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On-road emission characteristics of heavy-duty diesel vehicles in Shanghai

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Abstract

On-road vehicle tests of nine heavy-duty diesel trucks were conducted using SEMTECH-D, an emissions measuring instrument provided by Sensors, Inc. The total length of roads for the tests was 186 km. Data were obtained for 37,255 effective driving cycles, including 17,216 on arterial roads, 15,444 on residential roads, and 4595 on highways. The impacts of speed and acceleration on fuel consumption and emissions were analyzed. Results show that trucks spend an average of 16.5% of the time in idling mode, 25.5% in acceleration mode, 27.9% in deceleration mode, and only 30.0% at cruise speed. The average emission factors of CO, total hydrocarbons (THC), and NO_x for the selected vehicles are (4.96 ± 2.90), (1.88 ± 1.03) and (6.54 ± 1.90) $g\,km^{-1}$, respectively. The vehicle emission rates vary significantly with factors like speed and acceleration. The test results reflect the actual traffic situation and the current emission status of diesel trucks in Shanghai. The measurements show that low-speed conditions with frequent acceleration and deceleration, particularly in congestion conditions, are the main factors that aggravate vehicle emissions and cause high emissions of CO and THC. Alleviating congestion would significantly improve vehicle fuel economy and reduce CO and THC emissions.

Keywords: Heavy-duty diesel vehicles; On-road emission testing; SEMTECH-D; Shanghai; Traffic congestion

1. Introduction

Since the 1990s China's vehicle population has been increasing rapidly, and the annual rate of increase has averaged 10%. China had more than 16 million vehicles in 2000 (NBS, 2001), which is 2.9 times the vehicle population in 1990. Vehicle emissions have become a major source of urban air pollution in China (Mayer, 1999; Xie et al., 2000). To develop strategies for reducing vehicle emissions, research studies have been carried out in Beijing and Shanghai (Tsinghua University and others, 1997; SAES, 1997). Also, the MOBILE vehicle emission model (US EPA, 2002) has been used to study the vehicle emission characteristics of Beijing, Guangzhou, and Nanjing (Fu et al., 1997,

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2000; Zhu, 1997; He et al., 1998; Li et al., 2001), and it has been possible to create vehicle emission inventories using the model results (Hao et al., 2000; Reynolds and Broderick, 2000; Li et al., 2003).

To investigate the actual emission features of China's vehicle fleet, however, emission testing is necessary. Chassis dynamometer testing is a sound way to develop actual vehicle emission factors, and this approach has been widely used (Tao et al., 2003; Behrentz et al., 2004; El-Shawarby et al., 2005). This method is also used now in China. Vehicle driving-cycle surveys were conducted in Shanghai and Beijing since the mid-1990s (Chen et al., 1996, 1997; Dai et al., 1997; Zhou et al., 2000). In addition, these researchers carried out emission-factor tests of light-duty vehicles on chassis under actual vehicle driving-cycle conditions in Shanghai and Beijing. Deng and Shi (1999) tested light-duty vehicle emission factors on chassis according to ECE-15 driving conditions. On-road vehicle emissions testing by a portable emission measurement system (PEMS) has also proven to be a convenient and efficient approach. In an important pilot study, the California Air Resources Board (CARB, 1996) developed a methodology for on-road vehicle emission measurements. Subsequently, De Vlieger (1997), Holmen and Niemeier (1998), and Hart (2002) utilized on-road tests to study actual vehicle emissions in the real world. In China, Du et al. (2002) studied minivan emission characteristics under real-road conditions using an on-board emissions testing system. These research studies contributed a lot to the understanding of China's vehicle emissions and the design of appropriate strategies for emissions control.

However, due to the limitations of equipment and technology, these research studies mainly focused on light-duty vehicles. Current techniques can approximate the emission conditions of light-duty vehicles, but we know little about the emissions of heavy-duty vehicles and even less about heavy-duty diesel vehicle emissions. The Mobile Heavy-duty Diesel Emissions Laboratory developed by the University of California at Riverside (UCR) now makes it possible to do on-road heavy-duty vehicle emission testing (Norbeck et al., 2001; Cocker et al., 2004; UCR, 2005); however, such state-of-the-art test equipment is not available in China at present. In order to better understand the emission characteristics of heavy-duty vehicles, we have applied on-board diesel-vehicle emission testing equipment to do on-road heavy-duty vehicle emission testing, in collaboration with the World Resources Institute, US EPA, and UCR. In this way, we are able to generate basic data for Shanghai that can be used to develop medium- and long-term emission control strategies for heavy-duty vehicles, with broader implications for China as a whole.

2. Materials and methods

2.1. Road testing

Experiments were carried out in Shanghai on an urban highway (the Shanghai outer-ring road), an arterial road (Cao Bao Road), and several residential roads. The total effective length of the roads selected was 31.08 km, among which the urban highway length was 5.59 km, the arterial road was 14.35 km, and the residential roads were 11.14 km. The composition of our testing roads is similar to the actual distribution of road classes in Shanghai. We randomly selected nine heavy-duty diesel vehicles for this research, most of them under 5 years of age at the time of testing. The tested trucks are of the kind most frequently used in Shanghai and are representative of the truck fleet, since these types are among the top ones sold in the Chinese truck market. A description of these vehicles is presented in Table 1, including vehicle weight, load weight, and engine power. In 2006, the mileages of the vehicles are between 80,000 and 200,000 km, which are typical of such vehicles in Shanghai.

