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Development of database of real-world diesel vehicle emission factors for China

Xianbao Shen[1], Zhiliang Yao[2], Qiang Zhang[3], David Vance Wagner[4], Hong Huo[5], Yingzhi Zhang[1], Bo Zheng[1], Kebin He[1,6,*]

1. State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, China. E–mail: shenxb10@126.com
2. School of Food and Chemical Engineering, Beijing Technology and Business University, Beijing 100048, China
3. Ministry of Education Key Laboratory for Earth System Modeling, Center for Earth System Science, Tsinghua University, Beijing 100084, China
4. International Council on Clean Transportation (ICCT), San Francisco, CA 94104, USA
5. Institute of Energy, Environment and Economy, Tsinghua University, Beijing 100084, China
6. State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Tsinghua University, Beijing 100084, China

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ABSTRACT

A database of real-world diesel vehicle emission factors, based on type and technology, has been developed following tests on more than 300 diesel vehicles in China using a portable emission measurement system. The database provides better understanding of diesel vehicle emissions under actual driving conditions. We found that although new regulations have reduced real-world emission levels of diesel trucks and buses significantly for most pollutants in China, NOx emissions have been inadequately controlled by the current standards, especially for diesel buses, because of bad driving conditions in the real world. We also compared the emission factors in the database with those calculated by emission factor models and used in inventory studies. The emission factors derived from COPERT (Computer Programmer to calculate Emissions from Road Transport) and MOBILE may both underestimate real emission factors, whereas the updated COPERT and PART5 (Highway Vehicle Particulate Emission Modeling Software) models may overestimate emission factors in China. Real-world measurement results and emission factors used in recent emission inventory studies are inconsistent, which has led to inaccurate estimates of emissions from diesel trucks and buses over recent years. This suggests that emission factors derived from European or US-based models will not truly represent real-world emissions in China. Therefore, it is useful and necessary to conduct systematic real-world measurements of vehicle emissions in China in order to obtain the optimum inputs for emission inventory models.

Introduction

Diesel trucks have long been recognized as a major source of emissions in China, especially NOx and $PM_{2.5}$. It was found that diesel trucks contributed more than 20% of the total national NOx emissions in 2006 (Zhang et al., 2009). Diesel vehicles contributed 60% of the NOx and more than 90% of the $PM_{2.5}$ to the on-road emission inventory in 2009 (Ministry of Environmental Protection of China, 2010). In Beijing, diesel vehicles contribute more than 60% and 80% to 90% of the

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[*] *Corresponding author*. E-mail: hekb@mail.tsinghua.edu.cn (Kebin He).

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on-road NOx and PM emissions, respectively (Huo et al., 2011; Wu et al., 2011; Wang et al., 2010b). Although the emission factors of new vehicles have decreased since 2000 following the implementation of updated emission standards, the stock of diesel vehicles has increased considerably during the past decades because of China's rapid economic growth. Therefore, the total amount of emissions is expected to grow because of the significant increases in vehicle stock and distances traveled (Huo et al., 2012).

We tested the CO, HC, NOx, and fine particle ($PM_{2.5}$) emissions of 175 diesel vehicles in five cities using a portable emission measurement system (PEMS) (Huo et al., 2012). In other studies, a second Tsinghua University research team, including researchers from Beijing Institute of Technology, Wuhan University of Technology, China Automotive Technology & Research Center, Shanghai Academy of Environmental Sciences, Chinese Research Academy of Environmental Sciences, Zhejiang University, and Beijing University of Technology conducted on-board emission measurements of diesel trucks and buses, and the detailed information is shown in Table 1. The other groups tested 93 diesel trucks and 77 diesel buses; thus, more than 300 diesel trucks and buses have been tested using PEMS in the past decade in China.

Current emission inventory studies in China rely mostly on European or US vehicle emission databases, which might not reflect local conditions and technological performance (Huo et al., 2009). For example, Wang et al. (2008) used a bottom-up approach based on an International Vehicle Emission (IVE) model to develop a vehicle emission inventory for Shanghai. The modified and updated Computer Programmer to calculate Emissions from Road Transport (COPERT) and PART5 (Highway Vehicle Particulate Emission Modeling Software) models were used to estimate vehicle emission factors based on each major vehicle category in Beijing from 1995 to 2009 (Wu et al., 2011). The COPERT IV model was used by Wang et al. (2010a) to calculate the vehicular emission factors and trends in vehicular emissions in China's mega-cities from 1995 to 2005. Cai and Xie (2010) applied the COPERT IV model to calculate vehicular emission factors in China, which were used by Lang et al. (2012) to develop an emission inventory for the Beijing–Tianjing–Hebei region in 2008. Guo et al. (2009) used the MOBILE5 model to calculate vehicular emission factors in Chongqing, by comparing the differences between the emission factors derived from the MOBILE5 model and a chassis dynamometer. They found that the emission factors calculated by MOBILE5 are smaller than the actual emissions in Chongqing. Motor vehicle emission factors in Guangzhou were calculated using the COPERT IV model, which when integrated with information regarding the amounts and types of cars, were used to produce an emission inventory for Guangzhou for 2008 (Liao et al., 2011).

Although more than 300 diesel vehicles have been measured under real-world driving cycles in China, most data of emission factors used in inventory studies are derived from emission factor models, such as COPERT, IVE, and MOBILE; few emission inventories have been developed based on test results from China. It is very important and useful to understand real-world

Table 1 – Summary of PEMS testing by research teams in China.

		Total	THU	BIT	CATARC	SAES	ZJU	WHUT	CRAES	BJUT
LDDT[c]	China 0[a]	5	5							
<4500 kg	China I	45	44					1		
	China II	53	51				1	1		
	China III	11	8				1	2		
MDDT	China 0	8	7			1				
4500–12,000 kg	China I	11	11							
	China II	4	4							
	China III	4	4							
HDDT	China 0	3	1			2				
>12,000 kg	China I	43	34			8	1			
	China II	22	19				3			
	China III	55	51				1	1	2	
	China IV	2	2							
Diesel bus	China 0	2				2				
	China I	2						2		
	China II	14	9	2			1	2		
	China III	33	22	4	2		5			
	China IV	28	24	2						2
Total		345	296	8	2	13	13	9	2	2
References			1[b], 2, 3, 4	5, 6	7, 8	9,10,11	12	13,14	15	16

THU: Tsinghua University; BIT: Beijing Institute of Technology; WHUT: Wuhan University of Technology; CATARC: China Automotive Technology & Research Center; SAES: Shanghai Academy of Environmental Sciences, CRAES: Chinese Research Academy Environmental Sciences, ZJU: Zhejiang University; BJUT: Beijing University of Technology.

