	0.13 (104%)	0.002–0.04	0.20 (105%)
2-Methylpentane	0.004–0.01	0.08 (106%)	0.008–0.08	0.20 (131%)	0.005–0.05	0.39 (57%)	0.008–0.1	0.33 (88%)	0.005–0.05	0.41 (71%)
3-Methylpentane	0.002–0.04	0.06 (135%)	0.004–0.05	0.13 (136%)	0.003–0.03	0.25 (57%)	0.004–0.07	0.19 (93%)	0.006–0.04	0.28 (67%)
2-Methylhexane	0.003–0.02	0.05 (99%)	0.008–0.03	0.17 (110%)	0.003–0.02	0.19 (61%)	0.005–0.03	0.18 (65%)	0.006–0.02	0.25 (41%)
3-Methylhexane	0.004–0.03	0.06 (120%)	0.01–0.03	0.22 (105%)	0.009–0.02	0.23 (98%)	0.007–0.03	0.20 (65%)	0.01–0.02	0.37 (32%)
2-Methylheptane	0.001–0.003	0.01 (108%)	0–0.004	0.00	0–0.002	0.00	0–0.004	0.00	0.001–0.005	0.06 (82%)
3-Methylheptane	0.001–0.003	0.01 (106%)	0–0.005	0.01	0–0.001	0.00	0–0.005	0.00	0.001–0.005	0.06 (69%)
2,3,4-Trimethylpentane	0.001–0.01	0.01 (146%)	0.001–0.02	0.03 (139%)	0.002–0.01	0.10 (69%)	0–0.02	0.06 (178%)	0.001–0.01	0.08 (84%)
2,4-Dimethylpentane	0.001–0.01	0.05 (83%)	0.001–0.01	0.03 (139%)	0.001–0.006	0.05 (69%)	0–0.01	0.04 (196%)	0.001–0.007	0.07 (62%)
2,2,4-Trimethylpentane	0.002–0.04	0.05 (130%)	0.02–0.05	0.41 (96%)	0.006–0.06	0.42 (65%)	0.009–0.06	0.39 (82%)	0.01–0.04	0.52 (61%)
SUM		93.66		92.99		93.28		89.73		74.49
<i>Alkyne</i>										
Ethyne	0–0.1	0.02 (189%)	0.002–0.03	0.08 (151%)	0.002–0.02	0.05 (183%)	0.001–0.1	0.09 (174%)	0.002–0.06	0.07 (183%)
<i>Alkene</i>										
Ethene	0.004–0.6	0.32 (162%)	0.006–0.2	0.25 (178%)	0.008–0.07	0.24 (179%)	0.02–0.5	0.46 (166%)	0.01–0.2	0.51 (166%)
Propene	0.001–0.3	0.16 (166%)	0.003–0.1	0.11 (180%)	0.007–0.03	0.17 (168%)	0.01–0.3	0.29 (162%)	0.01–0.1	0.52 (149%)
1-Butene	0.001–0.1	0.10 (130%)	0.003–0.01	0.09 (113%)	0.002–0.02	0.16 (96%)	0.003–0.04	0.15 (118%)	0.005–0.03	0.35 (90%)
<i>i</i> -Butene	0.002–0.2	0.17 (138%)	0.003–0.05	0.13 (153%)	0.004–0.03	0.20 (160%)	0.009–0.09	0.24 (122%)	0.01–0.1	0.49 (139%)
<i>trans</i> -2-Butene	0.002–0.2	0.15 (115%)	0.005–0.02	0.17 (91%)	0.003–0.03	0.22 (74%)	0.005–0.07	0.21 (113%)	0.006–0.04	0.38 (73%)
<i>cis</i> -2-Butene	0.001–0.1	0.09 (115%)	0.003–0.02	0.10 (88%)	0.002–0.02	0.16 (61%)	0.003–0.04	0.14 (115%)	0.004–0.02	0.27 (73%)
1,3-Butadiene	0–0.02	0.00	0–0.004	0.00	0.00	0.00	0.00	0.00	0.003–0.2	0.00
1-Pentene	0.001–0.008	0.01 (114%)	0.001–0.01	0.02 (144%)	0.001–0.006	0.06 (68%)	0–0.01	0.03 (136%)	0.00	0.07 (57%)
Isoprene	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.001–0.006	0.00
<i>trans</i> -2-Pentene	0.002–0.03	0.03 (130%)	0.002–0.04	0.07 (142%)	0.002–0.02	0.18 (58%)	0.002–0.04	0.10 (89%)	0.00	0.19 (68%)
<i>cis</i> -2-Pentene	0.001–0.01	0.01 (107%)	0.001–0.02	0.03 (141%)	0.002–0.009	0.09 (64%)	0.001–0.02	0.04 (92%)	0.004–0.02	0.08 (68%)
3-Methyl-1-butene	0–0.005	0.01 (75%)	0.001–0.004	0.01 (138%)	0.001–0.004	0.03 (65%)	0.001–0.005	0.02 (75%)	0.001–0.009	0.03 (67%)
2-Methyl-1-butene	0.001–0.02	0.02 (86%)	0.002–0.02	0.04 (140%)	0.002–0.01	0.13 (63%)	0.002–0.03	0.06 (87%)	0.001–0.003	0.13 (65%)
2-Methyl-2-butene	0.002–0.02	0.03 (125%)	0.003–0.03	0.07 (139%)	0.002–0.02	0.18 (61%)	0.003–0.04	0.11 (85%)	0.003–0.01	0.17 (74%)
SUM		1.09		1.08		1.82		1.84		3.18
<i>Aromatics</i>										
Benzene	0.002–0.05	0.06 (78%)	0.002–0.008	0.08 (90%)	0.002–0.009	0.06 (160%)	0.004–0.02	0.10 (61%)	0.002–0.02	0.23 (105%)
Toluene	0.04–0.4	0.37 (128%)	0.05–0.2	0.95 (98%)	0.02–0.3	1.45 (97%)	0.03–0.7	2.08 (81%)	0.05–0.5	2.08 (114%)
Ethylbenzene	0.005–0.03	0.04 (135%)	0.002–0.02	0.09 (125%)	0.001–0.02	0.10 (116%)	0.003–0.03	0.12 (109%)	0.003–0.07	0.22 (131%)
<i>m</i> -Xylene	0.007–0.04	0.07 (143%)	0.002–0.03	0.08 (147%)	0.001–0.03	0.13 (136%)	0.002–0.06	0.20 (113%)	0.003–0.1	0.28 (146%)
<i>p</i> -Xylene	0.005–0.03	0.05 (130%)	0.002–0.03	0.07 (156%)	0.001–0.02	0.09 (130%)	0.003–0.04	0.14 (121%)	0.003–0.07	0.24 (135%)
<i>o</i> -Xylene	0.005–0.03	0.05 (131%)	0.001–0.03	0.06 (163%)	0.001–0.02	0.08 (135%)	0.002–0.04	0.10 (123%)	0.003–0.08	0.23 (130%)
<i>i</i> -Propylbenzene	0–0.002	0.00	0–0.002	0.00	0.00	0.00	0.00	0.00	0.00	0.03 (88%)
<i>n</i> -Propylbenzene	0.001–0.009	0.03 (102%)	0.002–0.008	0.06 (108%)	0.001–0.005	0.05 (154%)	0.002–0.01	0.05 (102%)	0.006–0.01	0.19 (39%)
<i>m</i> -Ethyltoluene	0.005–0.03	0.12 (103%)	0.01–0.06	0.59 (108%)	0.009–0.03	0.27 (151%)	0.01–0.08	0.49 (103%)	0.03–0.07	0.85 (49%)
<i>p</i> -Ethyltoluene	0.002–0.01	0.05 (99%)	0.003–0.02	0.11 (120%)	0.003–0.01	0.09 (157%)	0.004–0.04	0.11 (123%)	0.01–0.02	0.38 (48%)
<i>o</i> -Ethyltoluene	0.001–0.01	0.05 (100%)	0.003–0.02	0.12 (118%)	0.001–0.01	0.08 (160%)	0.003–0.03	0.08 (131%)	0.01–0.02	0.34 (50%)
1,3,5-Trimethylbenzene	0.002–0.01	0.06 (99%)	0.004–0.03	0.14 (125%)	0.003–0.01	0.09 (155%)	0.003–0.03	0.11 (120%)	0.01–0.02	0.37 (42%)
1,2,4-Trimethylbenzene	0.01–0.05	0.22 (105%)	0.02–0.10	0.79 (119%)	0.008–0.05	0.41 (160%)	0.02–0.1	0.50 (105%)	0.03–0.09	1.11 (44%)
1,2,3-Trimethylbenzene	0.002–0.02	0.08 (107%)	0.002–0.04	0.09 (162%)	0.002–0.03	0.08 (183%)	0.005–0.03	0.11 (112%)	0.01–0.02	0.31 (47%)
SUM		1.23		3.25		2.97		4.18		6.87

