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ScienceDirect

Journal of Environmental Sciences 2011, 23(3) 419–426

JOURNAL OF
ENVIRONMENTAL
SCIENCES
ISSN 1001-0742
CN 11-2629/X
www.jesc.ac.cn

On-road pollutant emission and fuel consumption characteristics of buses in Beijing

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Received 08 April 2010; revised 31 May 2010; accepted 12 June 2010

Abstract

On-road emission and fuel consumption (FC) levels for Euro III and IV buses fueled on diesel and compressed natural gas (CNG) were compared, and emission and FC characteristics of buses were analyzed based on approximately 28,700 groups of instantaneous data obtained in Beijing using a portable emissions measurement system (PEMS). The experimental results revealed that NOx and PM emissions from CNG buses were decreased by 72.0% and 82.3% respectively, compared with Euro IV diesel buses. Similarly, these emissions were reduced by 75.2% and 96.3% respectively, compared with Euro III diesel buses. In addition, CO_2, CO, HC, NOx, PM emissions and FC of Euro IV diesel buses were reduced by 26.4%, 75.2%, 73.6%, 11.4%, 79.1%, and 26.0%, respectively, relative to Euro III diesel buses. The CO_2, CO, HC, NOx, PM emissions and FC factors all decreased with bus speed increased, while increased as bus acceleration increased. At the same time, the emission/FC rates as well as the emission/FC factors exhibited a strong positive correlation with the vehicle specific power (VSP). They all were the lowest when VSP < 0, and then rapidly increased as VSP increased. Furthermore, both the emission/FC rates and emission/FC factors were the highest at accelerations, higher at cruise speeds, and the lowest at decelerations for non-idling buses. These results can provide a base reference to further estimate bus emission and FC inventories in Beijing.

Key words: vehicle specific power; PEMS; driving modes; fuel consumption factors

DOI: 10.1016/S1001-0742(10)60426-3

Citation: Wang A J, Ge Y S, Tan J W, Fu M L, Shah A N, Ding Y et al., 2011. On-road pollutant emission and fuel consumption characteristics of buses in Beijing. Journal of Environmental Sciences, 23(3): 419–426

Introduction

In recent years, bus population has experienced an exponential growth in Beijing. The number of in-use buses increased from 25,368 at the end of 2007 to 28,071 at the end of 2008. Furthermore, a total of annual passenger trips had exceeded 4.8 billion by the end of 2009 (BPT, 2010). However, with the increase in bus population and activity, bus emission and fuel consumption (FC) problems are becoming more and more serious. Since buses are mainly driven in the urban areas, their emissions greatly affect the pubic health. Despite significant improvements in fuel and engine technology, on-road buses in Beijing continue to be one of the primary sources of the urban pollution, and their FC issues are still very serious. Vehicle emissions and FC depend on many factors, such as vehicle design, maintenance, operating modes, ambient conditions, emission standards, fuel properties, driver behaviors, the number of stops, vehicle load, road grade, traffic control measures (Unal et al., 2004; Ang and Fwa, 1989; Wang et al., 2008). Among these factors, vehicle driving conditions, such as speed, acceleration and road grade, are highly associated with FC and emissions (El-Shawarby et al., 2005; Zhang and Frey, 2006; Chen et al., 2007; John et al., 1999; Joumard et al., 2000; Chan et al., 2004; Li et al., 2009). Therefore, it is necessary to analyze the on-road bus emission and FC characteristics to accurately estimate the bus emissions and FC.

Currently, four main methodologies, namely laboratory dynamometer measurement, tunnel testing, roadside remote sensing and on-road measurement, are being used around the globe for vehicle emission and FC measurements. Laboratory dynamometer measurement method is used to determine the vehicle emissions and FC by simulating the on-road driving conditions on a chassis