Reference: 1: Wu et al. (2012); 2: Huo et al. (2012); 3: Sebastian et al. (2007); 4: Sebastian et al. (2008); 5: Wang et al. (2011); 6: Ge et al. (2010); 7: Li et al. (2008); 8: Gao et al. (2011); 9: Jing et al. (2006); 10: Huang et al. (2007); 11: Chen et al. (2007); 12: Xue (2010); 13: Hou et al. (2010); 14: Yin et al. (2011); 15: Li et al. (2009); 16: Fan et al. (2012).

[a] The emission levels I to IV in China are equivalent to Euro I to IV standards, while China 0 means no emission control was applied.

[b] Only NOx emission factors were estimated; some data overlapped with other teams' results.

[c] LDDT: Light-duty Diesel Truck; MDDT: Medium-duty Diesel Truck; HDDT: Heavy-duty Diesel Truck.

emission factors in China, and it is necessary to ascertain whether the emission factors derived from models or used in inventory studies are consistent with real-world measurement results. The goals of this article are to develop a database of real-world diesel vehicle emission factors for China, and compare real-world measurements of emission factors with emission factors derived from models and used in inventory studies.

1. Review and summary of all currently available on-road emission data

1.1. *Light-duty diesel truck emissions*

Light-duty diesel trucks (LDDTs) are those whose gross vehicle weight (GVW) is lower than 4.5 ton. In the past decade, 114 LDDTs have been tested in China using PEMS. Wang et al. (2001) obtained the vehicles' average emission factors *via* tunnel tests. We summarized the CO, HC, NOx, and $PM_{2.5}$ emission factors of LDDTs acquired to the different emission standards in the literature, and calculated the averaged values. Few tests on China IV (equals to Euro IV) LDDTs have been reported in the literature and therefore, only the LDDT emission factors from China 0 (no emission control) to China III (equals to Euro III) are shown in Fig. 1. It can be seen that the range of CO, HC, and NOx emission factors is larger for the China 0 and China I LDDTs than other LDDTs; one reason for this may be the degradation of older LDDTs. The average emission factors of CO and HC decline obviously from China 0 to China III, and the average emission factors of $PM_{2.5}$ decline obviously from China I to China III, but the average emission factors of NOx do not exhibit the same trend. Few tests on China IV trucks in China have been reported in the literature; therefore, the emission factors for China IV LDDTs are absent. Additional China IV trucks need to be tested to ascertain their emission factors.

The average NOx emission factors for China I and II (equals to Euro I and II) quoted in the literature are higher than those for China 0. The average NOx emission factor rises from China 0 to China I, but declines from China I to China III (equals to Euro III). The CO, HC, and $PM_{2.5}$ emission factors found in separate studies all have similar declining trends from China 0 to China III, but the situation is different for NOx emission factors. In the studies by Huo et al. (2012) and Sebastian et al. (2008), the China II NOx emission factor is higher than the China I NOx emission factor. Our previous study (Liu et al., 2009) tested 77 LDDTs in 2007, and reported that China II LDDTs had slightly higher NOx emission factors (in g/kg of fuel) than China I LDDTs. However, in other studies (Wu et al., 2012; Sebastian et al., 2007; Xue, 2010; Hou et al., 2010), the NOx emission factors declined from China I to China III.

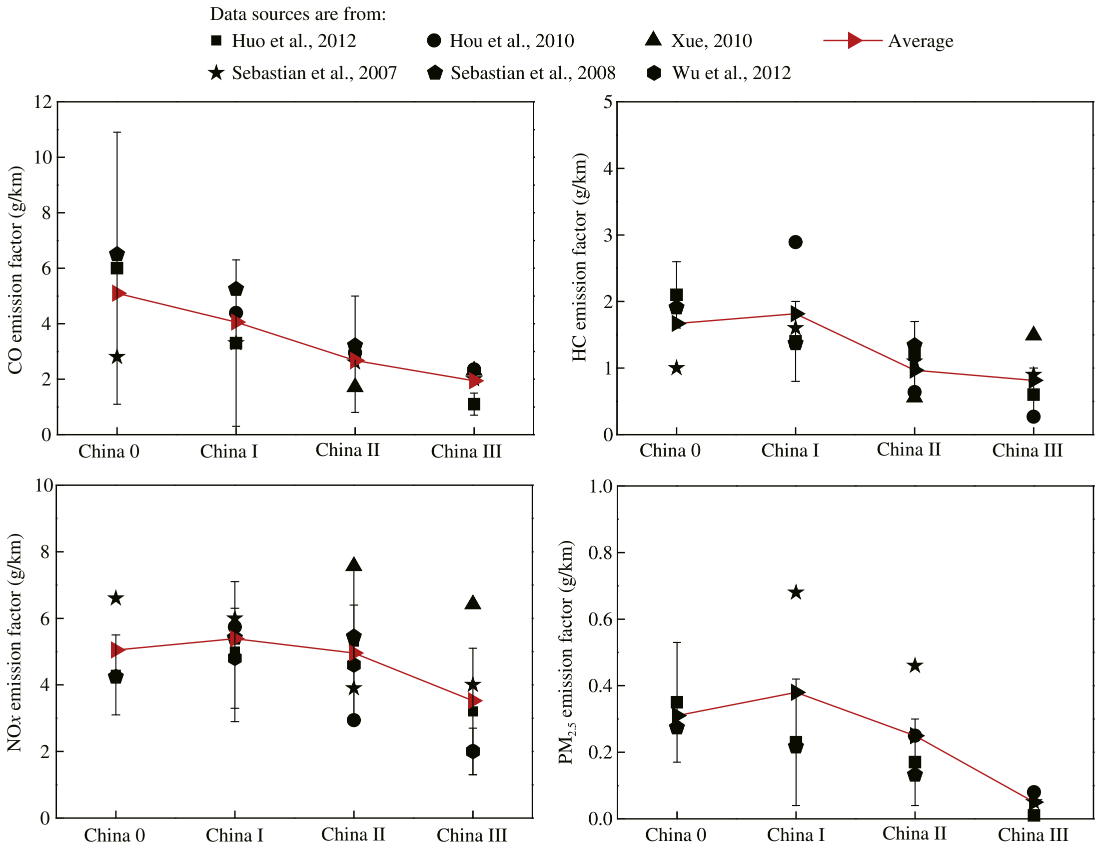

Fig. 1 – CO, HC, NOx, $PM_{2.5}$ emission factors of light-duty diesel trucks in literature. The emission levels I to IV in China are equivalent to Euro I to IV standards, while China 0 means no emission control was applied.

1.2. *Medium-duty diesel truck emissions*

Medium-duty diesel trucks (MDDTs) refer to those trucks whose GVW is between 4.5 and 12 ton. Other than our research team's previous study (Huo et al., 2012), which tested 26 MDDTs in Beijing, Jinan, Shenzhen, and Xiamen during 2007 and 2010, we found only one emission factor test of an MDDT in the literature. The average emission factors are shown in Table 2. The CO, HC, NOx, and $PM_{2.5}$ average emission factors decline obviously from China 0 to China III, except for China II; the reason for this may be that the GVWs of the tested China II MDDTs were significantly lower than the other MDDTs.