^a Minimum concentration–maximum concentration.

^b Median weight percent (Coefficient of Variation). The individual weight percentage was calculated by normalizing individual weight concentration (mg m⁻³) to total weight concentration.

factors of individual NMHC species at different driving speeds were estimated. Emission factors are useful for emission estimation and for simulations of atmospheric chemical and physical processes using chemical transport models. Table 4 lists the mean, minimum and maximum emission factors of NMHC species for the gasoline-fuelled

private cars at different driving speeds. The mean emission factors of total NMHCs measured by canister samples and of total hydrocarbons (THC) measured by HC analyzer at different driving speeds are also listed in the table. Overall, high emission factors were found for ethane, *i*-pentane, 2-Methylpentane, 2,2,4-Trimethylpentane,

ethene, benzene, toluene and *m*-xylene. Statistical analysis found that there were no significant differences in emission factor for each species among different driving speeds ($p > 0.05$), due to the large variations in concentration of NMHC species. It is noteworthy that the emission factor of total NMHCs decreased from 300 mg km⁻¹ at the speed of 25 km h⁻¹ to 128 mg km⁻¹ at 50 km h⁻¹ and then remained stable. Compared the mean emission factor of total NMHCs measured by canister samples to that of total hydrocarbons measured by HC

analyzer, it was found that at lower driving speeds i.e. ≤ 50 km h⁻¹, the results were comparable, whereas at higher driving speeds, the emission factor of total NMHCs measured by canisters was about twice that measured by the HC analyzer.

3.2.2. LPG-fuelled taxi

Table 5 shows the emission factors of NMHCs for the LPG-fuelled taxis at different driving speeds. The emission factors of C₂–C₄

Table 4

Emission factors of NMHCs species for gasoline-fuelled private cars (mg km⁻¹; the unit is mg h⁻¹ at idle state).