All the vehicles tested in this study were tested in the same way at the same time during working days, along the same lengths of the same testing roads. As the recharging process of the portable emission measurement system (PEMS) battery took 8 h after completing the daytime measurements, we were not able to measure emissions during the night. It can be expected that the vehicle driving pattern during the night will be different, since there will be less acceleration, deceleration, and congestion than during the day. The higher speed of the vehicles during the night should cause higher NO_x emissions and fewer CO and THC emissions, compared with emissions in the daytime.

2.2. Testing equipment

We used the SEMTECH-D (Sensors, Inc., http://www.sensors-inc.com/semtechd.htm) on-board vehicle emission testing equipment to carry out the

Table 1
Basic information on the trucks selected for emissions testing

Truck ID number	Weight (t)	Load (t)	Total weight (t)	Fuel type	Engine	Manufacturer	Engine power (kW)	Year of manufacture	Vehicle distance traveled (km)
1	3.4	3.0	6.4	Diesel	4105	Jianghuai	65	2002	78,240
2	5.0	6.9	11.9	Diesel	109233	Dongfeng	95	2001	107,298
3	3.0	2.0	5.0	Diesel	4110	Jiefang	70	1999	200,000
4	4.0	4.0	8.0	Diesel	6110	Jiefang	107	2001	149,000
5	3.0	3.0	6.0	Diesel	4102	Yuejin	50	2000	84,000
6	5.0	5.0	10.0	Diesel	E020820 1360	Dongfeng	100	2002	>100,000
7	5.2	8.0	13.2	Diesel	6113	Jiefang	175	2001	172,251
9	4.8	5.0	9.8	Diesel	6102	Dongfeng	96	1999	244,350
10	10.0	5.0	15.0	Diesel	6110	Jiefang	125	2002	162,067

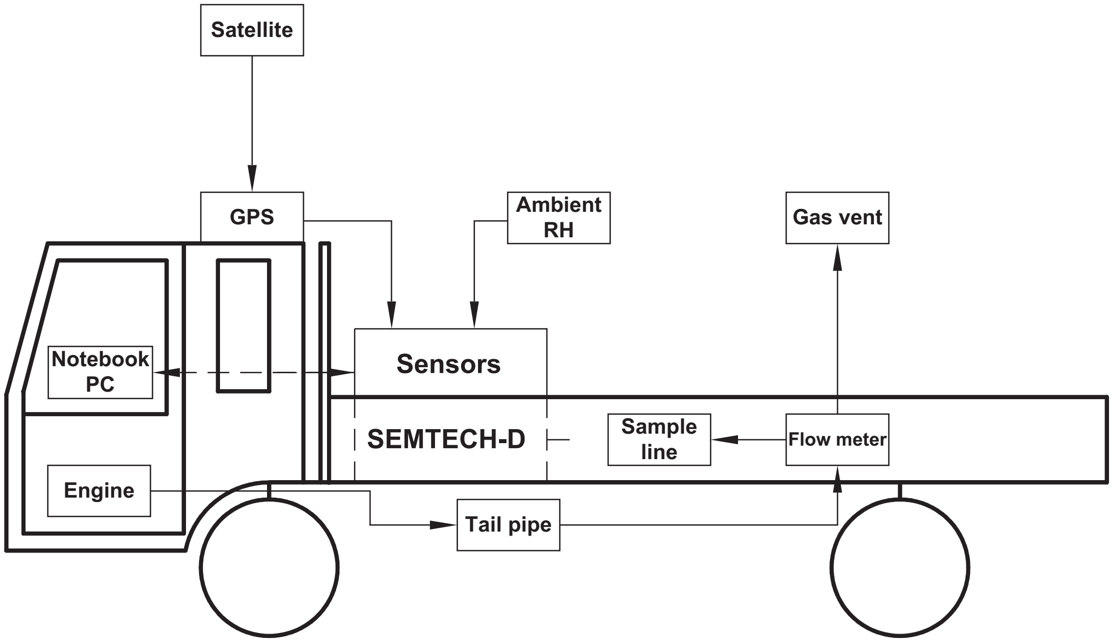

Fig. 1. Sketch of real-world vehicle emission measurement system.

heavy-duty diesel vehicle emissions testing. Non-dispersive infrared analysis (NDIR) was used to measure CO and CO_2 emissions, and a hydrogen flame ion detector (FID) was used to measure total hydrocarbons (THC). Non-dispersive ultraviolet (NDUV) analysis was used to measure NO and NO_2, and we used an electrochemistry method to measure O_2. Vehicle speeds were recorded with GPS, which can provide second-by-second data while the vehicle is moving, as well as the vehicle's location (longitude, latitude, and altitude). During the pre-heating phase, standard gases from the Fitzpatrick Container Company in the UK were used to verify accuracy of the instrument. Before real-road emission testing, these gases are used to zero the target pollutants. To investigate the temporal variation of vehicle emissions, second-by-second data on fuel consumption, air/fuel ratio, and vehicle pollutant concentrations were gathered. Fig. 1 presents a schematic diagram of the testing system used.