1.3. *Heavy-duty diesel truck emissions*

Heavy-duty diesel trucks (HDDTs) are those for which the GVW is greater than 12 ton. The emission factors of HDDTs are greater than LDDTs, especially for NOx and $PM_{2.5}$. Fig. 2 shows the CO, HC, NOx, and $PM_{2.5}$ emission factors of HDDTs reported in the literature. Only a few China IV HDDTs were tested in China in our previous study (Huo et al., 2012), and the HC sensor did not operate well during the measurements, which makes the HC emission results unreliable; therefore, the emission factors for China IV HDDTs are omitted. In Hou et al. (2010) study, PM emission factors were tested and reported as significantly higher than in other studies, because PM also includes particulate matter with diameter larger than 2.5 μm. Thus, the PM emission factors in Hou et al. (2010) study were not included in the average $PM_{2.5}$ emission factor. The average CO, HC, NOx, and $PM_{2.5}$ emission factors of HDDTs from China 0 to IV reported in the literature are shown in Fig. 2. The average HC emission factors decrease from China 0 to China III, and average CO and $PM_{2.5}$ emission factors decrease significantly from China 0 to IV, but the NOx emission factor does not exhibit the same trend. The China III NOx emission factor is higher than that of China II, the China IV NOx emission factor declines 44% compared with China 0, and the drop ratio for NOx is much lower than for other contaminants (CO, HC, and $PM_{2.5}$).

A similar phenomenon has also been found in Europe and the US (Rexeis et al., 2005; Yanowitz et al., 2000), and the reason for this has been attributed to the strategy of the engine manufacturers known as "cycle-beating" (Weaver et al., 2000). The reason for this phenomenon in China has yet to be investigated, but it is clear that the government must enforce stricter NOx standards for diesel vehicles, by requiring vehicle manufacturers to use more effective after-treatment technologies to achieve national targets of a 10% reduction in NOx emissions by 2015. China III vehicles may not exhibit the expected.

NOx reduction in the real world, but a significant reduction in NOx emissions is observed for China IV diesel trucks compared with China III trucks. According to our measurements, the average NOx emission factor of China IV HDDTs is 33% lower than that of China III vehicles. Rexeis et al. (2005) reported a reduction of 40% in NOx emission levels from Euro III to Euro IV heavy-duty vehicles, which is consistent with the findings of our previous study (Huo et al., 2012). Therefore, under current circumstances, implementing the China IV requirement nationwide is vitally important for reducing NOx emissions given the considerable growth in the number of diesel trucks in China.

Table 2 – PEMS-derived Chinese medium-duty diesel truck emission factors.

	CO (g/km)	HC (g/km)	NOx (g/km)	$PM_{2.5}$ (g/km)
China 0	5.4 ± 2.0	2.4 ± 1.3	10.7 ± 3.6	0.55 ± 0.45
China I	3.8 ± 1.7	1.4 ± 0.6	9.7 ± 2.6	0.49 ± 0.29
China II	1.1 ± 0.3	0.3 ± 0.1	3.6 ± 0.8	0.07 ± 0.05
China III	1.5 ± 1.2	0.2 ± 0.1	6.4 ± 1.9	0.11 ± 0.00

Data are presented as mean ± standard deviation.

1.4. *Diesel bus emissions*

The majority of urban buses in China utilize diesel engines. The average China 0 to China IV CO, HC, NOx, and PM emission factors of diesel buses tested in previous PEMS studies are summarized in Fig. 3. Few tests on China 0 diesel bus CO and PM emission factors have been reported and therefore, the CO and PM emission factors for China 0 diesel buses are omitted. In almost all studies (Yin et al., 2011; Fan et al., 2012; Wang et al., 2011; Xue, 2010; Ge et al., 2010; Li et al., 2008; Gao et al., 2011; Hou et al., 2010) the PM emission factors were measured using an electrical low pressure impactor, which can measure PM whose aerodynamic diameter is between 28 nm and 10 μm.

The average CO, HC, and PM emission factors of diesel buses decrease from China I to China IV. However, the NOx emission factor does not show a declining trend. The NOx emission factors of diesel buses and HDDTs NOx do not exhibit an obvious decrease from China I to III, because diesel buses and HDDTs both use similar engine technologies and cycle-beating. The real-world driving cycle of diesel buses is worse than that of diesel trucks. Diesel buses operate more frequently under stop-start traffic conditions and thus, their NOx emission factors are higher than HDDTs. The NO_X emission factors of China IV, III, and II are higher than China I, and the NOx emission factor of China III is higher than China II. The China IV NOx emission factor declines only 4% compared with China III, a drop ratio much lower than for the other pollutants and diesel trucks. China IV CO, HC, and PM emission factors all decrease compared with China I, but the China IV NOx emission factor increases compared with China I. However, only two China IV HDDTs were tested, which means the NOx emission factor of China IV HDDTs has a high level of uncertainty; the real NOx emission factor of China IV HDDTs might be higher than this.

2. Different vehicle emission comparison and analysis

During 2007 and 2012, our research team conducted on-board measurements of emissions of 195 diesel trucks in six Chinese cities: Beijing, Xi'an, Shenzhen, Jinan, Yichang, and Xiamen. Beijing is the capital of China, Xi'an is the capital city of Shaanxi Province (located in the mid-west of China),