	Vehicle speed, km h ⁻¹				
	0 (n = 6)	25 (n = 6)	50 (n = 6)	70 (n = 7)	100 (n = 6)
<i>Alkane</i>					
Ethane	77 (2–329) ^a	20 (0.04–54)	14 (0–44)	12 (0.11–35)	34 (2–90)
Propane	5 (0.2–19)	1 (0.01–2.6)	0.8 (0–2.5)	0.7 (0.02–2)	0.9 (0.1–3)
<i>i</i> -Butane	12 (0.6–53)	2 (0.01–7)	1 (0–4)	1 (0.03–3)	0.6 (0.08–2)
<i>n</i> -Butane	55 (1–262)	8 (0.01–23)	5 (0.01–21)	2 (0.07–6)	3 (0.7–10)
<i>i</i> -Pentane	351 (3–1692)	44 (0.05–152)	38 (0.02–143)	18 (0.4–60)	17 (3–59)
<i>n</i> -Pentane	66 (1–304)	9 (0.02–27)	8 (0.01–25)	5 (0.09–17)	4 (0.6–10)
<i>n</i> -Hexane	41 (0.5–187)	7 (0.03–19)	6 (0.01–17)	4 (0.1–21)	2 (0.3–6)
<i>n</i> -Heptane	39 (0.6–178)	8 (0.03–21)	7 (0.01–17)	5 (0.1–28)	3 (0.3–6)
<i>n</i> -Octane	9 (0.2–37)	3 (0–8)	2 (0–7)	3 (0.01–16)	0.8 (0.1–3)
<i>n</i> -Nonane	5 (0.1–20)	0.8 (0–2)	1 (0–4)	0.6 (0.01–3)	0.3 (0.05–0.6)
Decane	3 (0.2–11)	0.5 (0.01–1.6)	0.6 (0–1.5)	0.3 (0.01–1)	0.2 (0.03–0.5)
2,2-Dimethylbutane	2 (0.01–8)	0.6 (0–1.2)	0.5 (0–1)	0.4 (0–1)	0.3 (0.02–0.6)
2,3-Dimethylbutane	35 (0.1–170)	4 (0.02–15)	4 (0.01–15)	2 (0.01–4)	2 (0.3–6)
2-Methylpentane	116 (2–556)	15 (0.02–52)	14 (0.01–51)	6 (0.1–24)	6 (1–18)
3-Methylpentane	73 (1–348)	9 (0.02–32)	9 (0.01–30)	4 (0.1–15)	4 (0.6–11)
2-Methylhexane	43 (1–204)	5 (0.02–19)	5 (0.01–20)	2 (0.1–10)	2 (0.4–7)
3-Methylhexane	41 (1–192)	5 (0.02–18)	5 (0.01–18)	2 (0.1–10)	2 (0.3–6)
2-Methylheptane	19 (0.7–87)	3 (0–9)	3 (0–9)	1 (0.02–6)	0.9 (0.2–3)
3-Methylheptane	17 (0.6–80)	2 (0–8)	3 (0–9)	1 (0.02–5)	0.8 (0.1–2)
2,3,4-Trimethylpentane	67 (1–320)	7 (0.02–29)	6 (0.01–29)	1 (0.09–5)	2 (0.1–8)
2,4-Dimethylpentane	25 (0.3–119)	3 (0.01–12)	3 (0–12)	0.8 (0.04–2)	1 (0.2–4)
2,2,4-Trimethylpentane	240 (2–1157)	27 (0.04–105)	20 (0.02–100)	5 (0.3–21)	8 (0.7–36)
<i>Alkyne</i>					
Ethyne	1 (0.1–3.5)	0.06 (0–0.25)	0.06 (0–0.3)	0.1 (0.01–0.5)	0.6 (0–3)
<i>Alkene</i>					
Ethene	26 (1–94)	8 (0.01–29)	20 (0.01–76)	8 (0.1–39)	11 (1–34)
Propene	15 (0.4–58)	5 (0–20)	13 (0.01–61)	2 (0.06–5)	5 (1–21)
1-Butene	2 (0.01–7)	0.5 (0–2)	2 (0–9)	0.2 (0.01–0.5)	0.6 (0.1–2)
<i>i</i> -Butene	20 (0.03–81)	7 (0–29)	14 (0–47)	3 (0.06–9)	4 (1–14)
<i>trans</i> -2-Butene	3 (0.01–14)	0.8 (0–3)	2 (0–9)	0.3 (0.02–0.6)	0.5 (0.1–2)
<i>cis</i> -2-Butene	2 (0.01–10)	0.6 (0–3)	2 (0–7)	0.2 (0.01–0.5)	0.4 (0.07–2)
1,3-Butadiene	1 (0.02–2.8)	0.3 (0–1)	1 (0–4)	0.2 (0–0.5)	0.2 (0.02–0.8)
1-Pentene	1 (0.06–4)	0.2 (0–0.9)	0.8 (0–4)	0.09 (0.01–0.2)	0.2 (0.03–0.6)
Isoprene	0 (0–0)	0.2 (0–1)	0.02 (0–0.14)	0.04 (0–0.3)	0 (0–0)
<i>trans</i> -2-Pentene	4 (0.2–19)	0.8 (0.01–3)	2 (0–11)	0.3 (0.02–0.8)	0.4 (0.05–2)
<i>cis</i> -2-Pentene	2 (0.09–9)	0.4 (0–2)	1 (0–6)	0.1 (0.01–0.3)	0.2 (0.03–0.8)
3-Methyl-1-butene	1 (0.02–3.7)	0.2 (0–0.8)	0.6 (0–3)	0.08 (0.01–0.2)	0.2 (0.04–0.5)
2-Methyl-1-butene	4 (0.04–20)	1 (0–4)	2 (0–10)	0.3 (0.02–0.6)	0.4 (0.08–2)
2-Methyl-2-butene	12 (0.3–57)	2 (0.01–11)	5 (0–23)	0.6 (0.04–1)	1 (0.1–4)
<i>Aromatics</i>					
Benzene	83 (1–318)	13 (0.06–36)	12 (0–46)	8 (0.04–41)	9 (1–27)
Toluene	178 (4–536)	28 (0.1–70)	39 (0.06–180)	11 (0.5–32)	17 (3–50)
Ethylbenzene	10 (0.3–28)	6 (0.01–15)	4 (0–15)	2 (0–9)	2 (0.2–4)
<i>m</i> -Xylene	14 (1–35)	12 (0.01–35)	5 (0.01–18)	4 (0–20)	3 (0.2–10)
<i>p</i> -Xylene	11 (0.5–28)	7 (0.01–19)	3 (0.01–12)	3 (0–13)	2 (0.1–6)
<i>o</i> -Xylene	10 (0.4–27)	7 (0.01–20)	3 (0.01–10)	3 (0–13)	2 (0.1–5)
<i>i</i> -Propylbenzene	2 (0.3–6)	0.3 (0–0.9)	0.4 (0–1)	0.09 (0–0.3)	0.1 (0.02–0.3)
<i>n</i> -Propylbenzene	3 (0.6–6)	0.5 (0.01–1)	0.8 (0–3)	0.2 (0.01–0.7)	0.3 (0.05–0.6)
<i>m</i> -Ethyltoluene	17 (2.5–40)	3 (0.04–10)	4 (0.02–18)	1 (0.07–3)	2 (0.4–5)
<i>p</i> -Ethyltoluene	7 (1–14)	1 (0.02–4)	2 (0.01–7)	0.4 (0.03–1)	0.6 (0.1–2)
<i>o</i> -Ethyltoluene	6 (1–13)	1 (0.01–3)	2 (0.01–6)	0.3 (0.02–1)	0.5 (0.1–2)
1,3,5-Trimethylbenzene	10 (1–27)	1.7 (0.02–6)	2 (0.01–8)	0.6 (0.01–2)	0.7 (0.09–2)
1,2,4-Trimethylbenzene	29 (3–60)	4 (0.07–14)	6 (0.03–23)	2 (0.04–5)	2 (0.3–6)
1,2,3-Trimethylbenzene	9 (0.7–17)	1 (0.02–3)	1 (0.01–5)	0.5 (0.02–2)	0.6 (0.07–2)
Total NMHCs	1823 (59–7867)	300 (1–953)	128 (0.4–418)	129 (3–475)	158 (33–473)
THC (by HC analyzer)	2123 (64–7670)	209 (77–486)	132 (3–320)	69 (3–183)	71 (16–152)