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dynamometer or engine dynamometer in laboratory. This measurement method is accurate, reliable and with good repeatability. Nevertheless, its driving cycles may not be representative of actual on-road vehicle driving conditions. Tunnel testing is used to determine the average emissions and FC of all of vehicles passing through the tunnel. Tunnel testing device is easy to operate, and the data obtained can represent the real-world vehicle emission and FC characteristics in the tunnel. But the results of this testing can not represent the on-road vehicle emission and fuel-consumption levels in the real traffic networks where vehicle driving conditions are different from those in the tunnel. Furthermore, emission data collected by the tunnel testing device can not be classified on the basis of fuel type, vehicle technology, emission standards, etc. Roadside remote sensing is based on an infrared absorption principle to measure the emissions of vehicles traveling down the road. Remote sensing device can measure the on-road emissions of a large number of vehicles very fast and automatically, under real-world driving conditions per day without any interference with the normal traffic. But roadside remote sensing can not be used at any locations of interest, such as those locations close to intersections or across the multiple lanes of heavy traffic, due to the difficulties in placing the remote sensing device. Thus, it provides an instantaneous estimate of vehicle emissions only at specific locations. On-road emission measurement using a portable emissions measurement system (PEMS) has been proven to be a convenient, efficient and reliable emission measurement approach. On-road emission testing instruments are placed in the tested vehicles, and thus can collect instantaneous tailpipe emission, FC and driving pattern data from the vehicles under actual on-road driving conditions at any location and time. Compared with other testing methodologies, on-road emission measurement can represent reliably real-world changes in vehicle emissions and FC as a result of variations in vehicle location, vehicle driving modes, driver behaviors, etc. Furthermore, it is a unique technology which can quantify the impacts of real-world driving parameters on emissions and FC. In recent years, many scholars have applied this approach to study the actual on-road vehicle emissions (De Vlieger, 1997; Holmén and Niemeier, 1998; Hart, 2002; Du et al., 2002). However, in China, most of the on-road emission studies have been focused on light-duty vehicle; few studies regarding on-road emissions and FC of buses have been made.

The objective of this study was to test on-road emissions and FC of the heavy-duty buses in Beijing using a PEMS. The main aims of this research were to compare emission and FC levels of different buses in Beijing; analyze the impacts of bus speed, acceleration and vehicle specific power (VSP) on pollutant emissions and FC; evaluate the effect of different driving modes on emissions and FC. The results can be used to provide a reference/basis for developing bus emission and FC models, and, thus controlling the emissions and FC scientifically and effectively.

1 Experimental

1.1 On-road emission measurement system

A PEMS was used to test the on-road bus emissions and FC in Beijing. The system includes a SEMTECH-DS portable emission analyzer, an Electrical Low Pressure Impactor (ELPI) and some accessories. The SEMTECH-DS analyzer was used to test instantaneous gaseous emissions and FC. It includes a heated flame ionization detector (FID) with an accuracy of ±2% of reading used to measure THC, a Non-dispersive infrared (NDIR) analyzer with an accuracy of ±3% of reading used to measure CO and CO_2, a Non-dispersive ultraviolet (NDUV) analyzer with an accuracy of ±3% of reading used to measure NO_x, an Electrochemical sensor with an accuracy of ±1% oxygen used to measure O_2, a remote weather probe used to monitor ambient temperature, pressure and relative humidity, a Global positioning system (GPS) used to record second-by-second vehicle location, altitude and speed data, and an Exhaust flow meter (SEMTECH EFM) used to measure vehicle or engine exhaust flow, etc. The instantaneous mass emissions for gaseous pollutants are calculated by SEMTECH-DS and post-processor application software based on the exhaust flow and pollutant concentrations. The instantaneous FC is calculated by SEMTECH-DS and post-processor application software with carbon balance method on the basis of CO_2, CO, THC emission data. Before measurement, standard gases were used to verify the accuracy of the instruments and set the target pollutants to zero (Shahinian, 2007). The SEMTECH-DS analyzer has been reported to be accurate and precise in some studies (Durbin et al., 2007; Dearth et al., 2005). The ELPI was used for real-time monitoring of aerosol particle size distribution and providing second-by-second PM emission data with a minimum response time of less than 5 sec. This instrument can measure airborne particle size distribution in the size range of 7 nm to 10 μm. It consists of three main components: a corona charger, low-pressure cascade impactor and multichannel electrometer. Before testing, the instrument must be zeroed (Keskinen et al., 1992). The ELPI has proven to be an accurate and efficient instrument for second-by-second PM emission measurement (Marjamäki et al., 2000).

1.2 Test methods

Six tested buses were used, including two Euro III diesel, two Euro IV diesel and two compressed natural gas (CNG) buses, which were representative of bus technology types in Beijing. Before each experiment, a large number of bottles of water as well as operators and instruments were placed in the test buses to simulate the weight of 2/3 of full bus weight and the target pollutants were zeroed. During the experiments, the buses were driven by professional drivers and skillful operators were arranged to carry out the testing. Table 1 gives the detailed information regarding the test buses.

