Investigation of Diesel Emissions in China

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1. Executive Summary

Diesel trucks have been recognized as a major source of emissions in China, especially for oxides of nitrogen (NO_X) and particulate matter with diameter smaller than 2.5μm ($PM_{2.5}$). Diesel trucks have been estimated to contribute more than 20% of the total national NO_X emissions in China. China has set an aggressive target to reduce national NO_X emissions by 10% in the 12th Five-Year Plan from 2010 to 2015, and diesel trucks have been identified as a key target for NO_X control. Therefore, it is very necessary to pay more attention to emissions from diesel vehicles in China.

This project was carried out by Tsinghua University and was supported by the International Council on Clean Transportation. The purpose of this study is to understand emission factors of diesel vehicles in China based on existing research results as well as new on-road testing using a Portable Emissions Measurement System (PEMS).

All available emission factors for diesel vehicles tested in China using PEMS were collected and summarized. In total, 175 diesel trucks have been tested by our research group, with an additional 93 diesel trucks and 77 diesel buses tested by other research groups in China. According to the data, the real world emission factors of diesel trucks and buses in China were reduced significantly from Euro 0 to Euro III for all pollutants except NO_X. As compared with Euro 0, NO_X emissions from Euro II and Euro III trucks and buses failed to show a reduction as regulated by the standards. It can be concluded that the existing regulations are not enough to fulfill the national target of reducing NO_X emissions by 10% over the period 2010-2015. More stringent NO_X requirements (e.g. Euro IV and Euro V) need to be considered. Euro IV control technologies can achieve a real reduction in NO_X emissions ranging from 12 to 40% as compared to Euro III technologies. Unfortunately, the nationwide Euro IV standards were delayed in China two and a half years due to fuel quality problems. The Euro IV emission standard finally went into effect beginning July 1st, 2013, even though Euro IV diesel will not be supplied nationwide until 2015. The fuel quality problems should be solved as soon as possible.

New diesel truck testing was conducted in 2012 as part of this study. Twenty diesel trucks including 1 Euro 0, 7 Euro I, and 12 Euro III diesel trucks were tested using a Portable Emissions Measurement System (PEMS) in Xiamen and Beijing. For light duty diesel trucks (LDDTs), the test results show that the average HC and $PM_{2.5}$ emission factors are lower than the means in the literature, while the HC and NO_X emission factors are higher than those predicted by the COPERT-China model. For heavy duty diesel trucks (HDDTs), the HC, NO_X and $PM_{2.5}$ emission factors from testing have large ranges because of the variable real-world driving cycles. The CO_2 emission factors do not show any clear trend from Euro 0 to Euro III, but increase with increasing total mass.

Upon completion of the PEMS testing mentioned above, additional analysis was done to compare and analyze mean emission factors from the literature, the data in our previous and current PEMS studies, the emission factors calculated by the COPERT-China model, and the emission factors used in various existing China vehicle emissions inventory studies. The results show a lack of consistency between emission factors for diesel trucks and buses in China. The emission factors derived from the COPERT model (developed for Europe) and the MOBILE model (developed for the United States) both may underestimate emissions, while some updated models also may overestimate emission factors for China. The real-world measurement results are not consistent with emission factors used in recent emission inventory studies; this likely leads to inaccurate estimates of emissions from diesel trucks and buses for recent years. Due to the fact that emission factors are a key input into emissions inventory models, this finding indicates that model results based on European or US vehicle emissions models and databases likely do not accurately represent the real-world emissions in China. Therefore, it is useful and necessary to systematically conduct real-world vehicle emissions measurements in China in order to obtain the best inputs for the emissions inventory models. The comparison between the measurement results from this study and emission factors used in recent emissions inventory studies indicates that inventory studies may have underestimated or overestimated emissions from diesel trucks and buses for recent years. Emissions inventories for China should be developed based on local measurements.

A key finding regarding PM (particle matter) emission factors is that comparing results is complicated by the fact that different methods and instruments are commonly used to measure PM emission factors in the literature. PM is a dynamic pollutant that is constantly being influenced by its environment; therefore, its formation and size are constantly changing both in the exhaust stream and in the ambient air. Plus, particle size is divided into aerodynamic diameter and electric mobility diameter, with the different diameter PM tested by different instruments using different principles. In addition, the actual definition of PM varies between reports. Some reports use total PM, some $PM_{2.5}$ and others use PM_{10} emission factors. These varying definitions make it challenging to directly compare PM emission factors across different studies.

2. Project Background

Diesel trucks have been recognized as a major source of emissions in China, especially for NO_X and $PM_{2.5}$. Diesel trucks were found to contribute more than 20% of the total national NO_X emissions in 2006 (Zhang et al, 2009b). Diesel vehicles contributed 60% of total vehicular NO_X emissions and more than 90% of $PM_{2.5}$ in 2009 (Ministry of Environmental Protection of China, 2010). The conclusions given by Wang et al (2010b) are that vehicles contributed 66% of NO_X emissions in Beijing in 2008. In Huo's (2011) study, trucks accounted for more than 60% of NO_X emissions in Beijing in 2007, and diesel trucks could be responsible for about 40% of NO_X emissions in Beijing. In Beijing, diesel vehicles contribute 80%–90% of PM emissions from on-road sources (Huo et al., 2011; Wu et al., 2010; Wang et al., 2010a).

Over the past decade of rapid economic growth in China, the number of trucks has increased considerably, doubling from 7 million in 2000 to 15 million in 2010. Although emissions from new vehicles have decreased since 2000 due to the implementation of the Euro I, Euro II, and Euro III standards, the total amount of emissions is expected to grow owing to the strong increase in vehicle stock and distance traveled.

Despite the large estimated contribution of diesel trucks to national emissions, real-world, in-use emissions data for diesel trucks in China are relatively scarce. Current emissions inventory studies in China mostly rely on European or US vehicle emissions models and databases, which might not reflect the local conditions and performance of technologies (Huo et al., 2009). Some example of international emissions inventory models used to evaluate Chinese vehicle emissions are as follows:

- Wang et al. (2008) used a bottom-up approach based on the International Vehicle Emission (IVE) model to develop a vehicle emissions inventory for Shanghai.
- A modified and updated COPERT model and PART model were used to estimate vehicle emission factors by 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 vehicular emission factors and trends in vehicular emissions in China's mega cities from 1995 to 2005.
- Cai et al. (2010) applied the COPERT IV model to calculate vehicular emission factors in China.
- The COPERT IV model was also used by Lang et al. (2012) to develop an emission inventory for the Beijing-Tianjin-Hebei (BTH) 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, it was found that the emission factors calculated with the MOBILE5 model were smaller than the actual emissions in Chongqing.
- Motor vehicle emission factors for Guangzhou were calculated using the COPERT IV model; the data were integrated with information regarding the amounts and types of cars to produce an emission inventory of Guangzhou for the year 2008 (Liao et al., 2012).