^a Mean (minimum–maximum).

saturated hydrocarbons i.e. ethane, propane, *i*-butane and *n*-butane were significantly higher than that of other NMHC species at the corresponding driving speeds ($p < 0.001$). Propane had the highest emission factor at any driving speed. By inspection, it was found that the emission factor of major NMHC species emitted from the LPG-fuelled vehicle decreased significantly from low driving speed i.e. 25 km h⁻¹ to high speed i.e. 50 km h⁻¹ and then remained unchanged at higher speeds such as 70 and 100 km h⁻¹. In total, the

emission factor of total NMHCs steadily decreased from 30 mg km⁻¹ at the speed of 25 km h⁻¹–5 mg km⁻¹ at 100 km h⁻¹. By comparison, it can be seen that the mean emission factors of total NMHCs measured by canister samples were consistent with those of total hydrocarbons measured by HC analyzer at all corresponding steady-state driving speeds, whereas at idling state, the emission factor of total NMHCs measured by canisters was about half that measured by the HC analyzer.

Table 5Emission factors of major NMHCs species for LPG-fuelled taxis (mg km⁻¹; the unit is mg h⁻¹ at idle state).

	Vehicle speed, km h ⁻¹				
	0 (<i>n</i> = 4)	25 (<i>n</i> = 4)	50 (<i>n</i> = 4)	70 (<i>n</i> = 4)	100 (<i>n</i> = 4)
<i>Alkane</i>					
Ethane	120 (7–262) ^a	2.7 (0.4–6.7)	1.3 (0.2–3)	1.5 (0.3–3)	0.6 (0.2–1.4)
Propane	386 (13–1113)	12.9 (1–39)	4 (0.2–9)	4 (1–7)	1.5 (0.5–3)
<i>i</i> -Butane	180 (8–591)	6.5 (0.3–19)	2 (0.2–5)	1.5 (0.7–2.4)	1 (0.4–1.4)
<i>n</i> -Butane	232 (10–749)	6.6 (0.4–19)	2 (0.2–5)	1.7 (0.7–2.5)	1 (0.5–2)
<i>i</i> -Pentane	7 (0.8–21)	0.3 (0.07–0.8)	0.1 (0.02–0.2)	0.12 (0.04–0.3)	0.1 (0.03–0.2)
<i>n</i> -Pentane	1 (0.2–3)	0.06 (0.01–0.15)	0.02 (0.01–0.05)	0.03 (0.01–0.08)	0.03 (0.01–0.05)
<i>n</i> -Hexane	0.6 (0.1–1)	0.04 (0.01–0.08)	0.02 (0.01–0.03)	0.03 (0.01–0.07)	0.03 (0.02–0.05)
<i>n</i> -Heptane	0.5 (0.1–0.9)	0.03 (0.01–0.05)	0.01 (0.01–0.03)	0.02 (0.0–0.06)	0.02 (0.01–0.05)
<i>n</i> -Octane	0.1 (0.02–0.3)	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)
<i>n</i> -Nonane	0.04 (0.01–0.06)	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)
Decane	0.05 (0.03–0.08)	0.01 (0–0.01)	0 (0–0)	0 (0–0.01)	0 (0–0)
2,2-Dimethylbutane	0.07 (0.01–0.2)	0 (0–0.01)	0 (0–0)	0 (0–0.01)	0 (0–0)
2,3-Dimethylbutane	0.2 (0.1–0.3)	0.01 (0–0.01)	0.01 (0–0.01)	0.02 (0.01–0.07)	0 (0–0)
2-Methylpentane	0.7 (0.1–2)	0.06 (0.01–0.12)	0.02 (0–0.05)	0.03 (0.01–0.1)	0.02 (0.01–0.05)
3-Methylpentane	0.5 (0.07–1)	0.04 (0.01–0.08)	0.01 (0–0.03)	0.02 (0–0.06)	0.02 (0.01–0.04)
2-Methylhexane	0.3 (0.08–0.7)	0.03 (0.01–0.04)	0.01 (0–0.02)	0.01 (0–0.03)	0.01 (0.01–0.02)
3-Methylhexane	0.4 (0.1–0.7)	0.03 (0.02–0.05)	0.01 (0.01–0.02)	0.01 (0.01–0.03)	0.02 (0.01–0.02)
2-Methylheptane	0.05 (0.02–0.09)	0 (0–0.01)	0 (0–0)	0 (0–0)	0 (0–0)
3-Methylheptane	0.05 (0.02–0.09)	0 (0–0.01)	0 (0–0)	0 (0–0)	0 (0–0)
2,3,4-Trimethylpentane	0.1 (0.02–0.4)	0.01 (0–0.03)	0.01 (0–0.01)	0 (0–0)	0.01 (0–0.01)