In order to keep consistent with Beijing bus typical driving cycle (Wang, 2008), three typical routes were

Table 1 Detailed information regarding the test buses

No.	Vehicle length (m)	Engine displacement (L)	Kilometer traveled (km)	After-treatment device	Fuel type	Emission standard
1	12	5.9	78,260	None	Diesel	Euro III
2	12	5.9	81,621	None	Diesel	Euro III
3	12	6.7	59,220	SCR	Diesel	Euro IV
4	12	6.7	42,897	SCR	Diesel	Euro IV
5	12	5.9	40,336	Oxidation catalyst	CNG	Euro IV
6	12	5.9	39,823	Oxidation catalyst	CNG	Euro IV

Table 2 Pollutant emission and fuel consumption (FC) factors for all the test buses

No.	CO_2 (g/km)	CO (g/km)	NOx (g/km)	HC (g/km)	PM (g/km)	FC (g/km)
1	1128.1769	6.7032	12.0952	0.1358	2.9554	358.3696
2	1084.7942	4.7838	12.7720	0.1913	3.0857	346.4386
3	798.9498	1.3107	11.9665	0.0478	0.4085	255.6976
4	830.4300	1.5333	10.0575	0.0384	0.8534	266.0872
5	1133.4852	4.1381	3.2197	0.2495	0.0057	414.8291
6	1127.7820	12.7168	2.9514	1.0097	0.2178	423.5086

selected, which included arterials, residential streets and freeways. The FC and emission data were obtained during the experiment. The measurement time consisted of three periods: 7:00–9:00 am, 11:00 am–1:00 pm and 5:00–7:00 pm, designed to represent the peak and non-peak hours of city traffic.

1.3 Data collection

Approximately 28,700 groups of second-by-second valid data including vehicle instantaneous speeds, FC, CO_2, CO, THC, NOx and PM emissions were obtained for six heavy-duty tested buses. In this study, the engine-size parameter is assumed not to effect emissions and FC, since the engine sizes of the test buses are roughly same, and the buses are meeting required standards.

2 Results and discussion

2.1 Comparison of emissions and fuel consumption of the test buses

Table 2 summarizes the emission and FC levels in terms of their factors of all the test buses. It can be found that the emissions and FC factors are remarkably lower for Euro IV diesel buses with selective catalytic reduction (SCR) devices, compared with Euro III diesel buses without any exhaust after-treatment devices. From Euro III to Euro IV category, the average CO_2, CO, HC, NOx, PM emissions and FC of the diesel buses are decreased by 26.4%, 75.2%, 73.6%, 11.4%, 79.1% and 26.0%, respectively. In addition, the NOx and PM emissions of buses are significantly decreased due to the use of CNG. The average NOx and PM emissions emitted from CNG buses are very lower, relative to all the diesel buses. They are reduced by 72.0% and 82.3% respectively, compared with Euro IV diesel buses. Similarly, they are abated by 75.2% and 96.3% respectively, compared with Euro III diesel buses. The results show that the use of either CNG or SCR technologies in buses significantly contributes to reduce conventional diesel FC and emissions, and thus meet more stringent emission standards.

2.2 Effects of bus speed and acceleration on pollutant emissions and FC

2.2.1 Effect of speed on pollutant emissions and FC

To analyze the impact of bus cruise speed on pollutant emissions and FC, we select No. 2 Euro III diesel, No. 4 Euro IV diesel and No. 5 CNG buses (Table 1) as the examples to reveal the relationships among emissions, FC and speed. Figure 1 clearly demonstrates that the emission and FC factors decrease rapidly at first and then slowly as speed increases. The emission factors of CO_2, CO, HC, NOx and PM as well as FC factors are maximal in the speed range of 0–10 km/hr. For example, the average NOx emission factor of No. 2 Euro III diesel bus in the speed range of 0–10 km/hr is 44.32 g/km, which is about 8 times of that in the speed range of > 40 km/hr. With an increase of speed from 0–10 km/hr to 10–20 km/hr, the emission factors of CO_2, CO, HC, NOx and PM as well as FC factors decrease rapidly by 49.9%, 39.9%, 43.2%, 64.0%, 65.2%, 49.6%, respectively. Subsequently, the decreasing trend begins to slow down. The results show that low-speed operations of bus results in higher emission and FC factors. So bus drivers should avoid low-speed operations to reduce bus per kilometer emissions and FC.

In addition, Fig. 1 shows that the emission and FC factors of Euro IV diesel bus are lower compared to Euro III diesel bus, and that PM and NOx emission factors of CNG bus are the lowest among the three test buses.