The differences between results which rely on European or US vehicle emissions models or databases and real-world emissions can only be remedied by conducting local measurement studies. Early measurement studies focused primarily on analyzing the emissions performance of individual diesel engines (Zhang et al, 2009a) or a few trucks (Chen et al, 2007), and provided little understanding of the emissions levels of the entire truck fleet. Recent studies used more advanced measurement techniques and increased the number of samples. Westerdahl et al. (2009) derived vehicle emission factors in Beijing in 2007 on the basis of measurement results of on-road, roadside, and ambient air quality. Wang et al. (2012) conducted on-road chasing studies in Beijing and Chongqing and obtained emissions levels of black carbon (BC) and NO_X from 440 diesel trucks. These studies generated average emissions levels of the fleet; however, these data might be difficult to extrapolate to other years because the vehicle technology mix in China varies significantly over time (Huo et al., 2011).

Accurate estimation of emissions from diesel trucks also has great policy implications. In recognizing the significant negative impact of NO_X emissions on ambient environment, human health and ecological systems, China has set an aggressive target to reduce national NO_X emissions by 10% from 2010 to 2015 in the "Twelfth Five-Year Plan (2011-2015)." Diesel trucks have been identified as a key target for NO_X control. To achieve the target, it is important to understand the on-road emissions levels of diesel trucks in China so that effective measures can be implemented.

This project included the following three tasks:

(1) Review and summarize all available existing on-road emissions data for China

There are many measurements that have been done by multiple research groups over the last several years. However, these data have not yet been used for developing emissions inventories. We review and summarize all available existing on-road data, summarize the average emission factors in China from the literature, and compare against common EFs used in modeling.

(2) Carry out measurements of yellow-label diesel trucks

China's so-called yellow-label vehicles, which include all Euro 0, Euro I and Euro II diesel vehicles and all Euro 0 gasoline vehicles, are believed to have a significant contribution to total vehicle emissions. According to MEP (2010), Euro 0 and Euro I vehicles accounted for 17.1% and 25.7% of the vehicle fleet, but contributed 50% and 33% of CO emissions, 53.5% and 29.5% of HC emissions, 49.6% and 29.5% of NO_X emissions, and 55.9% and 28.4% of $PM_{2.5}$ emissions in 2009. In our previous work, we already found that yellow-label trucks have high emissions levels in terms of NO_X and PM. However, the numbers of samples were too limited to get reliable emission factors. To better understand the real world emissions, we initially planned to test 12-15 yellow-label diesel trucks in this project using PEMS. However, it was very difficult to find Euro 0 and Euro I diesel trucks in the real situation when we carried out this work, so we adjusted to test just 8 yellow-label trucks. In our previous work, we also found that Euro III diesel vehicles may have similar or even higher emission factors compared to Euro I or Euro II trucks. To confirm this finding, we tested 12 Euro III trucks. In total, we tested 20 diesel trucks (including 1 Euro 0, 7 Euro I and 12 Euro III diesel trucks). We collected CO, HC, NO_X, PM and CO_2 emission factors for these trucks using PEMS.

(3) Comparison and analysis

Finally, we analyze all the data, including the emission factor data measured by other groups as reported in the literature and in our previous study (Huo et al., 2012) (Chapter 3), the new measurement data (Chapter 4), the emission factors calculated by the China-COPERT model (Cai et al., 2010) and the emission factors used in various existing China vehicle emissions inventory studies (Chapter 5).

3. Summary of existing Chinese on-road emissions data gathered using PEMS

During 2007 and 2010, our research team conducted on-board emissions measurements of 175 diesel trucks in five Chinese cities – Beijing, Xi'an, Shenzhen, Jinan, and Yichang. Among the five cities, Beijing is the capital of China, Xi'an is the capital city of Shaanxi Province (located in the mid-west of China), 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), and Yichang is a mid-size city in Wuhan Province (located in the central part of China). Tailpipe CO, HC, NO_X, and fine particle ($PM_{2.5}$) emissions were measured using a portable emissions measurement system (PEMS).

Over the past several years, other research teams from Tsinghua University (THU), Beijing Institute of Technology (BIT), Wuhan University of Technology (WHUT), China Automotive Technology and Research Center (CATARC), Shanghai Academy of Environmental Sciences (SAES), Chinese Research Academy of Environmental Sciences (CRAES), Zhejiang University (ZJU), and Beijing University of Technology (BJUT) also conducted on-board emissions measurements of diesel trucks and buses. A summary of the total vehicles tested by these groups is shown in Table 3-1. In total, 93 diesel trucks and 77 diesel buses were tested by other groups. Reviewing and summarizing the results of these research teams is helpful for better understanding the emissions of diesel vehicles in China.

Table 3-1: Summary of existing PEMS testing by research teams in China.

		Total	THU	BIT	CATARC	SAES	ZJU	WHUT	CRAES	BJUT
LDDT <4,500 kg	Euro 0	5	5							
	Euro I	45	44					1		
	Euro II	53	51				1	1		
	Euro III	11	8				1	2		
MDDT 4,500 kg – 12,000kg	Euro 0	8	7			1				
	Euro I	11	11							
	Euro II	4	4							
	Euro III	4	4							
HDDT >12000kg	Euro 0	3	1			2				
	Euro I	43	34			8	1			
	Euro II	22	19				3			
	Euro III	55	51				1	1	2	
	Euro IV	2	2							
Diesel Bus	Euro 0	2				2				
	Euro I	2						2		
	Euro II	14	9	2			1	2		
	Euro III	33	22	4	2		5			
	Euro IV	28	24	2						2
Total		**345**	296	8	2	13	13	9	2	2
References			1, 2,3,4	5, 6	7, 8	9,10,11	12	13,14	15	16

Notes: 1-Wu et al., 2012; 2-Huo et al., 2012a; 3- Sebastian et al., 2007; 4- Sebastian et al., 2008; 5-Wang et al., 2012; 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 - only NO_X emission factors were estimated; some data overlapped with other teams' results

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

The following sections summarize the emission factors determined by these studies for various vehicle classes.

3.1 Light duty diesel trucks (LDDTs)

Light duty diesel trucks (LDDTs) are those whose gross vehicle weight (GVW) is lower than 4.5t, as show in the example in Figure 3-1. There are few reports in the literature about LDDT emission factors. In our previous study, a total of 87 LDDTs with model years ranging from 2007 to 2010 were tested in Beijing, Xi'an, Shenzhen, Jinan, and Yichang. Hou et al. (2010), using the OBS2200 and ELPI, measured LDDT emissions in Shenzhen in 2008. Xue (2010) conducted diesel truck tests in Ningbo using PEMS. Sebastian et al. (2007, 2008) conducted diesel vehicle measurements in Beijing in 2007 and in Xi'an in 2008.