2,4-Dimethylpentane	0.2 (0.03–0.3)	0.01 (0–0.02)	0 (0–0.01)	0.01 (0–0.01)	0 (0–0)
2,2,4-Trimethylpentane	0.4 (0.05–1)	0.05 (0.03–0.09)	0.02 (0.01–0.06)	0 (0–0.01)	0.02 (0.01–0.04)
<i>Alkyne</i>					
Ethyne	0.8 (0.01–3)	0.02 (0–0.05)	0.01 (0–0.02)	0.03 (0.01–0.09)	0.02 (0.01–0.07)
<i>Alkene</i>					
Ethene	6 (0.1–16)	0.1 (0.01–0.4)	0.03 (0.01–0.07)	0.12 (0.02–0.14)	0.08 (0.02–0.2)
Propene	4 (0.04–9)	0.05 (0–0.2)	0.02 (0.01–0.03)	0.07 (0.01–0.2)	0.06 (0.01–0.1)
1-Butene	1 (0.04–3)	0.01 (0–0.02)	0.01 (0–0.02)	0.02 (0–0.04)	0.02 (0.01–0.03)
<i>i</i> -Butene	2 (0.07–5)	0.03 (0.01–0.07)	0.02 (0–0.03)	0.03 (0.01–0.08)	0.04 (0.01–0.1)
<i>trans</i> -2-Butene	2 (0.04–6)	0.02 (0.01–0.03)	0.01 (0–0.03)	0.03 (0–0.06)	0.02 (0.01–0.04)
<i>cis</i> -2-Butene	1 (0.03–3)	0.01 (0.01–0.03)	0.01 (0–0.02)	0.02 (0–0.03)	0.01 (0.01–0.02)
1,3-Butadiene	0.12 (0–0.5)	0 (0–0.01)	0 (0–0)	0 (0–0)	0 (0–0)
1-Pentene	0.09 (0.02–0.2)	0.01 (0–0.02)	0 (0–0.01)	0 (0–0.01)	0 (0–0)
Isoprene	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)
<i>trans</i> -2-Pentene	0.3 (0.07–0.8)	0.02 (0–0.06)	0.01 (0–0.02)	0.01 (0–0.03)	0.01 (0–0.02)
<i>cis</i> -2-Pentene	0.12 (0.03–0.3)	0.01 (0–0.02)	0 (0–0.01)	0 (0–0.02)	0 (0–0)
3-Methyl-1-butene	0.05 (0.01–0.1)	0 (0–0.01)	0 (0–0)	0 (0–0)	0 (0–0)
2-Methyl-1-butene	0.2 (0.03–0.5)	0.01 (0–0.03)	0.01 (0–0.01)	0.01 (0–0.02)	0.01 (0–0.01)
2-Methyl-2-butene	0.25 (0.06–0.7)	0.02 (0–0.05)	0.01 (0–0.02)	0.01 (0–0.03)	0.01 (0–0.02)
<i>Aromatics</i>					
Benzene	0.5 (0.07–1)	0.01 (0–0.01)	0.01 (0–0.01)	0.01 (0–0.01)	0.01 (0–0.02)
Toluene	4 (1–10)	0.1 (0.08–0.3)	0.09 (0.02–0.3)	0.2 (0.02–0.6)	0.2 (0.06–0.6)
Ethylbenzene	0.3 (0.1–0.7)	0.01 (0–0.03)	0.01 (0–0.02)	0.01 (0–0.03)	0.02 (0–0.08)
<i>m</i> -Xylene	0.5 (0.2–1)	0.02 (0–0.04)	0.01 (0–0.03)	0.02 (0–0.05)	0.04 (0–0.1)
<i>p</i> -Xylene	0.3 (0.1–0.7)	0.02 (0–0.04)	0.01 (0–0.02)	0.02 (0–0.04)	0.03 (0–0.09)
<i>o</i> -Xylene	0.3 (0.1–0.7)	0.02 (0–0.05)	0.01 (0–0.02)	0.01 (0–0.03)	0.02 (0–0.08)
<i>i</i> -Propylbenzene	0.03 (0–0.06)	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)
<i>n</i> -Propylbenzene	0.1 (0.02–0.2)	0.01 (0–0.01)	0 (0–0.01)	0 (0–0.01)	0.01 (0.01–0.01)
<i>m</i> -Ethyltoluene	0.4 (0.1–0.7)	0.05 (0.02–0.1)	0.02 (0.01–0.03)	0.03 (0.01–0.07)	0.05 (0.03–0.08)
<i>p</i> -Ethyltoluene	0.2 (0.05–0.3)	0.02 (0.01–0.03)	0.01 (0–0.01)	0.01 (0–0.03)	0.02 (0.01–0.02)
<i>o</i> -Ethyltoluene	0.1 (0.04–0.3)	0.01 (0.01–0.03)	0.01 (0–0.01)	0.01 (0–0.03)	0.02 (0.01–0.02)
1,3,5-Trimethylbenzene	0.2 (0.05–0.4)	0.02 (0.01–0.04)	0.01 (0–0.01)	0.01 (0–0.03)	0.02 (0.01–0.02)
1,2,4-Trimethylbenzene	0.8 (0.3–1)	0.08 (0.03–0.2)	0.03 (0.01–0.05)	0.04 (0.02–0.1)	0.06 (0.03–0.09)
1,2,3-Trimethylbenzene	0.2 (0.06–0.6)	0.02 (0–0.07)	0.01 (0–0.03)	0.01 (0–0.02)	0.02 (0.01–0.02)
Total NMHCs	956 (43–2727)	30 (3–86)	10 (1–22)	9 (3–15)	5 (3–8)
THC (by HC analyzer)	2151 (700–3602)	29 (0–75)	12 (4–18)	7 (3–14)	5 (2–11)

^a Mean (minimum–maximum).