3. Measurement results

3.1. Variation of test parameters with time and driving patterns

For the nine heavy-duty diesel vehicles selected for on-road testing, 37,255 second-by-second data points

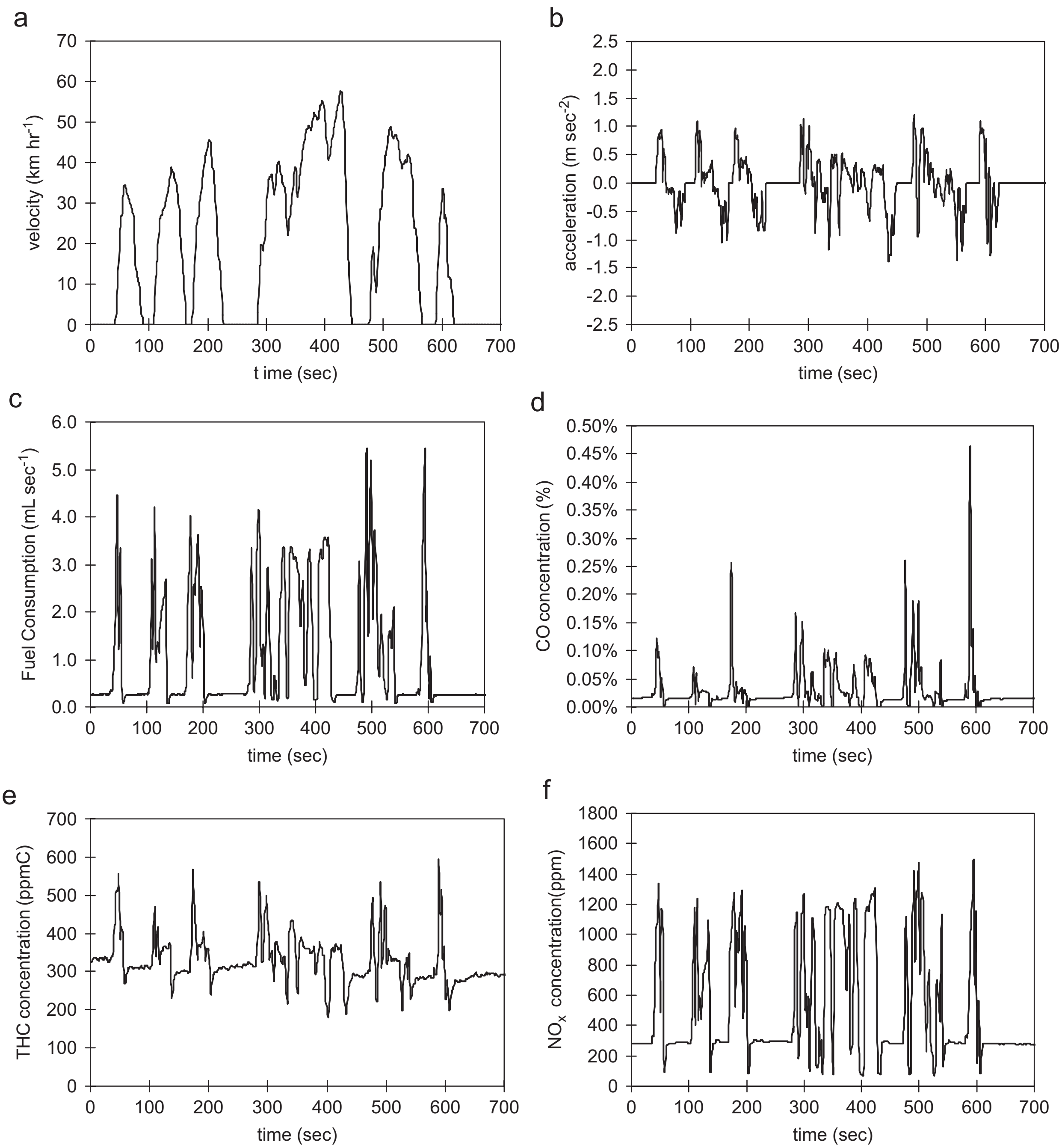

Fig. 2. Typical raw simultaneous measurement data of (a) velocity, (b) acceleration, (c) fuel consumption, (d) CO concentration, (e) THC concentration, and (f) NO_x concentration.

were obtained, consisting of measurements of speed, acceleration, fuel economy, exhaust gas flow, CO, THC and NO_x concentrations, and emission factors. Fig. 2 shows examples of the raw measurement data profiles from a single truck (no. 3), illustrating the temporal variations of speed, acceleration, fuel consumption, and CO, THC, and NO_x concentrations under actual driving conditions. Vehicle emissions are closely related to speed, acceleration, and fuel consumption; however, even under the same speed and acceleration conditions, emissions of the three pollutants can be quite different.