Based on existing reported results, we summarized the CO, HC, NO_X and $PM_{2.5}$ emission factors of LDDTs meeting different emission standards, and calculated the average values. Few Euro IV LDDTs were tested in the literature because Euro IV had not gone into effect in China for this vehicle class. Therefore, the LDDT emission factors from Euro 0 to Euro III only are shown in Table 3-2 and Figures 3-2 through 3-5. The results indicate that the range of CO and HC emission factors are larger for Euro 0 LDDTs than other LDDTs; the reason may be the degradation of Euro 0 LDDTs. The CO and HC average emission factors decline obviously from Euro 0 to Euro III. The $PM_{2.5}$ average emission factors also decline obviously from Euro 0 to Euro III. However, the NO_X average emission factors do not show the same declining trend. More Euro IV LDDTs need to be tested to learn the emissions trends of Euro IV LDDTs.

Figure 3-1 Example of an LDDT

Table 3-2 PEMS-derived Chinese LDDT average emission factors in the literature (Mean ± Std Dev)

	CO(g/km)	HC(g/km)	NO_X(g/km)	$PM_{2.5}$(g/km)
Euro 0	5.13±2.01	1.67±0.59	5.05±1.34	0.31±0.05
Euro I	4.06±0.95	1.82±0.72	5.39±0.50	0.38±0.26
Euro II	2.67±0.58	0.97±0.35	4.96±1.58	0.25±0.15
Euro III	1.94±0.58	0.82±0.52	3.53±1.83	0.05±0.04

The Euro I and Euro II average NO_X emission factors (g/km) in the literature are similar or higher than Euro 0. The average NO_X emission factor (g/km) increased from Euro 0 to Euro I, but declined from Euro I to Euro III. The CO, HC, and $PM_{2.5}$ emission factors in the separate studies all showed similar declining trends from Euro 0 to Euro IV, but the trend is different for NO_X emission factors. In Huo et al.'s (2012) and Sebastian et al.'s (2008) studies, the Euro II NO_X emission factor is higher than the Euro I emission factor. Our research team previously tested 77 LDDTs in 2007 (Liu et al., 2009), and also found that Euro II LDDTs had slightly higher NO_X emission factors (in g/kg of fuel) than Euro I LDDTs. But in others' studies (Hou et al., 2010; Sebastian et al., 2007; Wu et al., 2012; Xue, 2010), the NO_X emission factors declined from Euro I to Euro III.

NO_X emissions from diesel vehicles have raised considerable debate not only because NO_X is a precursor to ground level ozone, but also because of the unusual trend in emissions levels as regulations get stricter. Unlike emissions of other pollutants (e.g. HC and CO) that decline as stricter standards are implemented, the NO_X emissions factors have been found to be unchanged or even getting worse over the years. In Europe, it has been reported that real-world NO_X emissions from diesel cars were much higher than the results from the certification test procedures, and there was no significant improvement in NO_X reduction over 13 years during which Euro I, Euro II, and Euro III were implemented (European Federation for Transport and Environment, 2006). One possible explanation is that the differences between the test cycle and true road driving conditions allowed manufacturers to tune engines to reduce NO_X only on the test cycle (The European Federation for Transport and Environment, 2006). Whether this is also the case in China requires further investigation.

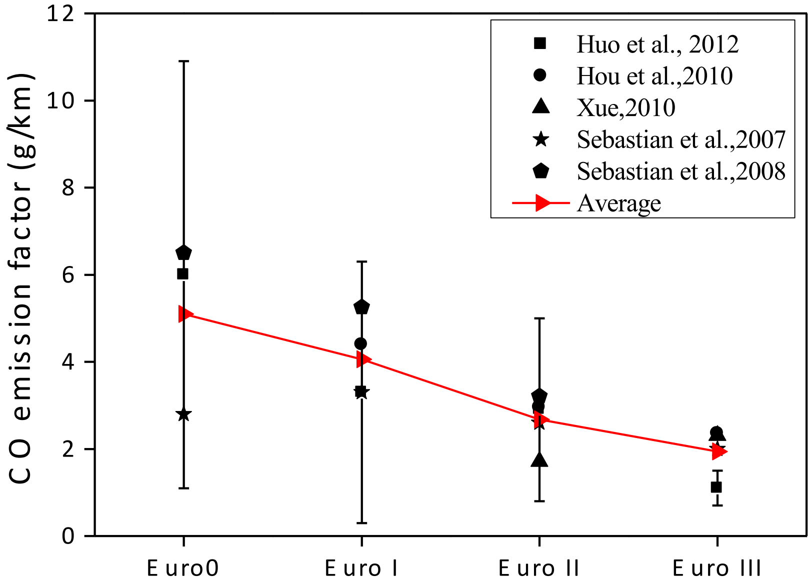

Figure 3-2 LDDT CO emission factors in the literature. *Error bars represent the standard deviations derived from Huo et al's (2012) study.*

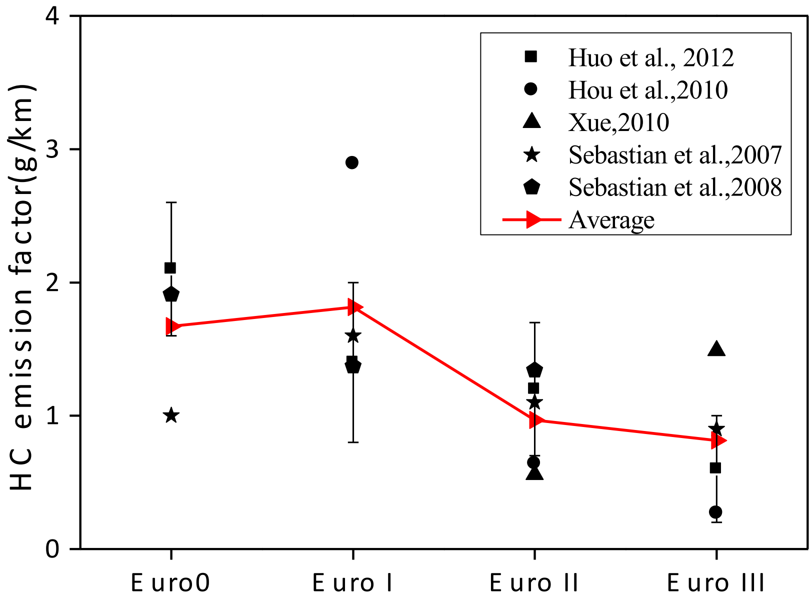

Figure 3-3 LDDT HC emission factors in the literature. *Error bars represent the standard deviations derived from Huo et al's (2012) study.*