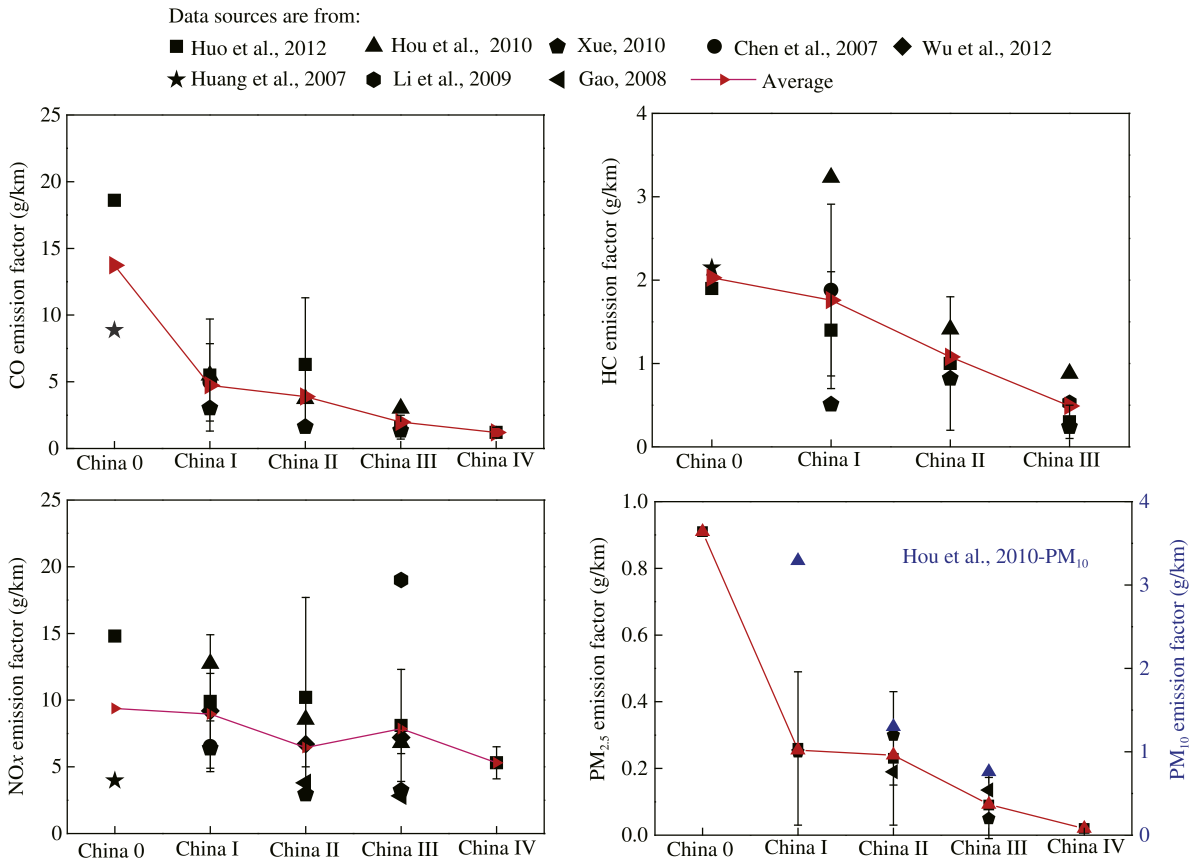

Fig. 2 – CO, HC, NOx, and $PM_{2.5}$ emission factors of heavy-duty diesel trucks in literature.

Shenzhen is one of the most economically developed cities in China (located in the south of China), Jinan is the capital city of Shandong Province (located in the east of China), Yichang is a mid-sized city in Wuhan Province (located in the central part of China), and Xiamen is an important port city (located in the southeast of China). Tailpipe CO, HC, NOx, and fine particle ($PM_{2.5}$) emissions were measured using a PEMS. Detailed information regarding the experiment can be found in our previously published papers (Huo et al., 2012; Yao et al., 2011). Table 3 summarizes the technological information of the test diesel trucks.

In addition to the direct on-board measurements using PEMS, modeling is also an important tool for estimating vehicle emission factors. For example, Cai and Xie (2010) applied the COPERT IV model to calculate emission factors of CO, CO_2, NOx, PM_{10}, NMVOC, SO_2, N_2O, CH_4, and NH_3 in China for various vehicle categories including gasoline, diesel, Liquefied Petroluem Gas (LPG), Compressed Natural Gas (CNG), and hybrid vehicles meeting different emission standards from China 0 through China VI. The modeling considered factors including driving conditions, fuel quality, and ambient temperature, all of which have an impact on vehicle emission factors. The average speed and the sulfur contents of gasoline and diesel were assumed to be 20 km/hr, and 50 and 500 ppm, respectively. The mean monthly maximum and minimum temperatures of 31 provinces in 2008 were used to represent the state levels. The emission factors in the "COPERT-China" model represent the results in the research by Cai and Xie (2010). The emission factors calculated by Cai and Xie (2010) were also used to calculate an emission inventory (Lang et al., 2012).

In the following, we compare and analyze existing emission factor data, including those in the literature, from our research team's measurements, and from the COPERT-China model reported in Cai and Xie (2010) study.

2.1. Light-duty diesel truck emission analysis

Fig. 4 presents LDDT distance-specific emission factors for CO, HC, NOx, and PM, as estimated by the different sources. There are few reports of emission factors for China IV LDDTs in the literature, and no China IV LDDTs were tested in our previous study; therefore, China IV LDDT emission factors are not shown.

The CO emission factors in the literature derived from measurement studies, *e.g.*, Huo et al. (2012), Hou et al. (2010), Sebastian et al. (2007, 2008), and Xue (2010), are much higher than the COPERT-China model results. It should be noted that the GVW of LDDTs used in the COPERT model was <3.5 ton, but it is defined as <4.5 ton in this study. The CO emission factors decrease as emission standards are tightened; the CO emission factors for China III LDDTs decreased by 65%, 65%, and 80% compared with China 0 LDDTs in the COPERT-China model, literature, and our study, respectively.

The mean emission factors of HC in the literature and our study are significantly higher than the COPERT-China

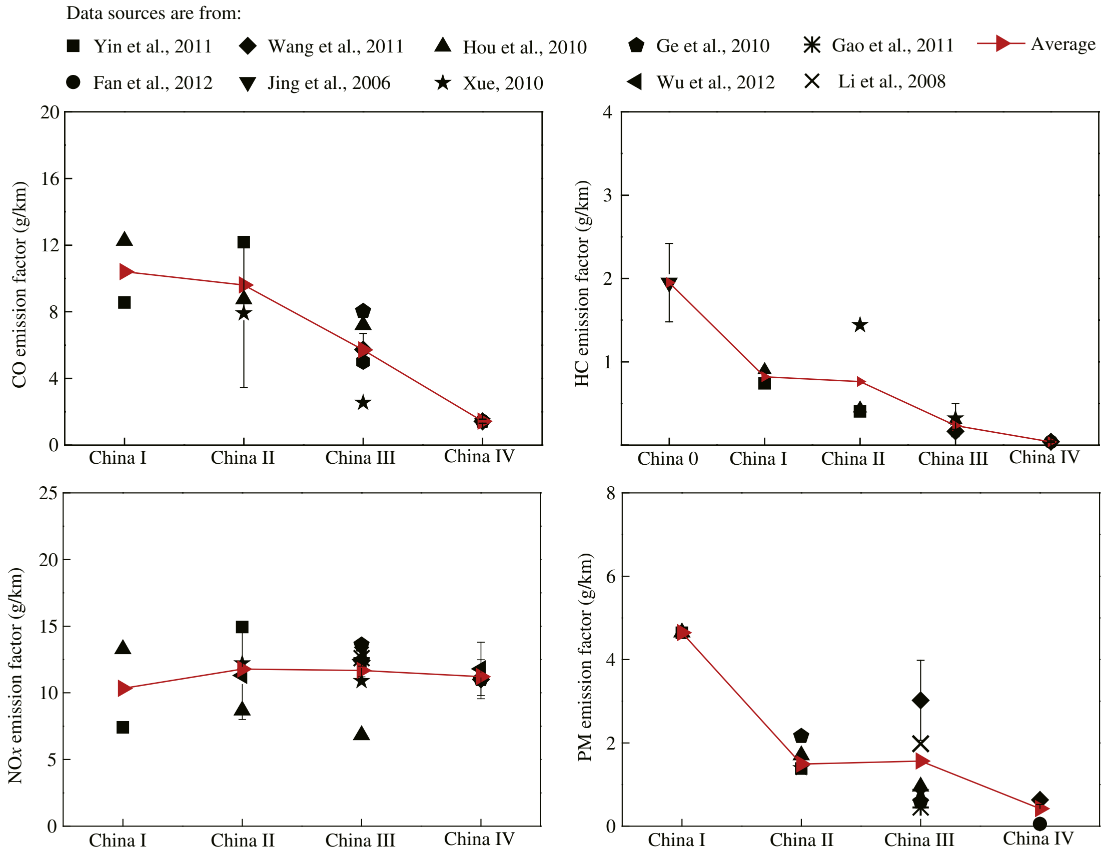

Fig. 3 – CO, HC, NOx, and $PM_{2.5}$ emission factors of diesel buses in literature.