2.2.2 Effect of acceleration on pollutant emissions and FC

Figure 2 illustrates the variations in bus emission and FC factors with the increase in acceleration in the same speed ranges. It can be seen that acceleration, especially sharp acceleration, increases emission and FC factors significantly although the effect of deceleration is of less significance. In the same speed range, most of the emission and FC factors in the deceleration mode are the lowest and remain constant. From deceleration to cruise speed, and to acceleration, emission and FC factors increase rapidly as acceleration increases. Furthermore, the emission and FC

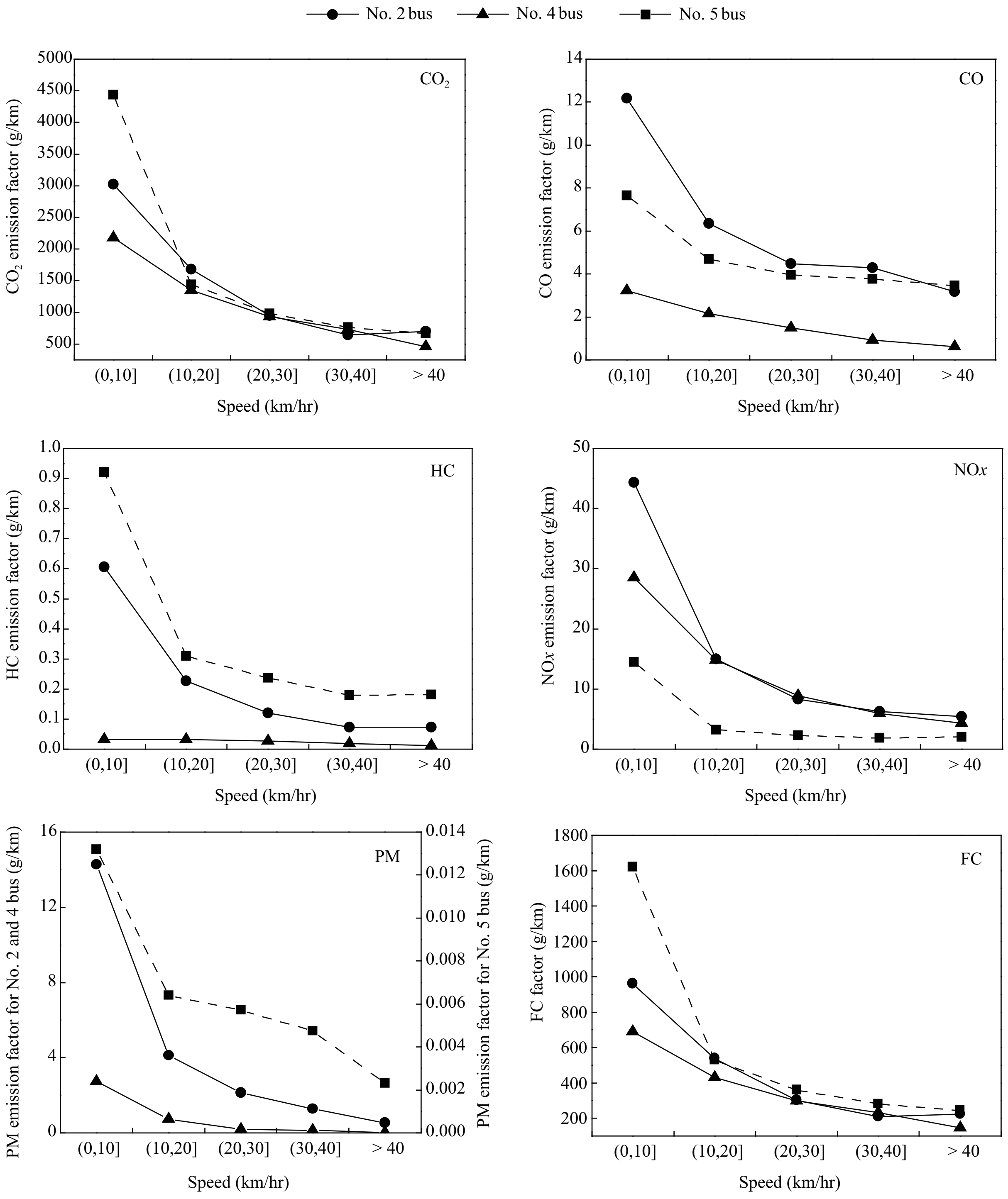

Fig. 1 Effect of speed on pollutant emissions and FC for Euro III diesel, Euro IV diesel and CNG buses.