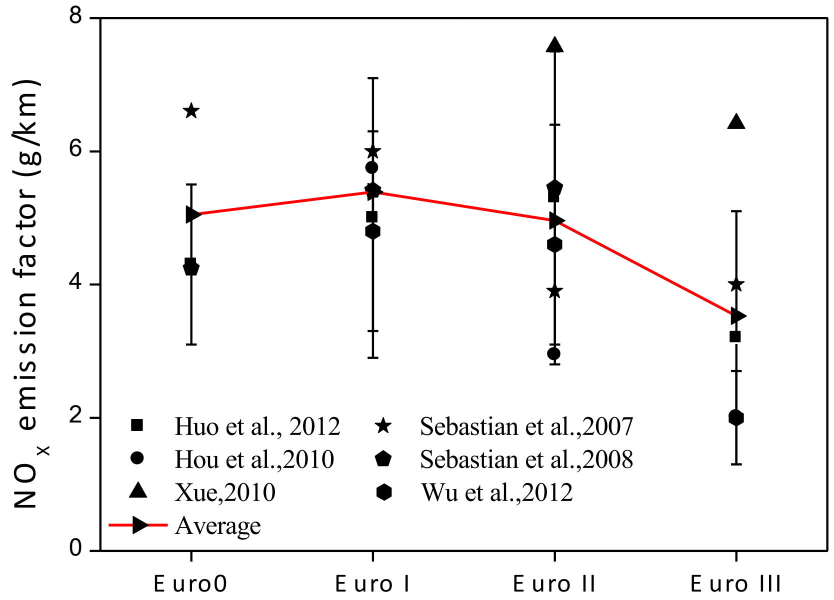

Figure 3-4 LDDT NO_X emission factors in the literature. *Error bars represent the standard deviations derived from Huo et al's (2012) study.*

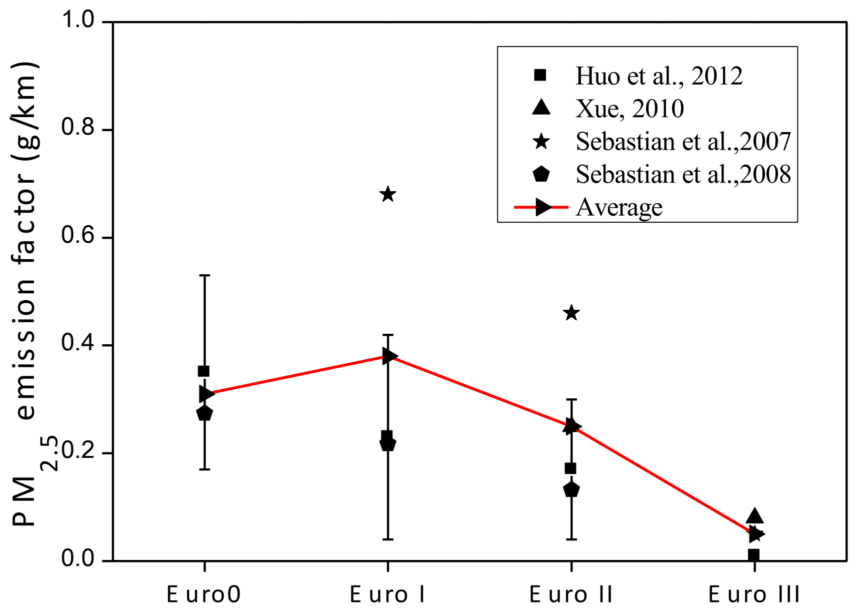

Figure 3-5 LDDT $PM_{2.5}$ emission factors in the literature. *Error bars represent the standard deviations derived from Huo et al's (2012) study.*

3.2 Medium duty diesel trucks (MDDTs)

Medium duty diesel trucks (MDDTs) refer to those trucks whose GVW is between 4.5t and 12t, for example in Figure 3-6. In our research team's previous study, we tested 26 MDDTs in Beijing, Jinan, Shenzhen and Xiamen during 2007 and 2010. Otherwise, there was only one emission factor test of a medium duty diesel truck in the literature. The average emission factors are shown in Table 3-3. The CO, HC, NO_X and $PM_{2.5}$ average emission factors decline obviously from Euro 0 to Euro III, except for Euro II. The reason for the low Euro II NO_x emission factor may be that the GVWs of the tested Euro II MDDTs were significantly lower than the other MDDTs.

Figure 3-6 Example of an MDDT

Table 3-3 PEMS-derived Chinese MDDT average emission factors in the literature (Mean±Std Dev)

	CO(g/km)	HC(g/km)	NO_X(g/km)	$PM_{2.5}$(g/km)
Euro 0	5.4±2.0	2.4±1.3	10.7±3.6	0.55±0.45
Euro I	3.8±1.7	1.4±0.6	9.7±2.6	0.49±0.29
Euro II	1.1±0.3	0.3±0.1	3.6±0.8	0.07±0.05
Euro III	1.5±1.2	0.2±0.1	6.4±1.9	0.11±0.08

3.3 Heavy duty diesel trucks (HDDTs)

Heavy duty diesel trucks (HDDT) are those whose GVW is higher than 12t, as show in the example in Figure 3-7. The emission factors of heavy duty diesel trucks are higher than light duty diesel vehicles, especially for NO_X and $PM_{2.5}$. The Euro 0 to Euro IV CO, HC, NO_X and $PM_{2.5}$ PEMS-derived emission factors of HDDTs in the literature are shown in Table 3-4 (averages) and Figures 3-8 to 3-11. Figure 3-9 shows the HC emission factors of HDDTs in the literature. Only a few Euro IV HDDTs were tested in China in our previous study (Huo et al., 2012). However, the HC sensor did not operate well during the measurements, making the HC emissions results unreliable. Therefore, the HC emission factors for Euro IV HDDTs are absent. Figures 3-8 and 3-10, respectively, show the CO and NO_X emission factors of HDDTs in the literature. Figure 3-11 shows PEMS-derived $PM_{2.5}$ emission factors of HDDTs in the literature. In Hou's (2010) study, the PM emission factors were significantly higher than those in other studies, because it also included particulate matter whose diameter was bigger than 2.5μm. (The PM emission factors in Hou's (2010) study were not included in the average $PM_{2.5}$ emission factor analysis.)

The results show that the average HC emission factors decrease from Euro 0 to Euro III. The average CO and $PM_{2.5}$ emission factors decrease significantly from Euro 0 to Euro IV. However, the NO_X emission factor does not have the same trend. The Euro III NO_X emission factor is higher than Euro II. The Euro IV NO_X emission factor only declined 44% compare to Euro 0, a lower reduction than other contaminants (CO, HC and $PM_{2.5}$). However, only 2 Euro IV HDDTs were tested, so the Euro IV HDDTs NO_X emission factor has a high level of uncertainty.