model results from China 0 to III. The on-road HC emission factors decrease as emission standards are tightened; the HC emission factors for China III LDDTs decrease by 51% and 77% compared with China 0 LDDTs in the literature and our study, respectively. However, the HC emission factors for the China II and I LDDTs in the COPERT-China model are 29% and 33% higher compared with China 0 LDDTs. The HC emission factors in the COPERT-China model are clearly different from the results of on-road tests reported in the literature. HC emissions for LDDTs based on results from the COPERT-China model might be significantly underestimated.

The average emission factors of NOx in the literature and our study are significantly higher than the COPERT-China model results from China 0 to III. The NO_X emission factors for China I and II LDDTs are 53% lower relative to China 0 LDDTs in the COPERT-China model. However, in our study, the on-road NO_X emission factors for China I and II LDDTs are 18% and 24% higher, respectively, relative to China 0 LDDTs. NOx emissions for LDDTs based on results from the COPERT-China model might be significantly underestimated.

Regarding PM, PM_{10} emission factors were calculated by the COPERT-China model (Cai and Xie, 2010), but $PM_{2.5}$ emission factors were measured in our previous study (Huo et al., 2012) and reported in other literature (Sebastian et al., 2007, 2008; Xue, 2010). In the tunnel study by Wang et al. (2001), the China 0 LDDT PM_{10} emission factor was 2.44 g/km. In the study by Hou et al. (2010), the China I, II, and III PM_{10} emission factors were 2.05, 0.76, and 0.44 g/km, respectively, which are significantly higher than the results from the COPERT-China model (Cai and Xie, 2010). The PM_{10} emission factors for China III LDDTs are 60% lower compared with the China 0 LDDTs in the COPERT-China model, but are the same as the China I and China II LDDTs. The on-road $PM_{2.5}$ emission factors for China II and China III are 34% and 90% lower, respectively, relative to the China 0 LDDTs in our study. The $PM_{2.5}$ emission factors for China II and China III are 33% and 88% lower, respectively, relative to the China I LDDTs in the literature.

Overall, the emission factors derived from the COPERT-China model are distinctly lower than real-world emission factors, and tend to be the same or even lower than the lowest values quoted in

Table 3 – Information of the test diesel trucks.

	China 0	China I	China II	China III	China IV	Total
LDDT <4.5 ton	5	36	42	7		90
MDDT 4.5–12 ton	7	11	4	4		26
HDDT >12 ton	2	30	13	32	2	79
Total	14	77	59	43	2	195[a]

[a] LDDT: Light-duty Diesel Truck; MDDT: Medium-duty Diesel Truck; HDDT: Heavy-duty Diesel Truck.

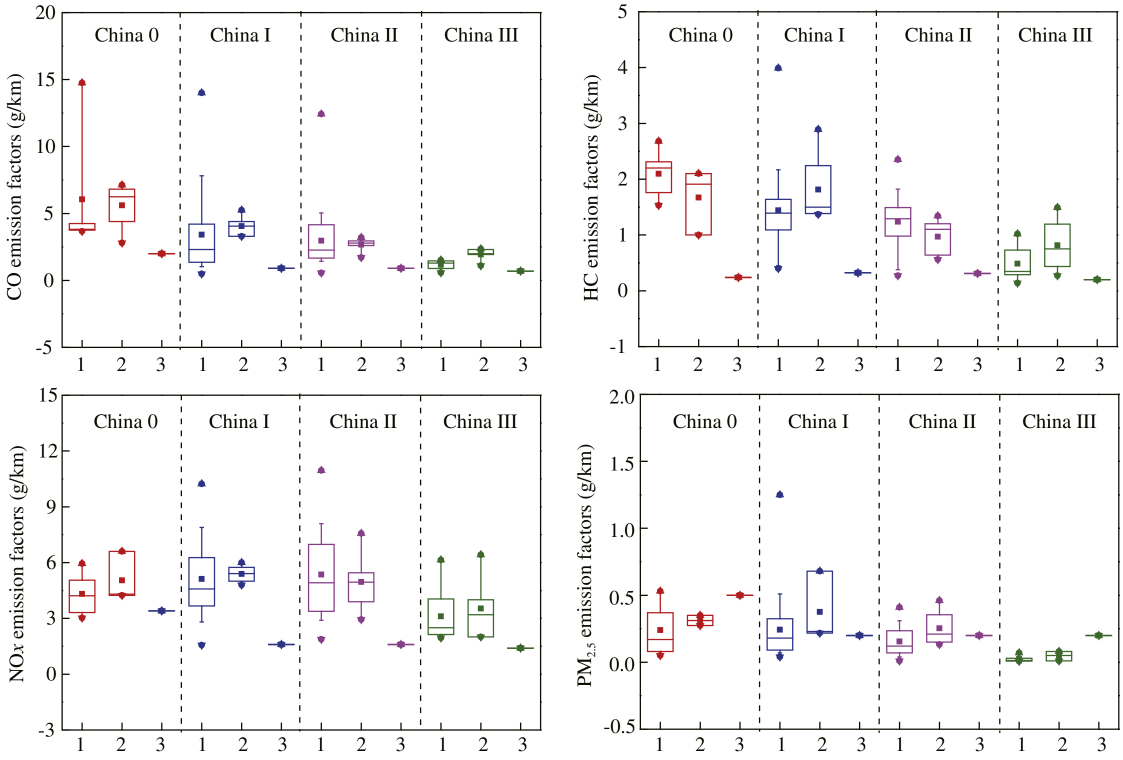

Fig. 4 – Comparison of the emission factors of light-duty diesel trucks from different sources. X-axis 1: emission factors from our study; X-axis 2: PEMS-derived emission factors in the literature; X-axis 3: emission factors in COPERT-China model.

the literature and our study. Table 4 summarizes the differences between on-road LDDT test results and emission factors estimated by the COPERT-China model. The table highlights the dramatic underestimation of emission factors by the COPERT-China model.

Because of the lack of test results on China IV LDDTs in the literature and our study, it is important that more China IV LDDTs be tested in the future.