Table 2
Driving patterns and real-world emission test results

Truck parameter		Arterial road	Highway	Residential road	All roads
Number of measurements		17,216	4,595	15,444	37,255
Speed ($km\,h^{-1}$)	Average	22.9	36.3	19.9	23.3
	Maximum	68.5	84.2	64.1	84.2
Time (%)	Idling	18.7	4.7	18.0	16.5
	Acceleration	24.1	34.4	24.4	25.5
	Cruise	29.3	34.2	29.4	30.0
	Deceleration	27.9	26.7	28.2	27.9
Vehicle distance driven (km)	Idling	0.0	0.0	0.0	0.0
	Acceleration	44.8	14.2	32.6	91.7
	Cruise	31.7	20.0	25.9	77.6
	Deceleration	33.2	12.1	26.8	72.2
Fuel consumption ($L\,h^{-1}$)	Idling	1.25	1.75	1.17	1.24
	Acceleration	11.65	7.23	8.89	9.80
	Cruise	3.34	5.94	2.74	3.45
	Deceleration	1.87	2.82	1.48	1.81
Fuel economy (L/100 km)		19.8	14.7	18.1	18.2
CO emission rate ($mg\,s^{-1}$)	Idling	12.5	20.7	12.1	12.7
	Acceleration	93.3	54.5	53.0	70.7
	Cruise	24.4	43.8	19.0	24.8
	Deceleration	17.6	23.9	12.4	16.2
THC emission rate ($mg\,s^{-1}$)	Idling	7.8	12.6	7.8	8.1
	Acceleration	23.5	14.0	19.3	20.2
	Cruise	9.8	15.3	9.9	10.6
	Deceleration	8.9	11.1	8.5	9.0
NO_x emission rate ($mg\,s^{-1}$)	Idling	15.5	25.5	15.7	16.1
	Acceleration	104.6	70.3	84.1	90.6
	Cruise	32.8	58.7	28.6	34.6
	Deceleration	21.7	33.6	19.3	22.1
CO emission rate ($g\,km^{-1}$)	Acceleration	8.65	6.06	6.12	7.35
	Cruise	3.88	3.44	3.32	3.58
	Deceleration	2.55	2.41	2.01	2.33
	All	5.79	4.07	4.38	4.96
THC emission rate ($g\,km^{-1}$)	Acceleration	2.18	1.56	2.22	2.10
	Cruise	1.57	1.20	1.73	1.53
	Deceleration	1.29	1.12	1.39	1.30
	All	1.96	1.35	2.07	1.88
NO_x emission rate ($g\,km^{-1}$)	Acceleration	9.69	7.82	9.71	9.41
	Cruise	5.22	4.61	5.01	4.99
	Deceleration	3.15	3.39	3.13	3.18
	All	6.87	5.39	6.73	6.54

3.2. Distribution characteristics of driving pattern measurements

Table 2 summarizes the measured parameters for the three different kinds of roadways. The on-road vehicle emission testing results show that the maximum speed of the nine tested vehicles on the selected roads is $84.2\,km\,h^{-1}$, with an average speed of $23.3\,km\,h^{-1}$. On average, for all road types, vehicles spend 16.5% of their time idling. The acceleration profile is mainly distributed in the range of -1.0 to $+1.0\,m\,s^{-2}$, as shown in Fig. 3.