factors in the same acceleration range all decrease as speed increases. The emission and FC factors are highest in the low-speed and high-acceleration range (speed 0–10 km/hr; acceleration > 0.3 m/sec^2). The maximum values of the emission factors of CO_2, CO, HC, NOx and PM as well as FC factors are 2.2, 1.2, 1.7, 2.4, 2.4 and 2.2 times of those at cruise speeds under the same speed, respectively. Similarly, the maximum values of the emission factors of CO_2, CO, HC, NOx and PM as well as FC factors are 6.7, 3.6, 3.6, 7.8, 8.4 and 6.5 times of those at deceleration under the same speed, respectively. The analysis reveals that the low-speed or high-acceleration operations lead to higher emission and FC levels. So buses should avoid operating at low speeds or high accelerations to improve their emission and FC levels.

2.3 Effect of vehicle special power (VSP) on pollutant emissions and FC

VSP is the power demand on the engine per unit vehicle mass. This parameter represents the tractive power exerted by a vehicle to move itself and its cargo or passengers. VSP for buses were estimated based on typical coefficient values which are representative of the types of buses used in the study (Andrei, 2001; Zhai et al., 2006; Frey et al.,

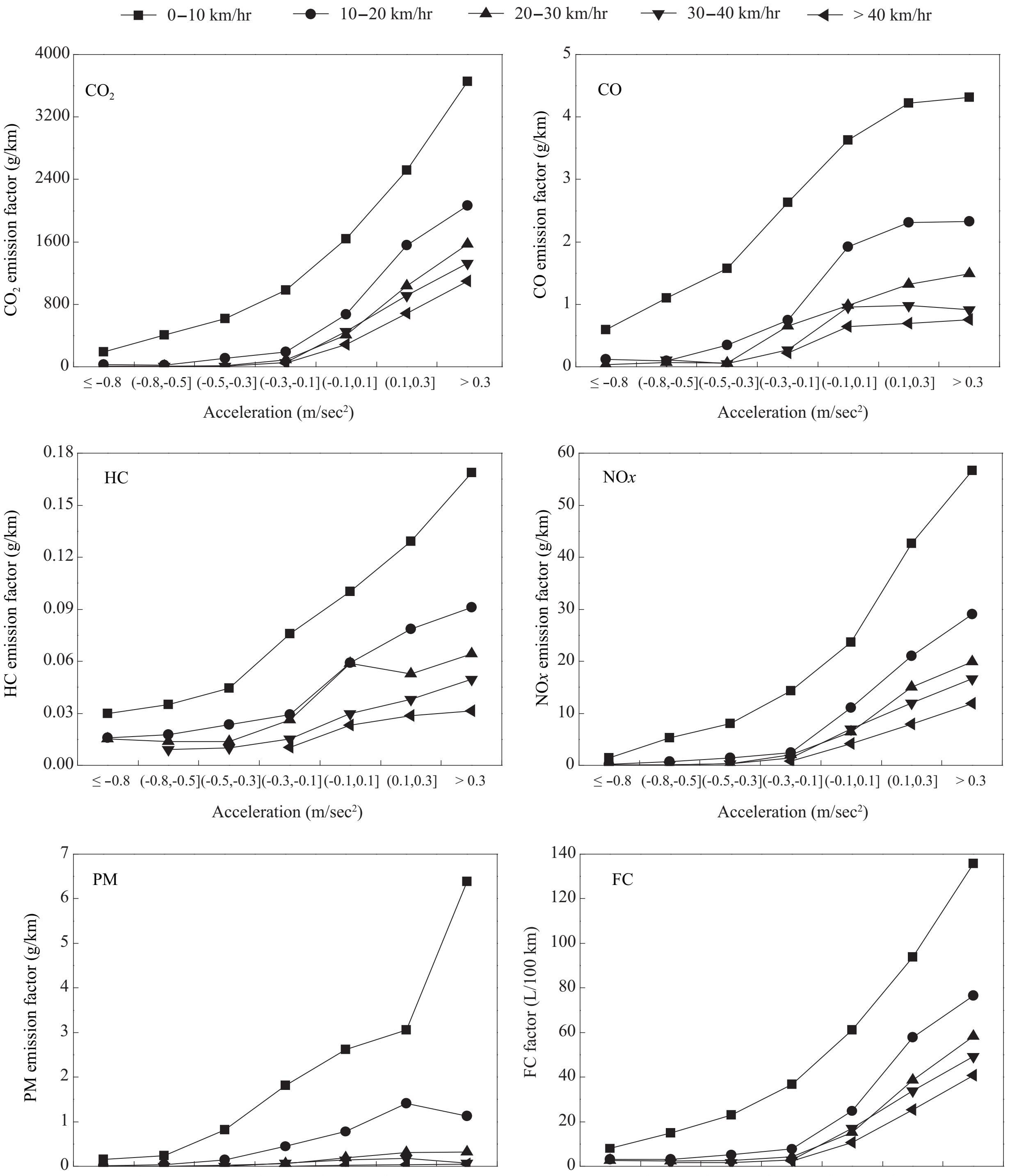

Fig. 2 Effect of acceleration on pollutant emissions and FC of No. 3 bus in each speed range.

2007):

$$\mathrm{VSP} = v \times (a + 9.81\sin(\varphi) + 0.092) + 0.00021v^3 \qquad (1)$$

where, VSP (kW/ton) is the vehicle specific power; ν (m/sec) is the instantaneous speed at which the vehicle is traveling; α (m/sec^2) is the instantaneous acceleration of the vehicle; φ is the instantaneous road grade (decimal fraction); 0.092 is the rolling resistance coefficient; and 0.00021 is the drag coefficient.

Figure 3 shows that not only CO_2, CO, HC, NOx, PM emission rates and FC rates but also the corresponding emission factors and FC factors have similar increasing trends as VSP increases. The emission and FC rates as well as the emission and FC factors are the lowest when VSP < 0. Hereafter, they all increase rapidly as VSP continues to increase. In general, the emission/FC rates and emission/FC factors present strong correlations with VSP. Moreover, the FC rates and factors, and CO_2 and NOx emission rates and factors exhibit their linear trends with VSP when VSP > 0. Therefore, the VSP as a function of