Figure 3-7 Example of an HDDT

Table 3-4 PEMS-derived Chinese HDDT average emission factors in the literature (Mean±Std Dev)

	CO(g/km)	HC(g/km)	NO_X(g/km)	$PM_{2.5}$(g/km)
Euro 0	13.73±6.89	2.03±0.18	9.38±7.67	0.91
Euro I	4.74±1.17	1.76±1.14	8.95±2.63	0.26±0.01
Euro II	3.89±2.34	1.08±0.30	6.44±3.08	0.24±0.06
Euro III	1.98±0.89	0.49±0.29	7.86±5.87	0.09±0.04
Euro IV	1.20		5.30	0.02

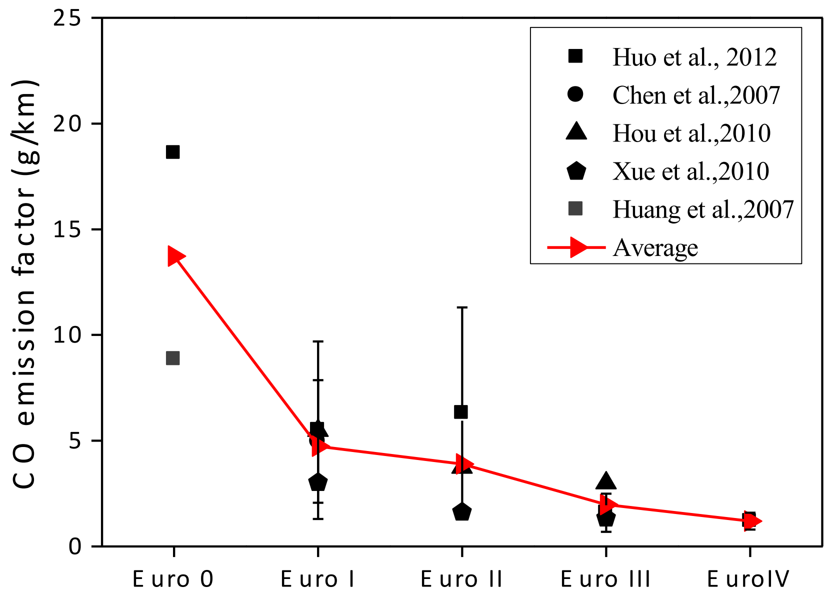

Figure 3-8 HDDT CO emission factors in the literature. *Error bars represent the standard deviations derived from Huo et al's (2012) study.*

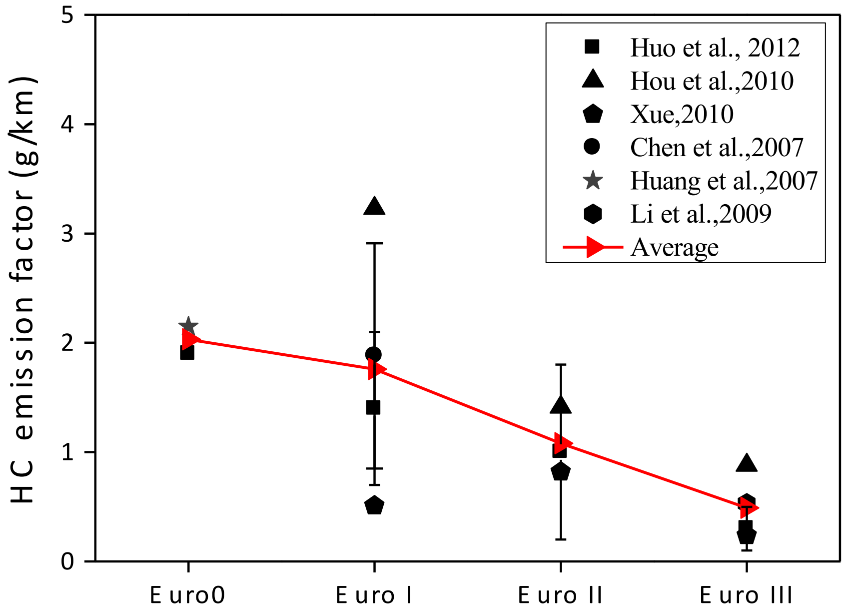

Figure 3-9 HDDT HC emission factors in the literature. *Error bars represent the standard deviations derived from Huo et al's (2012) study.*

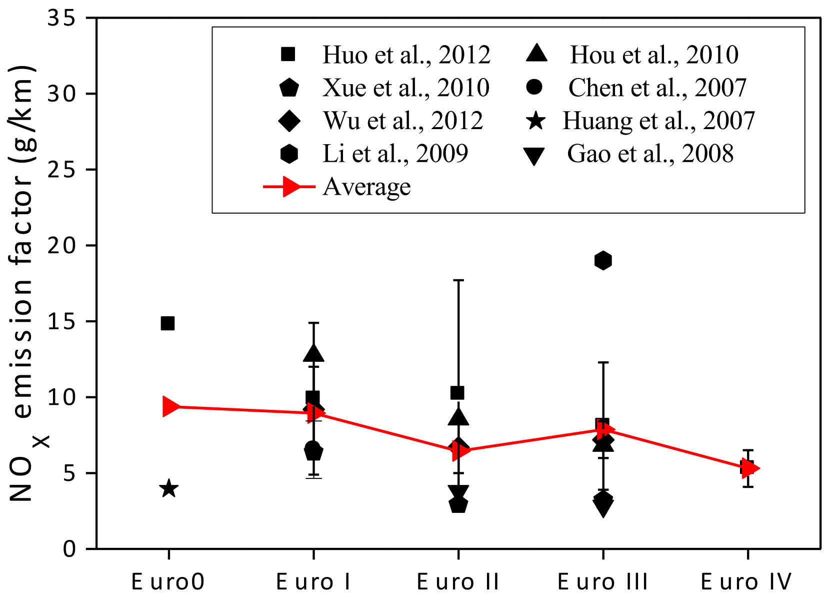

Figure 3-10 HDDT NO_X emission factors in the literature. *Error bars represent the standard deviations derived from Huo et al's (2012) study.*

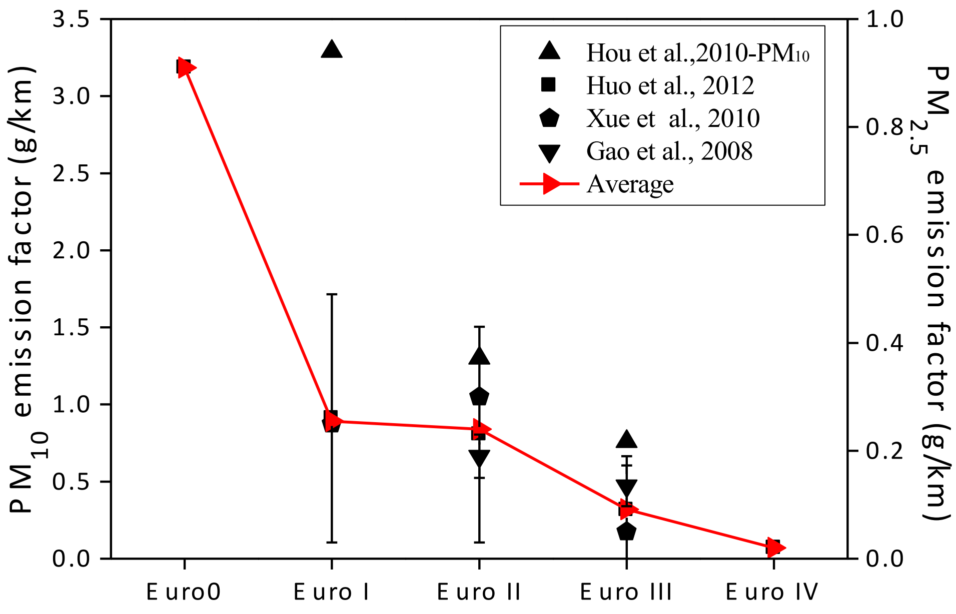

Figure3-11 HDDT PM emission factors in the literature. *Error bars represent the standard deviations derived from Huo et al's (2012) study.*

Some potential causes of the lack of significant NOx emissions reduction trend from Euro 0 to Euro IV are discussed as follows.