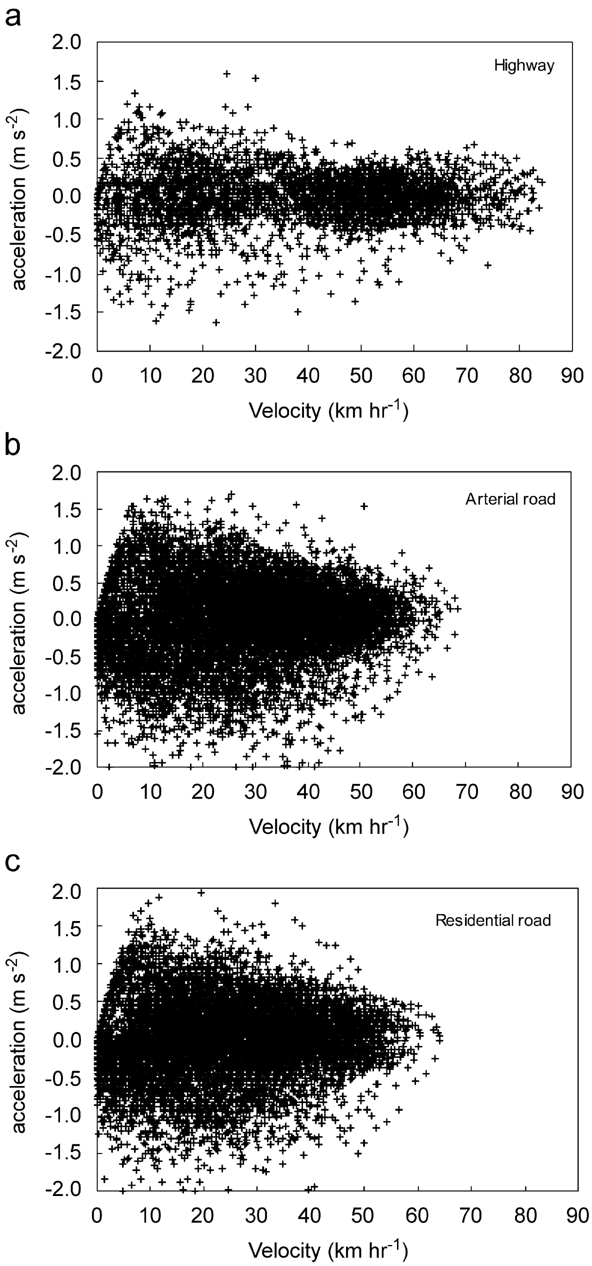

Fig. 3. Distribution of speed–acceleration driving pattern measurements.

Fig. 3 also shows that on the urban highway, velocities are mainly concentrated in the ranges of 10–25 and 55–60 km h^{-1}. The driving condition was close to steady. For the arterial road and residential roads, velocities tend to be lower. The average speeds were 22.9 and 19.9 km h^{-1}, respectively. More acceleration and deceleration conditions occurred on these two types of roads. Since the vehicles are driven within the actual traffic flow, the speed and acceleration characteristics reflect typical running conditions on Shanghai roads.

4. Analysis and discussion

4.1. Impact of speed and acceleration on fuel economy

To investigate the influence of speed and acceleration on fuel consumption, we chose truck no. 3 as an example and selected the instances when the vehicle passed through intersections after idling and fast acceleration periods to reveal the relationships among speed, acceleration, and fuel consumption. Fig. 4 illustrates the changes of fuel consumption, speed, and acceleration in the complete process when the truck is waiting for a traffic light to change from red to green and then passes through the intersection with fast acceleration. In this figure, the acceleration/fuel consumption curve shows a clockwise circle, while the acceleration/speed curve shows a counter-clockwise circle. Within a period of 0–6 s, the fuel consumption of the engine changes from 1 L h^{-1} in idle condition to 6 L h^{-1}, which is three times the amount used in normal running conditions. After the vehicle starts to move, the fuel consumption continues to increase until it reaches 10 L h^{-1}. It can be seen that more fuel needs to be provided to the vehicle during the “stop-go” periods. Traffic signals and congestion conditions cause these “stop-go” driving patterns and lead to higher fuel consumption.

4.2. The influence of speed and acceleration on vehicle emissions

Fig. 5 shows the dependence of CO, THC, and NO_x emission rates on vehicle acceleration, drawn with all test-driving measurements. This figure shows that vehicle emission rates are widely distributed. Even under the same acceleration, the emission rates of CO, THC, and NO_x can be quite different. CO emissions in particular show a wide variation. Taking an acceleration value of 1.0 m s^{-2} as an example, the variation range of the CO emission rate is 0.00–0.20 g s^{-1}, THC is 0.000–0.040 g s^{-1}, and NO_x is 0.00–0.20 g s^{-1}. The emission rate clearly has a close relationship with vehicle driving cycle and fuel combustion.

Fig. 6 further illustrates the influence of speed and acceleration on emissions during “stop-go” periods. It can be seen from this figure that, during the first

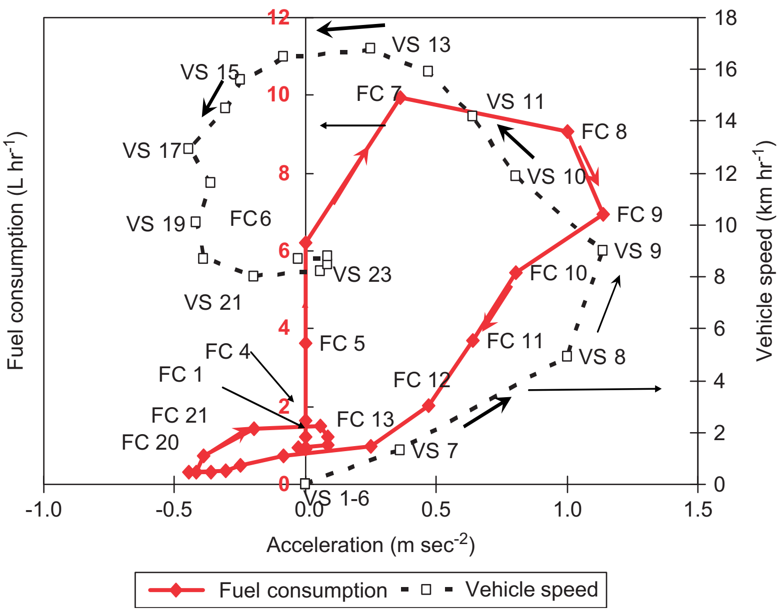

Fig. 4. Profile of vehicle speed, acceleration, and fuel consumption when the vehicle passes through an intersection. Points labeled FCn and VSn indicate second-by-second, simultaneous measurements of fuel consumption and vehicle speed.