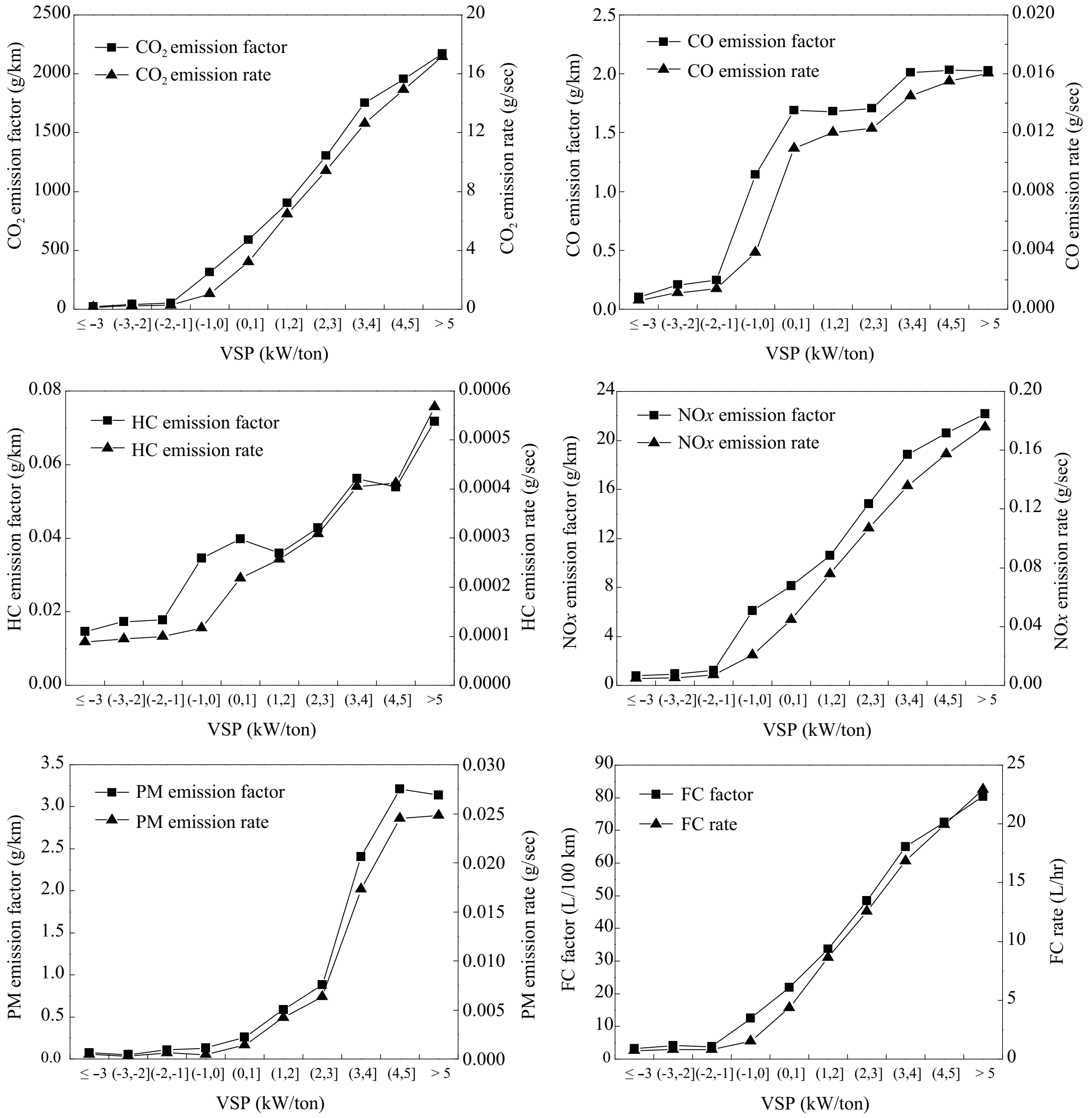

Fig. 3 Effect of vehicle special power (VSP) on pollutant emissions and FC.

speed, acceleration and road grade can be used to quantify bus emissions and FC, and thus model bus emission and FC characteristics under the different driving conditions.

2.4 Effect of driving modes on pollutant emissions and FC

The contributions of No. 2, 3 and 5 buses to the pollutant emission and FC in different driving modes are illustrated in Fig. 4. It can be seen that the contributions to the emissions and FC are the highest at accelerations, the moderate at cruise speeds and the lowest at decelerations for the non-idling buses. The average emissions/FC rates for CO_2, CO, HC, NOx and PM as well as fuel in acceleration mode are 1.38–2.03, 1.47–1.77, 1.46–1.9, 1.5–2.05, 1.13–2.12 and 1.38–1.97 times of those in cruise-speed mode respectively, while 4.41–9.04, 3.9–7.52, 2.14–7.93, 3.15–9.69, 1.73–4.73 and 4.2–8.07 times of those in deceleration mode, respectively. Similarly, the average emission/FC factors of CO_2, CO, HC, NOx, PM and fuel in acceleration mode are 1.62–2.43, 1.75–2.32, 1.81–2.23, 1.77–2.45, 1.33–2.53 and 1.62–2.36 times of those in cruise-speed mode respectively, while 4.29–8.71, 3.91–7.0, 2.08–7.38, 3.07–9.34, 1.61–4.6 and 4.09–7.78 times of those in deceleration mode, respectively. The acceleration of buses results in thicker fuel-air mixtures and worse combustion situations, which in turn cause higher emissions and FC. The frequent acceleration, especially sharp acceleration, will increase the emissions and FC. So the improvements in traffic conditions and the reduction in frequency of acceleration and deceleration will be very beneficial to reduce bus emissions and FC.

3 Conclusions

By studying the on-road emission and FC characteristics of three kinds of typical buses (Euro III diesel, Euro IV