3.2.3. Comparison with other studies

Table 6 compares the emission factors of NMHCs estimated in other studies with this study in Hong Kong. The major species i.e. ethane, propane, *i/n*-butanes emitted from LPG-fuelled taxis in this study are consistent with the observation of Ho et al. (2009). However, our estimation of emission factors was usually one magnitude lower than the tunnel study results (Ho et al., 2009). Compare to the study conducted by Chan et al. (2007), the THC emission factor for LPG-fuelled vehicles in this study (5–29 mg km⁻¹) was also much lower than the results obtained from remote sensing system (92–758 mg km⁻¹).

On the other hand, in both our study and the study carried out by Ho et al. (2009), the emission factors of *i*-pentane, toluene, xylenes and ethane were higher for gasoline-fuelled vehicles. Nevertheless, the emission factors of alkanes and alkenes in this study were generally higher than those reported by Ho et al. (2009), but the emission factor values of aromatics such as toluene, ethylbenzene and xylenes were in line with those estimated by Ho et al. (2009). In term of the emission factor of total hydrocarbons (THC), the value of THC measured in this study was in the lower range of the results obtained by Chan et al. (2007).

3.3. Ozone formation potential of NMHCs

Considering the population density and the need for daily commuting in urban area, the concept of using LPG as the preferred choice of fuel over gasoline has been reported as an effective means to reduce ozone formation potential (OFP) (Chang et al., 2001; Luis et al., 2003; Lai et al., 2009). In this study, the emission data from gasoline-fuelled and LPG-fuelled vehicles provided us the opportunity to compare the OFP values from different types of vehicles.

3.3.1. Gasoline-fuelled private car

Table 7 presents the OFP values of major NMHCs emitted from the gasoline-fuelled private cars at different driving speeds. Please note, NMHC species that made ignorable contributions to OFP values were not listed in the table. Here, the OFP value = emission factor × MIR coefficient with unit of mg-O₃ produced per km. It can be seen that aromatics were the largest contributor (over 80% at idling state) to the total OFP for gasoline-fuelled vehicles, followed

Table 6

Comparison of emission factors of NMHCs (mg km⁻¹) with other studies in Hong Kong.

NMHCs	LPG-fuelled vehicle		Gasoline-fuelled vehicle	
	Other studies	This study ^b	Other studies	This study
Ethane	7.65 ± 2.14 ^a	0.6–2.7	3.08 ± 0.49 ^a	12–34
Ethene	N/A	0.03–0.12	0.21 ± 3.06 ^a	8–20
Propane	36.6 ± 10.1 ^a	1.5–12.9	N/A	0.7–1.0
Propene	N/A	0.02–0.07	1.23 ± 1.78 ^a	2–13
<i>i</i> -Butane	34.1 ± 10.5 ^a	1–6.5	N/A	0.6–2.0
<i>n</i> -Butane	49.6 ± 15.1 ^a	1–6.6	N/A	2–8
<i>i</i> -Pentane	N/A	0.1–0.3	12.3 ± 2.6 ^a	17–44
<i>n</i> -Pentane	N/A	0.02–0.06	3.64 ± 0.75 ^a	4–9
Ethyne	N/A	0.01–0.03	1.67 ± 1.32 ^a	0.06–0.6
Benzene	N/A	0.01–0.01	2.21 ± 1.03 ^a	8–13
Toluene	N/A	0.09–0.2	25.7 ± 3.56 ^a	11–39
Ethylbenzene	N/A	0.01–0.02	3.00 ± 0.43 ^a	2–6
<i>m</i> -Xylene	N/A	0.01–0.04	5.72 ± 0.97 ^a	3–12
<i>p</i> -Xylene	N/A	0.01–0.03	2.26 ± 0.40 ^a	2–7
<i>o</i> -Xylene	N/A	0.01–0.02	3.46 ± 0.68 ^a	2–7
1,2,3-Trimethylbenzene	N/A	0.01–0.02	4.64 ± 1.59 ^a	0.5–1
1,2,4-Trimethylbenzene	N/A	0.03–0.08	8.03 ± 2.65 ^a	2–6
THC	92–758 ^c	5–29	94–1797 ^c	69–209

^a Tunnel study, Ho et al., 2009.

^b The range covers speeds from 25 to 100 km h⁻¹.

^c Remote sensing test, Chan et al., 2007.

by alkenes (~14% at idling state). Among aromatics, high contribution of toluene to the OFP value at all driving speeds was observed, contributing 12–28% to the total OFPs (Table 7). The total OFP value for aromatics at idling state was the highest (804 mg-O₃ produced h⁻¹), 2–5 times that at other driving speeds, whereas the total OFP value for alkenes at 50 km h⁻¹ had the maximum value (495 mg-O₃ km⁻¹), 2–4 times that at other 4 driving speeds. Especially when the driving speed reached 70 km h⁻¹ or above, the total OFPs were 2 times lower than that at lower speeds.

3.3.2. LPG-fuelled taxi

Table 8 shows the OFP values of major NMHCs emitted from LPG-fuelled taxis at different driving speeds. Again, those NMHC species which made negligible contributions to OFP were not shown in the table. Propane and *i/n*-butanes made the most significant contribution (about 80% at idling state and over 82% at 25 km h⁻¹) to the total OFP for LPG-fuelled vehicles. With the increase of steady-state driving speeds, the contributions of the three species to the OFP values decreased from 82% at 25 km h⁻¹ down to 46% at 100 km h⁻¹. On the other hand, the contributions of total aromatics increased from 4% at idling state to 30% at 100 km h⁻¹. By inspecting the total OFP values at different steady-state driving speeds, it was found that the total OFP value at 25 km h⁻¹ (30 mg-O₃ km⁻¹) was the highest, 3–4 times those at other driving speeds. In addition, propane, *i*- and *n*-butane contributed over 76% to the total OFP value at driving speed of 50 km h⁻¹ or below, suggesting that the contribution of unburned LPG to the ground-level O₃ formation was predominant at lower driving speeds.