6 s when the vehicle is starting to accelerate, the gas mixture accumulates quickly and the combustion situation deteriorates. Thus, the THC concentration is the highest, followed by a peak in the CO concentration. Then, with the improvement of combustion conditions, the concentrations of THC and CO slowly decrease, while the NO_x concentration increases due to the higher temperature in the exhaust gas. Fig. 6 shows why emission rates can be very different for different species under the same acceleration. It also shows that to control emissions in the vehicle acceleration mode is of great importance for improving urban air quality.

4.3. Vehicle driving cycles and emission factors

Fig. 7 and Table 2 show the average contributions of the nine selected heavy-duty diesel vehicles to speed, acceleration, fuel economy, and emission factors under different driving cycles. Vehicle idling time occupies 16.5% of the driving period, during which the fuel consumption is 5% of the total, and the emissions of CO, THC, and NO_x comprise 7%, 11%, and 6%, respectively, of total emissions. The acceleration mode represents 25.5% of the total time and 38% of the vehicle distance traveled, while the fuel consumption is 59% of the total, and the emissions of CO, THC, and NO_x comprise 56%, 42%, and 55%, respectively, of total emissions. The cruise-speed time is 30.0% of the total time, the vehicle distance traveled is 32% of the total, the fuel consumption is 24% of the total, and the emissions of CO, THC, and NO_x comprise 23%, 26%, and 25%, respectively, of total emissions. Finally, the deceleration mode occupies 27.9% of the total time, the vehicle distance traveled is 30% of the total, the fuel consumption is 12% of the total, and the emissions of CO, THC, and NO_x comprise 14%, 21%, and 15%, respectively, of total emissions. Average emission factors of CO, THC, and NO_x for the vehicles tested are 4.96, 1.88, and 6.54 g km^{-1}, respectively; standard deviations are 2.90, 1.03, and 1.90 g km^{-1}. The standard deviations divided by the averages of the emission factors of CO, THC, and NO_x are 0.58, 0.55, and 0.29, respectively.

From Table 3, we can see that vehicles show different vehicle specific power (VSP) profiles due to different average speed, vehicle mass, and distribution of speed and acceleration. Thus, emission factors are different, which is similar to other research results (Jimenez et al., 1999; Jimenez-Palacios, 1999; Hart, 2002). Moreover, the technology levels of the different trucks tested are closely related to emissions (Tao et al., 2003; Yao et al., 2006). Due to limitations in the number and types of trucks that could be tested in our study, the impact of technology level could not be extensively analyzed. Other factors such as maintenance and

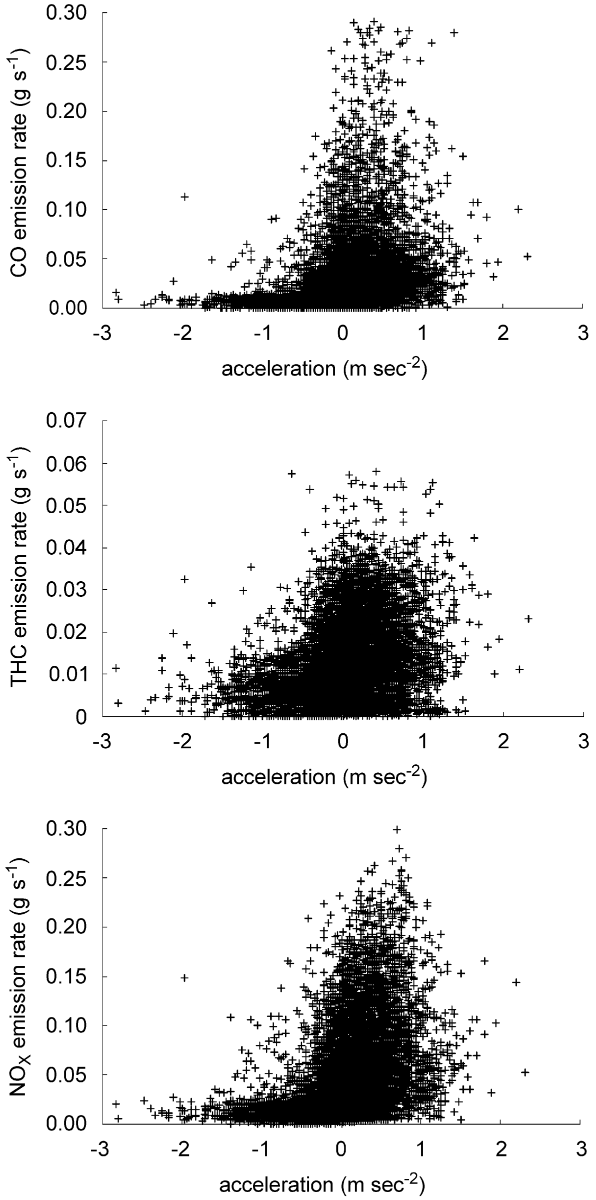

Fig. 5. Relationship among speed, acceleration, deceleration, and emission rates.