Yanowitz et al. (2000) found, on the basis of chassis dynamometer results of 250 different vehicles, that average emissions of PM, CO, and HC of heavy duty diesel vehicles (over 8500 lb in GVW) in the U.S. were reduced during the two decades from 1977 to 1997. During this period, emissions limit requirements equivalent to Euro I, Euro II, and Euro III were implemented in the U.S. However, average emissions of NO_X did not change, and they concluded that emissions regulations had apparently not been effective at reducing in-use NO_X. This conclusion was further proven by recent remote sensing and tunnel studies conducted in the U.S. that showed no clear decreasing trend in fleet average NO_X emission factors from 1997 to 2008 (Dallmann and Harley, 2010). Yanowitz et al. (2000) argued that it might be because some engine manufacturers used electronic controls to operate engines in a low emissions mode during the certification test, but under conditions that are not characteristic of the FTP test cycle (U.S. Federal Test Procedure), the electronic controls operate the engine in a higher fuel economy mode, resulting in considerably higher NO_X emissions for in-use vehicles.

The NO_X emissions reduction from Euro II to Euro III has been found to depend on the driving conditions. Rexeis et al. (2005) indicated that Euro III HDVs had 20-25% lower NOx emissions levels (in g/km) than Euro II HDVs under fast highway driving conditions, but equivalent NOx emission levels in slow stop & go traffic. Liu et al. (2009) concluded that Euro III LDDTs were higher in NOx emission factors (in g/km) by 2% and 10% than Euro II LDDTs under highway and urban driving conditions, respectively. Hausberger and Rexeis (2004) and Rexeis et al (2005) explained this phenomenon as follows: truck engines are optimized by manufacturers towards high fuel efficiencies in off-cycle ranges of the ESC test cycle (European Steady State Cycle) because fuel costs are a major factor for the competitiveness of HDV engines. However, this optimization results in relatively high NO_X levels, especially under stop & go traffic. In our previous study (Huo et al., 2012), we also found that Euro III HDDTs could emit up to 20% less NO_X than comparable Euro II vehicles. This might be caused by the fact that most tests for Euro III trucks were performed on highways or rural roads because trucks are usually not allowed in urban areas in Chinese cities. However, the Euro III trucks did not meet the expected reduction as required by the standards (a reduction of 30% compared to Euro II HDDTs).

While the reason for the small reduction or even increase in NO_X emissions as regulations got stricter in Europe and the U.S. were attributed to the strategies of engine manufacturers known as “cycle-beating” (Weaver, et al., 2000; European Federation for Transport and Environment, 2006), the reason in China has yet to be investigated. Regardless, it is clear that the government needs to enforce a stricter NO_X standard for diesel vehicles by requiring vehicle manufacturers to use more effective after-treatment technologies in order to achieve the national target of reducing NO_X emissions by 10% during the 12th Five-Year Plan. Euro III vehicles may not offer as much NO_X reduction as expected in the real-world, but significant reductions in NO_X emissions were observed for Euro IV diesel trucks compared to Euro III trucks. According to our measurement results, the average NO_X emission factor of Euro IV HDDTs is 33% lower than that of Euro III vehicles. Rexeis et al. (2005) reported a reduction of 40% in NO_X emission levels from Euro III to Euro IV HDVs, which is consistent with the finding of our previous study (Huo et al., 2012). Therefore, under the current circumstances, implementing the Euro IV requirement nationwide is greatly important to reducing NO_X emissions given the considerable growth in the number of diesel trucks in China.

3.4 Diesel Buses

The majority of urban buses in China utilize diesel engines. The average Euro 0 to Euro IV CO, HC, NO_X and PM emission factors are summarized in Table 3-5. Figures 3-12 to 3-15 show the CO, HC, NO_X and PM emission factors of diesel buses tested in previous PEMS studies. Few Euro 0 diesel bus CO and PM emission factors were tested, so the CO and PM emission factors for Euro 0 diesel bus are absent. In almost all the studies (Yin et al., 2011; Fan et al., 2012; Wang et al., 2011; Xue et al., 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 ELPI. The ELPI can measure PM whose aerodynamic diameter is between 28nm and 10μm.

Table 3-5 PEMS-derived Chinese bus average emission factors in the literature (Mean ± Std Dev)

	CO(g/km)	HC(g/km)	NO_X(g/km)	PM(g/km)
Euro 0		1.95		
Euro I	10.41 ± 2.62	0.82 ± 0.11	10.34 ± 4.16	4.6 ± 0.007
Euro II	9.60 ± 2.26	0.76 ± 0.59	11.78 ± 2.6	1.66 ± 0.37
Euro III	5.71 ± 2.13	0.24 ± 0.09	12.72 ± 3.63	1.30 ± 1.00
Euro IV	1.43 ± 0.01	0.04 ± 0.002	11.21 ± 0.39	0.34 ± 0.41

The average CO and PM emission factors of diesel buses decrease from Euro I to Euro IV. The average HC emission factors of diesel buses decrease significantly from Euro 0 to Euro IV. However, the NO_X emission factor does not show a declining trend.

Neither the diesel bus nor the HDDT NO_X emission factors obviously decrease from Euro I to Euro III. This could be because diesel buses and HDDTs both use similar engine technologies, or because both may use the “cycle-beating” strategy mentioned earlier. Furthermore, the real-world driving cycle of diesel buses includes more frequent stop & go traffic, which contributes to the higher NO_X emission factors of diesel buses as compared with HDDTs. The Euro II and III NO_X emission factors are higher than Euro I, and the Euro III NO_X emission factor is higher than Euro II. The Euro IV NO_X emission factor only declines 35% as compared to the Euro III emission factor, a drop ratio much lower than for the other pollutants or the diesel trucks. Euro IV CO, HC and PM emission factors all decrease compare to Euro I, but the Euro IV NO_X emission factor increases compared to Euro I.