Table 7

Ozone (O₃) formation potential of major NMHCs emitted from gasoline-fuelled private cars at different driving speeds (OFP = Emission factor × MIR coefficient; emission factor units, mg km⁻¹; MIR units, dimensionless, gram of ozone produced per additional gram of NMHC species. Emission factor unit is mg h⁻¹ at idle state).

Compound	MIR ^a	O ₃ formation potential (mg-O ₃ km ⁻¹)				
		0 km h ⁻¹	25 km h ⁻¹	50 km h ⁻¹	70 km h ⁻¹	100 km h ⁻¹
Ethane	0.31	3.6	6.2	4.4	3.7	10.6
Propane	0.56	0.6	0.6	0.5	0.4	0.5
<i>i</i> -Butane	1.35	1.3	3.0	2.0	1.3	0.9
<i>n</i> -Butane	1.33	3.4	10.0	6.7	3.1	3.6
<i>i</i> -Pentane	1.68	21.2	46.8	63.5	29.9	28.2
<i>n</i> -Pentane	1.54	7.9	11.2	12.4	6.9	5.5
2-Methylpentane	1.8	9.1	26.8	25.8	11.6	10.0
3-Methylpentane	2.07	7.0	19.1	18.1	8.4	7.3
2,2,4-Trimethylpentane	1.44	12.0	39.3	28.7	7.6	11.8
<i>Subtotal</i>		66	163	162	73	78
Ethene	9.08	65.6	69.8	183.7	70.9	96.1
Ethyne	1.25	0.3	0.07	0.07	0.2	0.8
Propene	11.58	35.0	56.4	153.5	23.6	61.1
<i>i</i> -Butene	6.35	23.9	46.8	88.9	16.7	27.7
2-Methyl-2-butene	14.45	11.9	33.1	68.4	9.0	13.5
<i>Subtotal</i>		136	206	495	120	199
Benzene	0.81	16.0	10.3	9.7	6.3	7.4
Toluene	3.97	281.8	111.6	155.4	42.1	68.6
Ethylbenzene	2.79	11.1	17.3	10.9	6.0	4.4
<i>m/p</i> -Xylene	7.43	94.0	147.3	58.3	50.3	31.1
<i>o</i> -Xylene	7.49	34.2	52.5	22.9	20.0	11.3
<i>m</i> -Ethyltoluene	9.37	86.4	28.6	42.1	9.5	14.6
<i>p</i> -Ethyltoluene	3.75	16.6	4.4	6.3	1.6	2.3
<i>o</i> -Ethyltoluene	6.61	22.2	7.0	10.2	2.3	3.5
1,3,5-Trimethylbenzene	11.22	57.1	10.0	25.6	6.8	7.9
1,2,4-Trimethylbenzene	7.18	123.6	31.2	41.3	11.2	14.8
1,2,3-Trimethylbenzene	11.26	61.0	13.3	15.9	5.2	7.2
<i>Subtotal</i>		804	434	399	161	173
<i>Total</i>		1006	803	1056	354	450

^a Data from California Air Resources Board (CARB). <http://www.arb.ca.gov/regact/mir2003/fro.pdf>.

Table 8

Ozone (O₃) formation potential of major NMHCs emitted from LPG-fuelled taxis at different driving speeds (Emission factor unit is mg h⁻¹ at idle state).

Compound	MIR ^a	O ₃ production potential (mg-O ₃ km ⁻¹)				
		0 km h ⁻¹	25 km h ⁻¹	50 km h ⁻¹	70 km h ⁻¹	100 km h ⁻¹
Ethane	0.31	37.2	0.8	0.4	0.4	0.2
Ethene	9.08	54.0	1.1	0.2	1.0	0.8
Ethyne	1.25	1.0	0.02	0.01	0.03	0.02
Propane	0.56	216.2	7.2	2.2	2.1	0.8
Propene	11.58	41.3	0.6	0.2	0.8	0.6
<i>i</i> -Butane	1.35	242.9	8.8	2.6	2.0	1.4
<i>n</i> -Butane	1.33	308.6	8.8	2.8	2.2	1.5
<i>i</i> -Butene	6.35	14.2	0.2	0.1	0.2	0.3
<i>i</i> -Pentane	1.68	11.3	0.5	0.2	0.2	0.2
<i>n</i> -Pentane	1.54	1.5	0.1	0.04	0.04	0.04
Benzene	0.81	0.4	0.01	0	0.01	0.01
Toluene	3.97	14.9	0.6	0.4	0.8	0.8
Ethylbenzene	2.79	0.9	0.04	0.02	0.04	0.07
<i>m/p</i> -Xylene	7.43	6.0	0.2	0.12	0.3	0.5
<i>o</i> -Xylene	7.49	2.4	0.1	0.04	0.1	0.2
<i>m</i> -Ethyltoluene	9.37	3.6	0.5	0.2	0.3	0.4
1,2,4-Trimethylbenzene	7.18	5.8	0.6	0.2	0.3	0.4
Total		962	30	10	10	8

^a Data from California Air Resources Board (CARB). <http://www.arb.ca.gov/regact/mir2003/fro.pdf>.

By comparison, the total OFP values dramatically decreased over 96% at steady-state driving speed if the gasoline-fuelled car was replaced by the LPG-fuelled taxi. However, replacing gasoline-fuelled cars by LPG-fuelled taxis did not necessarily reduce the overall OFP value at idling state (only 4% of the total OFP value was reduced), indicating that the adverse effect of vehicle emission on human health and ground-level O₃ formation can only be reduced by using LPG-fuelled vehicles at steady-state driving speeds. Similar findings were reported by Luis et al. (2003), Chen et al. (2001) and Lai et al. (2009).