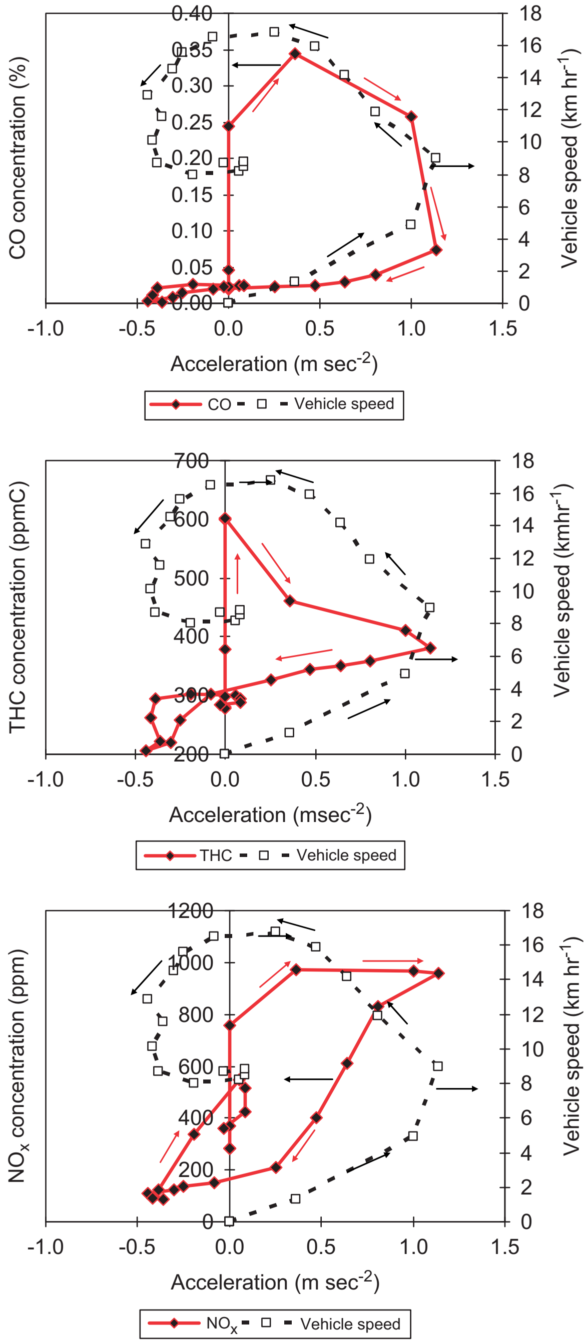

Fig. 6. Vehicle speed and air pollution levels when a vehicle passes through an intersection.

vehicle age also have a strong relationship with vehicle emissions. Older vehicles without good maintenance usually emit more pollutants than newer ones, according to Kuhns et al. (2004) and Chan et al. (2004) from their remote sensing studies. It can be seen from Table 3 that the older trucks (like truck nos. 7 and 9) had higher CO emission factors but lower NO_x emission factors due to poor engine combustion associated with their high usage rates and no maintenance. We recommend that further studies be conducted on these kinds of factors with a wider sample size.

The weights of the test vehicles are between 3.4 and 5.2 t. Thus, these vehicles belong to the heavy-duty diesel vehicle type “2b” (HDDV2b), as defined in the US MOBILE model (US EPA, 2002). The

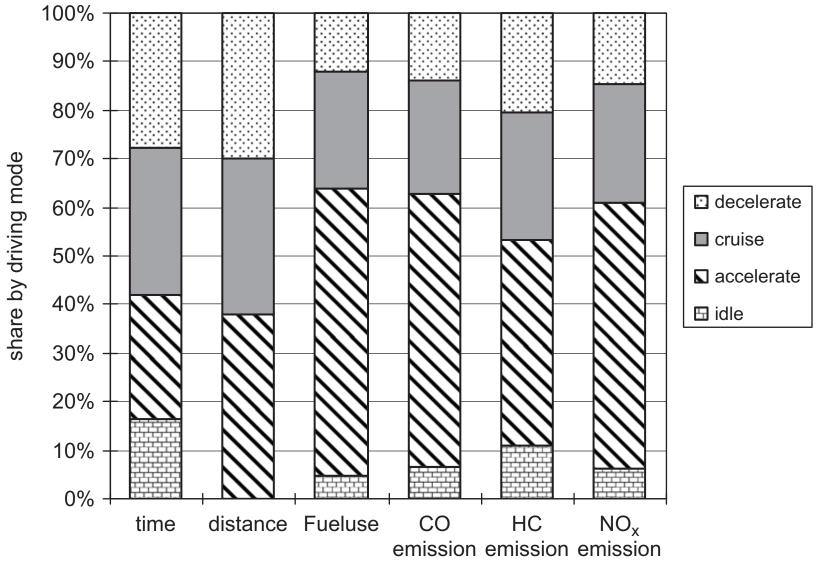

Fig. 7. Contributions of different driving patterns to vehicle emissions and other factors.