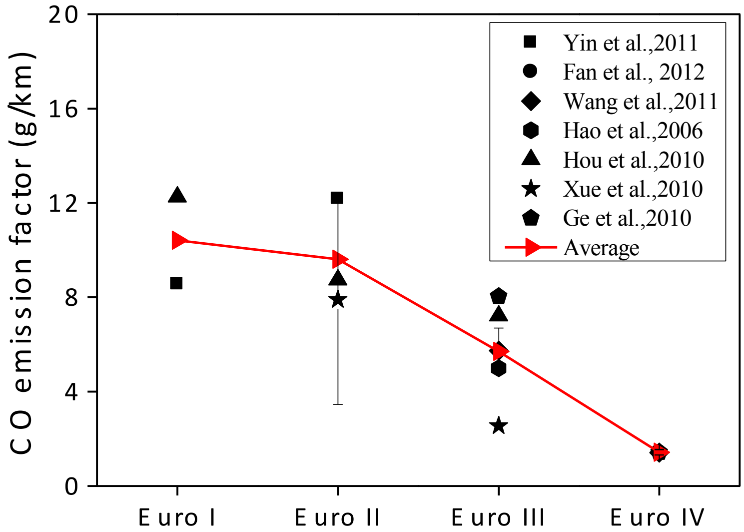

Figure 3-12 Diesel bus CO emission factors in the literature

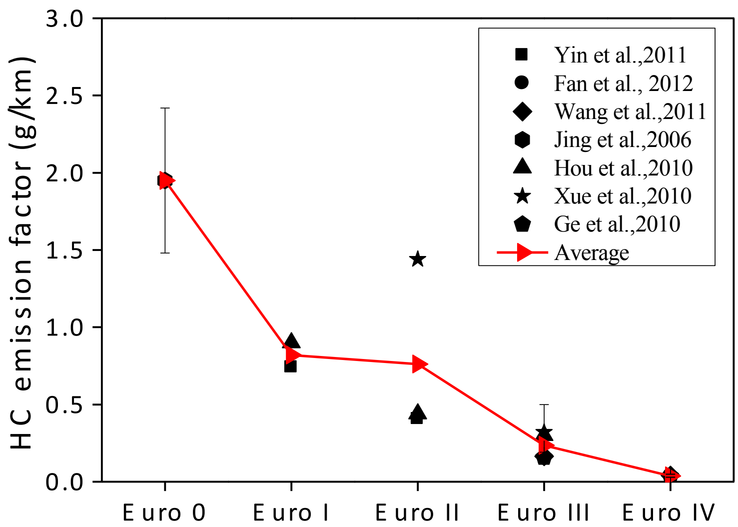

Figure 3-13 Diesel bus HC emission factors in the literature

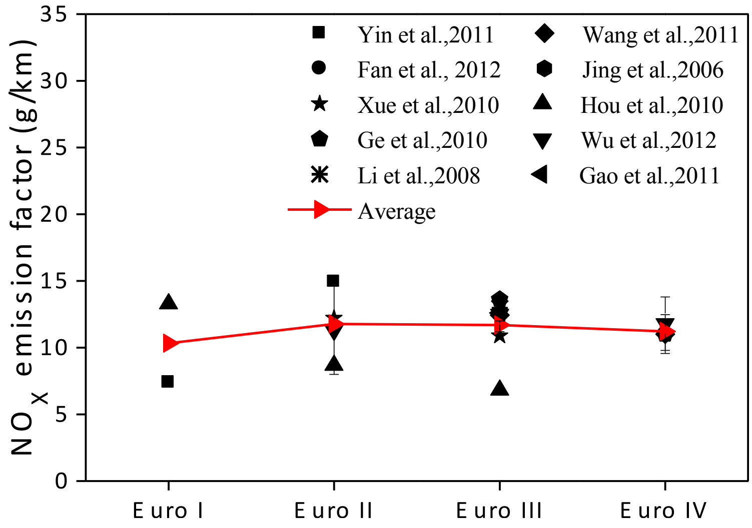

Figure 3-14 Diesel bus NO_X emission factors in the literature

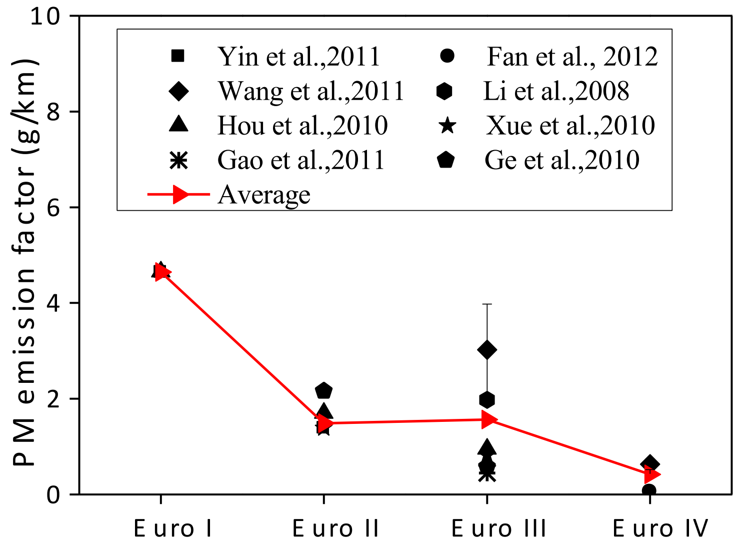

Figure 3-15 Diesel bus PM emission factors in the literature

4. New PEMS measurements of diesel truck emissions in China

In this study, we carried out new measurements of diesel truck emissions on real roads in Xiamen and Beijing using PEMS. In this chapter, we introduce the new tests and the results.

4.1 Real road emissions test for diesel vehicles

4.1.1 Test system

The test system consisted of a SEMTECH-DS gaseous pollutant analyzer, an EFM2 exhaust mass flow meter, a DMM-230 particle analyzer, a FPS-4000 dilution and sampling system, a data acquisition system, and other auxiliary instruments. The system could perform emissions tests for gaseous pollutants and particles emitted from diesel vehicles. It could also be used to test pollutant emissions from other vehicles powered by fuels such as gasoline, Natural Gas (NG), and Liquified Petrol Gas (LPG).

(1) SEMTECH-DS gaseous pollutant analyzer

Gaseous pollutants were measured by a SEMTECH-DS on-board exhaust analyzer, produced by Sensors, an American company. Vehicle emissions tests were conducted on real roads. Among the exhaust pollutants, CO and CO_2 were measured with Non Dispersive Infrared Analyzer (NDIR), THC measured with Flame Ionization Detector (FID), NO and NO_2 measured with NDUV, and O_2 measured with electrochemical method. The technical specifications for the SEMTECH-DS are shown in Table 4-1. The instrument needs 1 hour for warm-up after turning on, and then highly pure N_2 is used for its zero setting. Standard gases are used to calibrate its accuracy and veracity.

In addition, GPS carried in the SEMTECH-DS was able to record the geographical position (longitude, latitude, and altitude) and speed while the vehicle moved each second.

Table 4-1 Technical specifications for SEMTECH-DS

Pollutant	Range	Resolution	Accuracy
CO_2	0-20%	0.01%	±0.1%
CO	0-8%	10 ppm	±50 ppm
NO	0-2500 ppm	1 ppm	±15 ppm
NO_2	0-500 ppm	1 ppm	±10 ppm
	0-100 ppm	0.1 ppm	±2 ppm
THC	0-1000 ppm	1 ppm	±5 ppm
	0-10000 ppm	1 ppm	±10 ppm

(2) DMM-230 particle measurement instrument

Particles emitted from the diesel vehicles were measured with a DMM-230 particle analyzer, designed to test the mass concentration of particles at the moment of emission. The DMM-230 is produced by Dekati, a Finnish company.