3.4. Ratios of NMHC species

Ratios of specific NMHCs are often used to study the NMHC characteristics of vehicle emissions. Hoekman (1992) suggested that ethene and ethyne at molar ratios (E/E ratio) of approximately 2.8:1–6.4:1 from catalyst-equipped cars was indicative of a well functioning catalytic converter. Higher value of E/E ratio suggests that the combustion process is more effective. The ratios of NMHCs emitted from private cars and taxis at different driving speeds were calculated and tabulated in Table 9. The average E/E ratio for the private cars ranged from 10.0 to 25.3, much higher than those measured in Beijing, Taiwan and the United States (0.8–4.3) (Chang et al., 2001; Watson et al., 2001; Lu et al., 2003; Tsai et al., 2003). The high E/E molar ratios for the private cars in this study suggest that on average the gasoline-powered vehicles had efficient operating catalysts. The E/E ratios at lower driving speeds (≤ 50 km h⁻¹) were similar in the emission of the private car (~ 18). The ratio was the lowest at 70 km h⁻¹ (10), whereas the highest E/E ratio of 25.3 was found at 100 km h⁻¹.

The E/E ratios in the emission of taxi at different driving speeds in this study were close to those measured by Chang et al. (2001) in Taiwan, implying that the combustion efficiency of LPG-fuelled taxis in Hong Kong was similar to that in Taiwan. The E/E ratio in the emission of taxi at different driving speeds was about half that in the emission of private car at corresponding driving speeds. The lowest E/E ratio was measured at idling state and the highest E/E ratio was obtained at 100 km h⁻¹ (4.8 and 8.0, respectively).

Toluene/benzene ratio (T/B) has been widely used to characterize emissions from gasoline vehicles. The T/B ratio in the emission of

Table 9

E/E and T/B ratios of emissions from private cars and taxis at different driving speeds.

	Private cars		Taxis
	E/E ratio ^a	T/B ratio ^b	E/E ratio ^a
Idling	18.1	2.9	4.8
25 km h ⁻¹	18.2	2.5	5.2
50 km h ⁻¹	18.4	4.7	4.9
70 km h ⁻¹	10.0	3.2	5.9
100 km h ⁻¹	25.3	2.6	8.0

^a E/E: Ethene/ethyne.

^b T/B: Toluene/benzene.

private car varied from 2.5 to 4.7 among different driving speeds. The highest toluene and lowest benzene contribution at 50 km h⁻¹ resulted in the highest T/B ratio among the 5 driving speeds. The T/B ratios measured in this study were similar to those found in Taiwan (Tsai et al., 2003), but higher than those observed in Beijing and the United States (Watson et al., 2001; Lu et al., 2003). Toluene is used as an unleaded gasoline additive to increase the octane number in Hong Kong. Our previous study found that the toluene content in the gasoline fuel used in Hong Kong was as high as 21% (Tsai et al., 2006), while the benzene content in gasoline fuel was restricted from 5% to 1% in 2001 (HKEPD, 2001). This high toluene and low benzene content in gasoline fuel in Hong Kong led to high toluene/benzene ratio in gasoline-fuelled vehicle emission.

4. Summary and conclusions

In order to study the effect of driving speed on the NMHC emissions, six private cars and four taxis were chosen to represent gasoline- and LPG-fuelled vehicles in this study. The tested vehicles were driven on a chassis dynamometer at idling state and 4 different steady speeds, and air samples were collected at the exhaust tailpipe using clean and evacuated canisters. A total of 51 NMHCs were analyzed and reported.

In the emission of gasoline-fuelled private car, no significant differences in the weight percent contribution ($p > 0.05$) were found for each species except ethane. The dominant species for private car were ethane, *n*-butane, *i*-pentane, *n*-pentane, 2,2,4-trimethylpentane, ethene, benzene, toluene, *m/p*-xylene and 1,2,4-Trimethylbenzene among the driving speed ranges. On the other hand, the most abundant species emitted from LPG-fuelled taxi were propane, *i/n*-butanes and ethane, and the emission of unsaturated hydrocarbons and aromatics increased with the increase of driving speed. Uniquely, the contribution of ethane in Hong Kong was much higher than that in Taiwan, Beijing and Guangzhou. By comparison, the total NMHC concentrations in LPG-fuelled taxi emissions were much lower than those in gasoline-fuelled vehicle emissions. In addition, analysis found that there were no statistical differences in emission factor for each species among different driving speeds for gasoline-fuelled cars. Saturated hydrocarbon species such as ethane, *n*-butane, *i/n*-pentanes, methylpentanes, trimethylpentane, and aromatics i.e. benzene and toluene, were found to have high emission factor for private cars. On the other hand, the emission factors of C₂–C₄ saturated hydrocarbons were significantly higher than that of other NMHC species at the corresponding driving speeds for LPG-fuelled taxi, and the emission factor of major NMHC species emitted from the LPG-fuelled vehicle decreased significantly from low driving speed i.e. 25 km h⁻¹ to high speed i.e. 50 km h⁻¹ and then remained unchanged at higher speeds such as 70 and 100 km h⁻¹.

The ozone formation potential (OFP) of individual NMHCs for gasoline-fuelled and LPG-fuelled vehicles were assessed. Aromatics particularly toluene were the major contributors to OFP for gasoline-fuelled vehicles whereas C₂–C₄ alkanes made the most

significant contribution to OFP for LPG-fuelled taxi. Remarkably, the total OFP value for LPG-fuelled taxi was significantly reduced when the driving pattern was changed from idling state to steady-state driving speeds.

The large variations of E/E ratio reflected the different efficiency of catalytic converters installed in the private cars. In comparison, the E/E ratio for taxis had smaller variation than that of private cars. The largest E/E ratio was also obtained at 100 km h⁻¹ for taxis, suggesting the highest combustion efficiency at this driving speed. In addition, the maximum T/B ratio was measured at driving speed of 50 km h⁻¹ due to the decreased contribution of benzene.

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