2.2. Heavy-duty diesel truck emission analysis

Fig. 5 shows the HDDT distance-specific emission factors of CO, HC, NOx, and PM from different sources. Table 5 summarizes the differences between the on-road HDDT test results and emission factors estimated by the COPERT-China model.

The average emission factors for CO in the literature and our study are higher than the results from the COPERT-China model for China 0–China IV HDDTs. The HDDT CO emission factors increase by 18% from China II to China III in the COPERT-China model (Cai and Xie, 2010). Conversely, our study shows that CO emission factors decrease by 60% over the same transition.

The average emission factors for HC in the literature and our study are higher than the COPERT-China model results for China 0 and China III HDDTs, but lower for China I and China II HDDTs. The on-road HC emission factors decrease as emission standards are tightened. The HC emission factors decrease by more 75% from China 0 to China III HDDTs both in the literature and in the COPERT-China model.

The differences in NOx emission factors between the literature, our study, and the COPERT-China model are shown in Table 5 and illustrated in Fig. 5. The NOx emission factors do not show a clear reduction from China I to III. The fuel-based NOx emission factors were tested by Wang et al. (2012), conducting on-road chasing studies in Beijing and Chongqing, and there is also no clear correlation between emission controls and NOx emissions from the sampled on-road trucks. Previous policy evaluations (Wu et al., 2011; Zhou et al., 2010) have widely assumed a continuous decrease

Table 4 – Comparison of light-duty diesel truck distance-specific emission factors for CO, HC, NOx, and $PM_{2.5}$ from different sources with the COPERT-China model.

	CO		HC		NOx		$PM_{2.5}$	
	This study	Literature	This study	Literature	This study	Literature	This study	Literature
China 0	202%	180%	773%	596%	27%	48%	−52%	−38%
China I	279%	351%	350%	467%	220%	237%	22%	88%
China II	230%	197%	299%	212%	234%	210%	303%	27%
China III	69%	177%	143%	308%	122%	152%	−88%	−77%

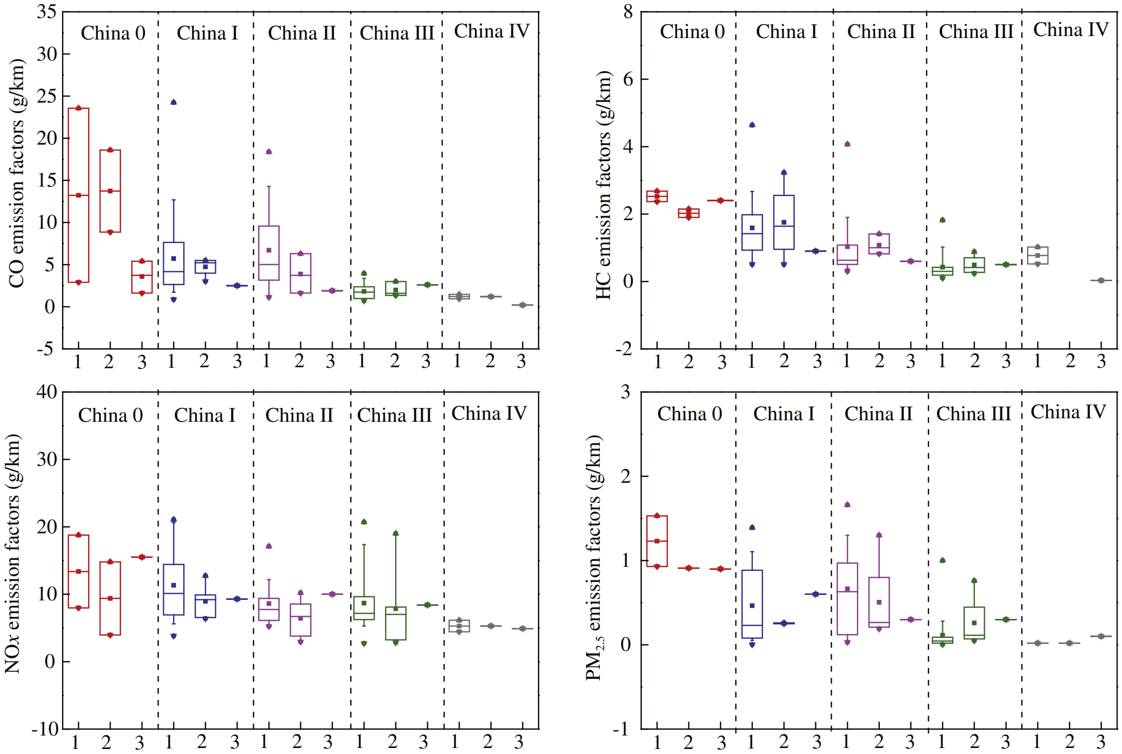

Fig. 5 – Comparison of emission factors of heavy-duty diesel trucks from different sources. Nos. X-axis 1–3 are the same as those in Fig. 4.

in NOx emission factors as emission standards for HDDTs have been tightened. Thus, based on these new results, NOx emissions for China's diesel truck fleet might be significantly underestimated.

The average $PM_{2.5}$ emission factors in the literature and our study are lower than the PM_{10} emission factors from the results of the COPERT-China model for China I–IV HDDTs. PM is a dynamic pollutant and its measurement is affected by many factors, such as sampling conditions, driving cycles, and measurement methods, plus there are obvious differences between $PM_{2.5}$ and PM_{10}. Over the last five years, many cities including Beijing have been greatly affected by continual "hazy days", characterized by high concentrations of $PM_{2.5}$. Motor vehicle emissions have become a major source of air pollutants, especially in urban areas; light and heavy-duty vehicles are major sources of ambient PM; thus, it is very important for us to understand the characteristics of $PM_{2.5}$ emissions. However, PM_{10} emission factors were calculated in some models, while $PM_{2.5}$ emission factors were measured by PEMS; therefore, the PM emission factors used in models and measurements should be unified.

The on-road $PM_{2.5}$ emission factors decrease as emission standards are tightened. The $PM_{2.5}$ emission factors for China IV HDDTs decrease by 98%, 89%, and 98% compared with China 0 HDDTs in the literature, COPERT-China model results, and our study, respectively.

2.3. Diesel bus emission analysis

Fig. 6 compares the diesel bus distance-specific emission factors for CO, HC, NOx, and PM in the COPERT-China model and the literature. The mean CO and PM emission factors in the literature are significantly higher than the COPERT-China model for China I–IV; the phenomenon might be caused by lower-speed driving, frequent acceleration and long-duration engine idle operation for city buses in real-world driving conditions. The differences in HC and NOx emission factors between the COPERT-China model and the means in the

Table 5 – Comparison of heavy-duty diesel truck distance-specific emission factors for CO, HC, NOx, and $PM_{2.5}$ from different sources with the COPERT-China model.