Table 3
Vehicle speeds and emission factors of individual heavy-duty vehicles from on-road testing

Truck ID number	Average speed ($km\,h^{-1}$)	Maximum speed ($km\,h^{-1}$)	CO emission rate ($g\,km^{-1}$)	THC emission rate ($g\,km^{-1}$)	NO_x emission rate ($g\,km^{-1}$)
1	24.4	80.0	0.96	0.96	8.81
2	18.5	64.6	5.55	3.20	9.63
3	22.5	61.1	3.03	1.30	8.28
4	23.4	70.3	4.65	3.23	6.94
5	19.6	56.2	1.73	1.49	4.43
6	29.0	84.2	2.90	0.29	7.12
7	30.2	72.7	8.52	1.11	5.43
9	23.7	66.8	9.82	2.16	3.98
10	25.3	60.0	3.04	2.34	6.53
All	23.3	84.2	4.96	1.88	6.54

results show that our average emission factors of CO, THC, and NO_x for heavy-duty diesel vehicles in Shanghai are (4.96 ± 2.90), (1.88 ± 1.03), and (6.54 ± 1.90) $g\,km^{-1}$, respectively. Our measured values can be compared with emission factors calculated by Li et al. (2003) using the MOBILE5a model (CO: $5.63\,g\,km^{-1}$, THC: $4.19\,g\,km^{-1}$, NO_x: $24.10\,g\,km^{-1}$). Our CO emission factors are similar, while our THC and NO_x emission factors are 55% and 73% lower than the MOBILE results; this is probably due to differences between the vehicle technologies, fuel economy, and driving patterns of the vehicles tested in real-world Shanghai conditions and the ones used in the MOBILE model. In order to estimate the urban air quality impacts of vehicle fleets, many countries—including China (Fu et al., 1997, 2000; He et al., 1998; Zhu, 1997; Li et al., 2001)—have modified US- or European-based emissions models to reflect local conditions. However, in many cases, these models can lead to significant errors in emission estimates (Davis et al., 2005). For light-duty vehicles, the ratio between MOBILE model calculations and measurement results in the real world has been shown to vary between 59% and 139% (Hu et al., 2004), while for heavy-duty vehicles, Wang et al. (2006) have suggested that the MOBILE model cannot properly reflect the actual emissions.

5. Conclusions

This study presents the first extensive measurements of the characteristics of driving patterns and emissions of heavy-duty diesel trucks in China. In contrast to laboratory studies and model calculations, it reflects the real emissions from actual heavy-duty vehicles on real roads under typical driving conditions. These measurements are important for improving our knowledge of truck emissions in Chinese megacities. Based on more than 37,000 simultaneous measurements of speed, acceleration, fuel consumption, and pollutant emissions, we conclude that:

(1) The average vehicle speed is $22.9\,\mathrm{km\,h^{-1}}$ on arterial roads, $19.9\,\mathrm{km\,h^{-1}}$ on residential roads, and $36.3\,\mathrm{km\,h^{-1}}$ on highways. The average speeds in the test are low for all cases, since the test routes are in Shanghai suburban areas with large traffic volumes. It is therefore not appropriate to apply these results to the driving cycles of heavy-duty trucks in high-speed mode. However, the results do reflect the real emissions from heavy-duty trucks under typical driving conditions in Shanghai. The results of this study can be transferred to other Chinese cities and to high-exposure situations, if the conditions are similar to that in Shanghai.
(2) Even under the same rate of acceleration, the emission rates of CO, THC, and NO_x are different at different speeds. Results show that low speed and frequent acceleration have a negative effect on fuel economy and vehicle emissions. Therefore, strengthening traffic management will not only improve traffic capacity but also have a positive effect on reducing vehicle emissions.
(3) The average emission factor of CO on all urban roads combined is $4.96 \pm 2.90\,\mathrm{g\,km^{-1}}$, THC is $1.88 \pm 1.03\,\mathrm{g\,km^{-1}}$, and NO_x is $6.54 \pm 1.90\,\mathrm{g\,km^{-1}}$.
(4) In addition to CO, THC, and NO_x, the exhaust also contains fine particulate matter such as PM_{10}; all of which have been shown to be harmful to human health. However, due to limitations of the equipment and method, we could not measure emissions of PM_{10} from diesel vehicles in this study. This will be the subject of future research. Our study approach is, of course, also applicable to gasoline vehicles.
(5) With the rapid development of the economy in China, the numbers of freight trucks are growing very rapidly and contributing greatly to the transportation system. The truck fleet increased from 3.68 million in 1990 to 8.93 million in 2004 (NBS, 2005). Our study showed that heavy-duty diesel trucks emit high levels of NO_x, which exacerbated the urban air pollution situation. Euro III standards will be adopted for heavy-duty vehicles from 2007, which can be expected to reduce emissions and improve air quality in Chinese cities; however, better maintenance practices will still be required to prevent emission deterioration of trucks during long-term operation.

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