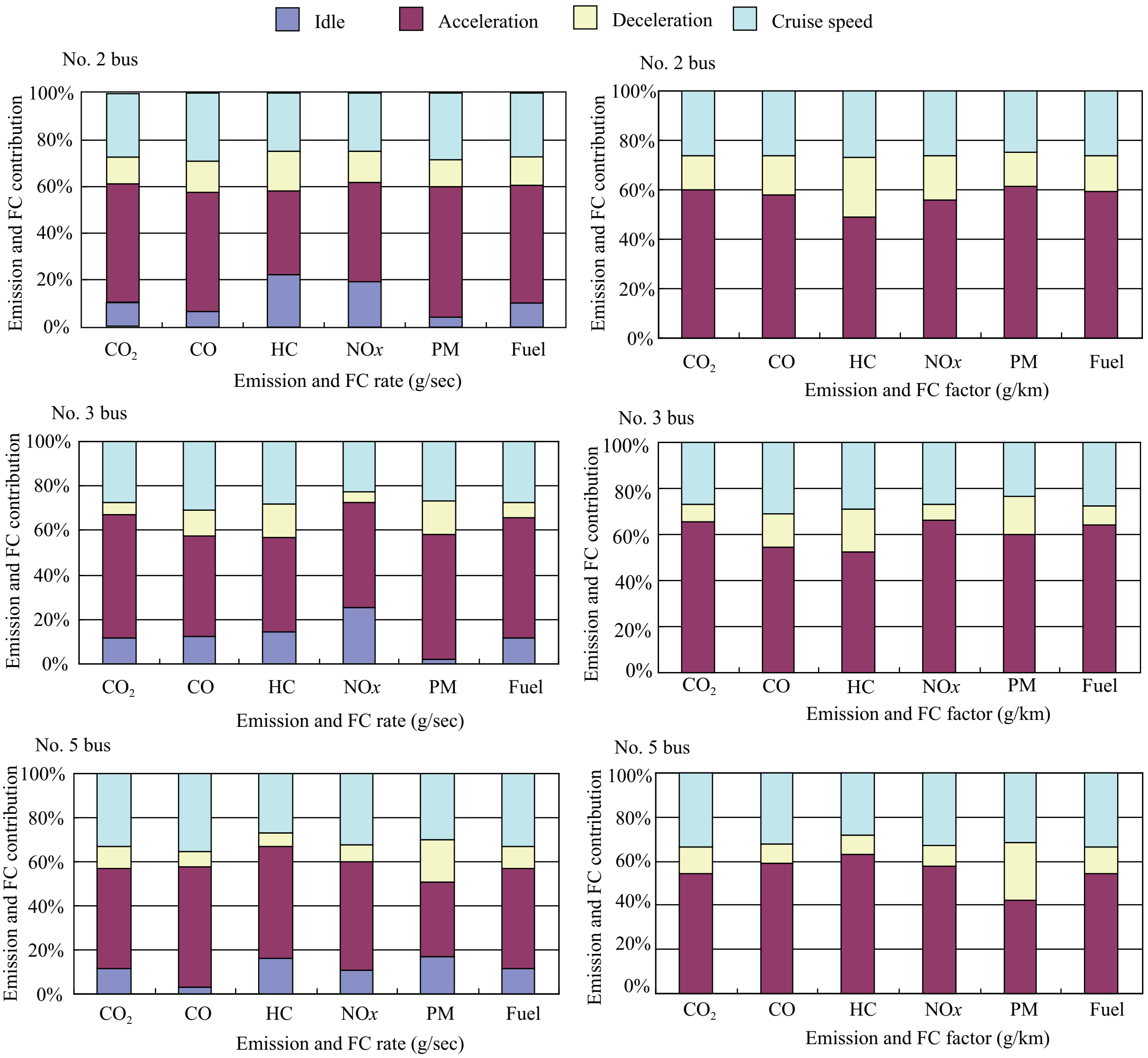

Fig. 4 Contributions of various driving modes to pollutant emissions and FC for No. 2, No. 3 and No. 5 buses.

diesel and CNG buses) based on the driving patterns, the following conclusions can be drawn.

(1) The advanced SCR technology has successfully improved diesel bus emissions and FC. Meanwhile, the use of CNG as an alternative to diesel fuel in buses has not only avoided the diesel FC, but also significantly reduced the NO*x* and PM emissions.

(2) The emission factors of CO_2, CO, HC, NO*x* and PM as well as FC factors for Euro III diesel, Euro IV diesel and CNG buses are closely related to speed and acceleration. They all decrease as speed increases. In addition, they all increase as acceleration increases. The acceleration, especially sharp acceleration, significantly increases bus emissions and FC although the effect of deceleration is of less significance. The low-speed or acceleration operations can easily lead to higher emission and FC levels. But bus low-speed or acceleration operations occur frequently due to serious traffic congestion in Beijing. So relieving traffic congestion will be helpful to reduce bus emissions and FC.

(3) Both the emission/FC factors and the corresponding emission/FC rates for CO_2, CO, HC, NO*x*, PM and fuel present similar changing trends as a result of the variations of VSP.

(4) Instantaneous emission/FC rates and emission/FC factors of buses are the highest at acceleration, higher at cruise speed and the lowest at deceleration for non-idling buses. The frequent acceleration, especially sharp acceleration, will increase the emissions and FC. Thus, the improvements in traffic conditions and reduction in frequency of acceleration and deceleration will significantly contribute to reduce bus emissions and FC.

Acknowledgments

This work was supported by the State Key Laboratory of Engines (No. 200906) and the National Natural Science Foundation of China (No. 40805053).

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