	CO		HC		NOx		$PM_{2.5}$	
	This study	Literature	This study	Literature	This study	Literature	This study	Literature
China 0	145%	154%	5%	−16%	−14%	−39%	37%	1%
China I	102%	90%	57%	95%	7%	−4%	−24%	−58%
China II	131%	105%	176%	79%	−48%	−36%	468%	68%
China III	−30%	−24%	−15%	−3%	3%	−6%	−62%	−14%
China IV	503%	500%			8%	8%	−80%	−80%

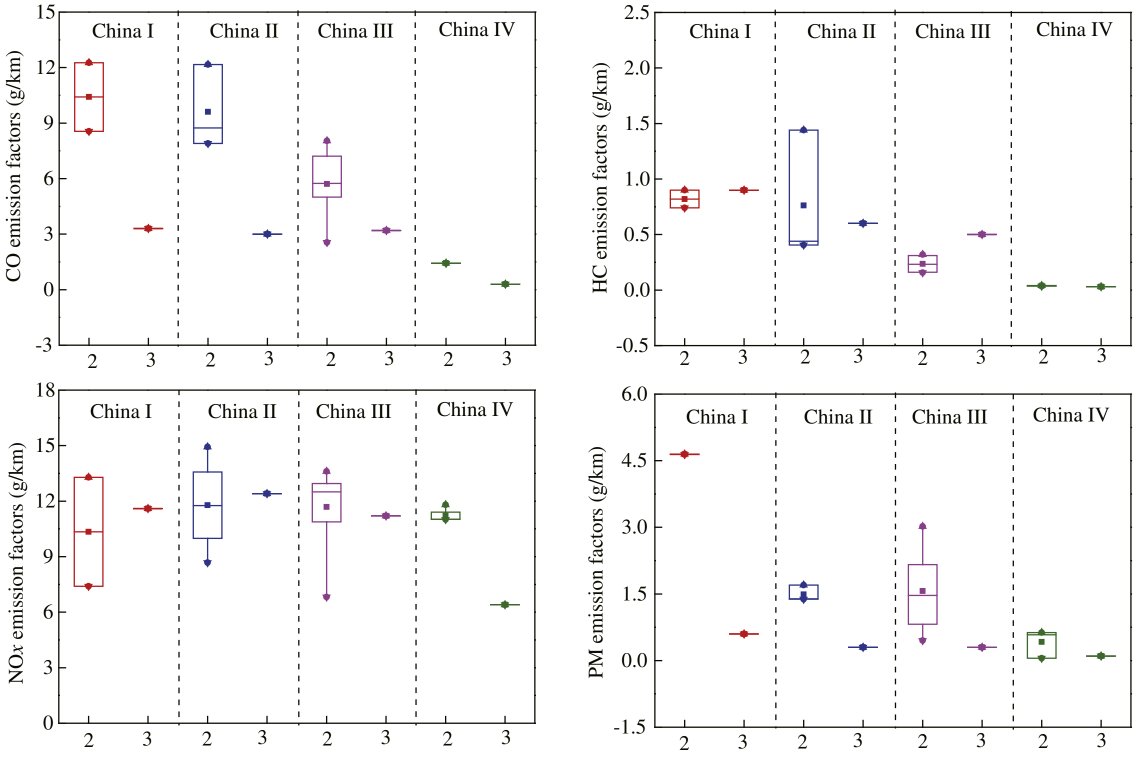

Fig. 6 – Comparison of emission factors of diesel bus from different sources. Nos. 1–3 are the same as those in Fig. 4.

literature are smaller than in CO and PM. The NOx emission factors in the COPERT model are highly similar to the means in the literature; neither shows a deceasing trend from China I–III. The NOx emission factor for Euro IV buses predicted by the COPERT-China model is much lower than those measured by PEMS, and the NOx emission factor for Euro IV buses is lower than the Euro III buses in the COPERT-China model, but the NOx emission factor for Euro IV buses is similar to the Euro III buses in real-world measurements; the phenomenon might be caused by the occurrence of frequent stops and congestion for the bus fleet in urban areas, with more idling time and more low-speed time in real-world driving cycles, and the fact that the SCR did not perform well due to the low exhaust temperature (Wu et al., 2012).

Diesel buses may be the major PM source in urban areas because in China, diesel trucks are commonly limited or banned from driving in cities, and gasoline vehicles have very low PM emission factors. Therefore, it is very important for us to understand clearly the emission factors of diesel buses. Because the existing samples of tested diesel buses are limited, additional tests should be performed on diesel buses.

3. Evaluation of emission factors used in recent emission inventory studies

One important objective of measurement studies is to provide emission factor data for inventory studies, to help evaluate inventory estimates.

Fig. 7 summarizes the on-road CO, HC, NOx, and $PM_{2.5}$ emission factors utilized in recent inventory studies, and the average emission factors in this study. It should be noted that the emission factors used in the inventories are the fleet-average emission factors; thus, 1994, 1995, and 1999–2010 HDDT fleet-average emission factors are calculated based on the measured emission factor database according to different emission standards and technology distribution data in Beijing, Shanghai, and other cities in China.

The CO, HC, NOx, and $PM_{2.5}$ emission factors in the inventory studies show a declining trend over time. The CO emission factors used in some inventory studies, *e.g.*, Wang et al. (2005, 2008, 2010a) and Wu et al. (2011), are higher than the fleet-average emission factors derived from measurements, especially those in the studies by Wang et al. (2008, 2010a), in which the CO emission factors are seven times higher than the fleet-average emission factors in the literature. However, the CO emission factors used in some other inventory studies, *e.g.*, Guo et al. (2009) and Liao et al. (2011), are lower than the fleet-average emission factors derived from measurement. The CO emission factors used by Wang et al. (2010a) are also obtained from the COPERT model, but they have an order of magnitude difference with the results of the COPERT-China model (Cai and Xie, 2010).

For HC, the emission factors used in some inventory studies, *e.g.*, Wu et al. (2011) and Wang et al. (2008), are higher than the average emission factors in the literature. For NOx, the emission factors used in some inventory studies, *e.g.*, Wu et al. (2011) and Zhang et al. (2007), are higher than the average emission factors in the literature for the period 1995–2001. For $PM_{2.5}$, the emission factors used in Wang's (2005) study are higher than the average emission factors in the literature because the results come from tunnel testing. The average emission factors in the literature are

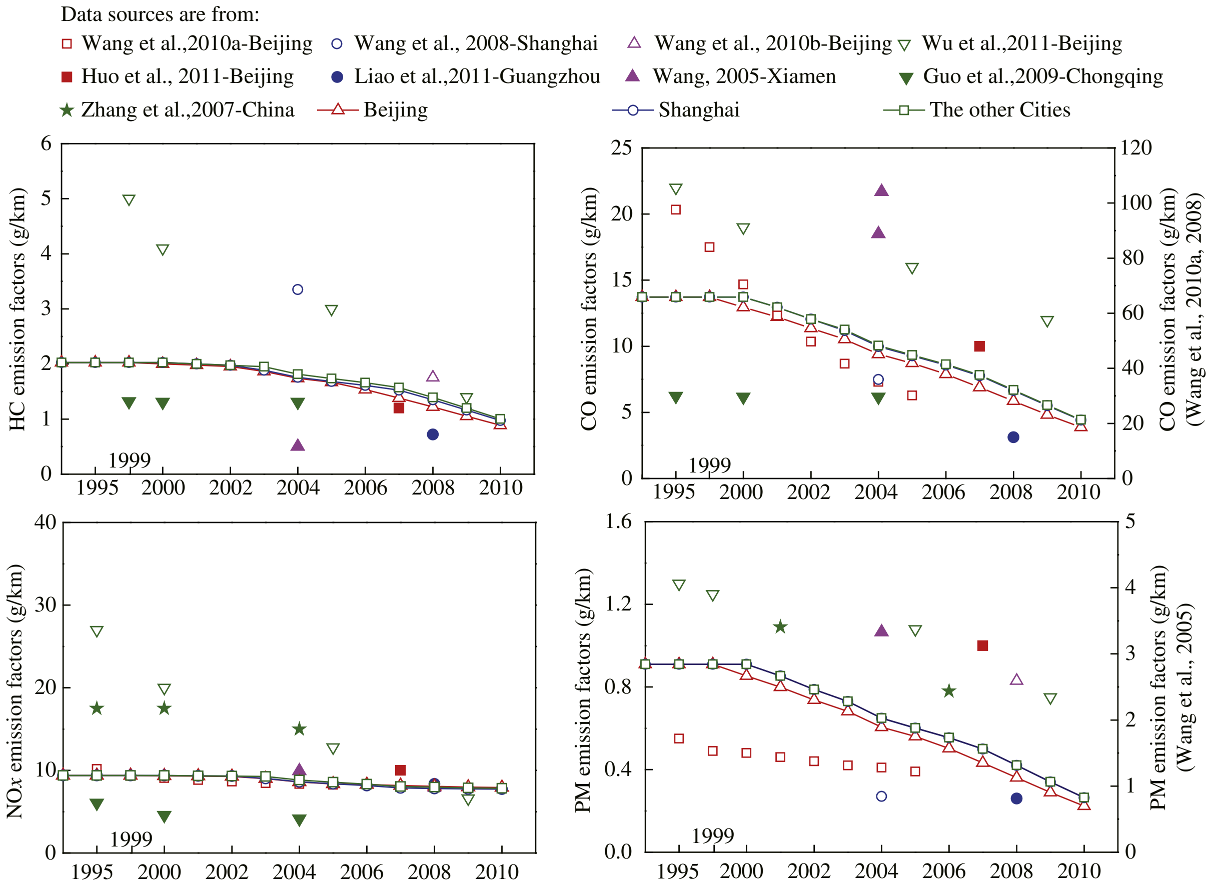

Fig. 7 – Comparison of emission factors of heavy-duty diesel trucks used in inventory studies and from measurements. Measurements mean the fleet-average emission factors in Beijing, Shanghai, and other cities in China derived from the average emission factors in the literature.

lower than the emission factors used in the study by Lang et al. (2012) for China I–IV.

The emission factors used by Guo et al. (2009) and Liao et al. (2011) were derived from the MOBILE5 and COPERT IV models, respectively; both are lower than the measurement data. The emission factors in the study by Wu et al. (2011), derived from the COPERT and PART5 models and updated by measurements in China, are higher than the fleet-average emission factors in this study. The study by Wang et al. (2010a,2008) obviously overestimates the CO emission factors, but underestimates the PM emission factors. Overall, the emission factors derived from both COPERT and MOBILE might be underestimates of the real emission factors, and the updated models might overestimate the emission factors in China. The real-world measurement results and emission factors used in recent emission inventory studies are inconsistent, which will lead to inaccurate estimates of emissions from diesel trucks and buses over recent years. The best-case scenario is to develop an emission inventory based on real-world measurements from China.

4. Conclusions and suggestions

In China, diesel trucks are a significant source of NOx and other pollutants such as PM (Zhang et al., 2009). Over recent years, on-board emission measurements have been conducted on more than 300 diesel trucks and buses in China, contributing to a better understanding of diesel truck and bus emissions.

In this study, the CO, HC, NOx, and PM emission factors of LDDTs, HDDTs, and buses reported in the literature were summarized. The results show that real world emission factors of CO, HC, and PM from diesel trucks and buses in China have been reduced significantly as the emission standards have become more stringent from China 0 to China III; however, the same trend is not true for NOx. China II and III trucks and buses have failed to show a reduction in NOx, as regulated by the standards, compared with China 0 trucks and buses. Therefore, it appears that the existing regulations are insufficient to fulfill the national targets of reducing NO_X emissions by 10% by 2015, in comparison with 2010. This trend is likely to be exaggerated further when considering the future growth in both the truck population and annual driving distances, which are projected to grow by 20% and 10%, respectively, from 2010 to 2015 (Huo et al, 2012). More stringent NOx requirements (*e.g.*, China IV and China V) need to be considered to mitigate this problem. China IV control technologies can achieve a reduction in NOx emissions of 12% to 40% compared with China III technologies. Implementation of China IV requirements has been delayed in China by two and a half years because of fuel quality problems. Currently, China IV requirements have been in effect since July 2013.

There are significant differences in emission factors of LDDTs, HDDTs, and diesel buses between the measured results, those reported in various literature sources, and those estimated by the COPERT-China model. This suggests that inventory model results based on European or US vehicle emission databases will be inherently unrepresentative of the conditions of real-world emissions in China. Therefore, it is useful and necessary to conduct vehicle emission measurements in China for direct input into emission inventory models. In addition, it is necessary to develop specific vehicle emission models based on local measurement data. Follow-up work from this study should include further measurements to complete the database that has been compiled to date. The database included in this study does not include the following: China 0 and China IV LDDTs and MDDTs, China IV HDDTs, and China 0 and China I diesel buses.

It has been found that the emission factors being utilized as inputs in emissions inventory studies come from many different sources. For example, some studies (Wu et al., 2011; Wang et al., 2010a; Lang et al., 2012; Liao et al., 2011) use emission factors derived from model results based on European databases; others, *e.g.*, Wang et al. (2008), Huo et al. (2011), Zhang et al (2009), and Guo et al. (2009), use US vehicle emission databases. This study shows that real-world measurement results and emission factors used in recent emission inventory studies are inconsistent, which will lead to inaccurate estimates of emissions from diesel trucks and buses over recent years. The best-case scenario is to develop an emission inventory based on real-world measurements from China.

Further thought should be given to PM emission factors. In order for PM emission factors to be comparable, it is recommended that similar methods and instruments be used to measure PM emissions. In addition, the definition of PM should be defined consistently. PM, $PM_{2.5}$, and PM_{10} emission factors have different meanings, yet all three definitions appear in the literature. This makes it difficult to compare reported PM emission factors from different literature studies.

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