(3) EFM2 exhaust mass flow meter

EFM2 is a strong and compact exhaust mass flow meter, designed by Sensors, capable of measuring the exhaust mass flow of both compression or spark ignition engine and the vehicle. It is fixed to the testing vehicle though vacuum chuck or buckle and connected with the vehicle's exhaust pipe through a high temperature hose. SEMTECH-DS can calculate, by combining the data on flows from the EFM2 and the data on concentrations from the gas analyzer, the pollutant's instant and overall mass emissions. A mass flow meter with 4 inch inner diameter, designed to measure the exhaust mass flow of all vehicles with engine cylinder displacement of less than or equal to 12 liters, was used in this study on diesel vehicles.

(4) FPS-4000 dilution and sampling system

FPS-4000 dilution and sampling system, produced by Dekati, is designed to measure the dilution and sampling of highly concentrated particles emitted from pollution sources such as vehicles and power plants. The system can realize dilution ratio adjustment at all times, and it can obtain the real-time dilution ratio throughout the process of sampling by real-time monitoring on parameters such as pressure and temperature. The system is comprised of main frame, diluted air filter, diluted air dryer, intake pressure controller for diluted air, double-level dilution channels, diluted air heater, and other parts. Key parameters are as follows: inlet flow of diluted air:

200L/min; intake pressure: 4500mbar; dilution ratio range: 1:1-1:200. In real practice of the study, dilution ratios ranging from 20 to 80 times were mostly adopted for vehicles that emit high concentration of particles. In addition, the temperature of first-level dilution air was controlled to 110℃.

(5) Data acquisition system

The entire testing system entails a laptop to collect data. SEMTECH-DS was linked to the laptop via wireless network for data communications. The special software for SEMTECH-DS installed in the laptop is able to operate SEMTECH-DS and store the data. DMM-230 and FPS-4000 are linked to the laptop via 2 USB-R232 wires for data communications. The data obtained in the test is received by and stored in these instruments, and it can be monitored from the software's interface in real time. It is detectable whether the measurement has been carried out in a correct way based on the variation curve.

(6) Other instruments

In addition to the above instruments, the entire experimental system also includes a vacuum pump, an air compressor, and two generators.

4.1.2 Test routes and vehicles

The tests were conducted in the suburbs of Xiamen and Beijing. In Xiamen, the total length of the test routes was about 31.6 km, of which 11 km were highways, as shown in Figure 4-1. As for Beijing, the total length of the test routes was about 33.2 km, of which 14.9 km were highways, as shown in Figure 4-2.

Figure 4-1 Test routes in Xiamen

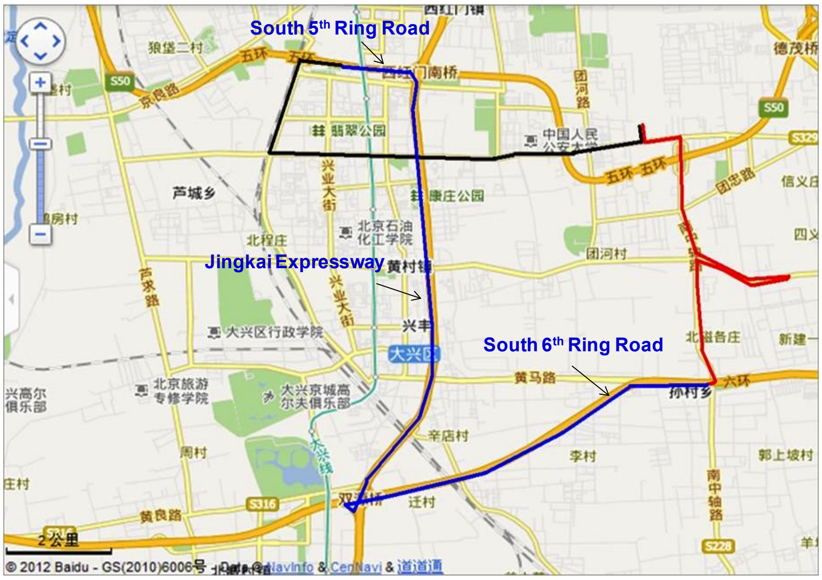

Figure 4-2 Test routes in Beijing

The tests were conducted on 11 on-road diesel trucks in Xiamen and 9 diesel trucks in Beijing. Detailed information of the tested vehicles is listed in Table 4-2.

Table 4-2 Information of the tested diesel trucks

Test No.	Test location	Vehicle Type	Model year	Total mass (kg)	Odometer (km)	Standard
01	Xiamen	HDDT	2006	20495	600,000	Euro I
02	Xiamen	HDDT	2007	20010	360,000	Euro I
03	Xiamen	HDDT	2006	24375	300,000	Euro I
04	Xiamen	HDDT	2008	16010	172,958	Euro I
05	Xiamen	HDDT	2011	25000	39,912	Euro III
06	Xiamen	HDDT	2010	31000	144,507	Euro III
07	Xiamen	HDDT	2009	28010	236,902	Euro III
08	Xiamen	HDDT	2003	17100	700,000	Euro I
09	Xiamen	HDDT	1999	14900	6,000,000	Euro 0
10	Xiamen	HDDT	2002	15560	560,000	Euro I
11	Xiamen	HDDT	2004	13890	490,500	Euro I
12	Beijing	LDDT	2009	4395	119,900	Euro III
13	Beijing	LDDT	2010	4495	47,000	Euro III
14	Beijing	LDDT	2010	4410	48,000	Euro III
15	Beijing	MDDT	2009	8290	93,673	Euro III
16	Beijing	MDDT	2009	8290	99,092	Euro III
17	Beijing	HDDT	2009	13470	140,000	Euro III
18	Beijing	HDDT	2009	15585	145,260	Euro III
19	Beijing	HDDT	2009	12140	135,865	Euro III
20	Beijing	MDDT	2007	8290	125,170	Euro III

4.2 Results

Based on the test data, we calculated the CO, HC, NO_X, $PM_{2.5}$ and CO_2 emission factors of the diesel trucks based on kilometer traveled. The new EF results are shown in Table 4-3. The CO_2 emission factors do not show an obviously declining trend from Euro 0 to Euro III (Figure 4-3a); rather, they increase with increasing of total mass (Figure 4-3b). The CO, HC, NO_X and $PM_{2.5}$ emission factors are analyzed and compared against previous results in the next chapter.

Table 4-3 EFs of the tested diesel trucks in Xiamen and Beijing

Test	EFs based on kilometer traveled (g/km)					
No.	CO	HC	NO_X	$PM_{2.5}$	CO_2	Average Speed (km/hr)
01	2.24	1.42	5.61	0.13	454.18	26.45
02	4.82	1.81	18.23	0.97	651.66	29.29
03	2.99	1.31	12.82	0.05	684.85	30.98
04	2.64	1.12	13.34	0.06	967.67	23.97
05	2.26	1.82	9.29	0.28	865.53	27.33
06	2.66	0.92	17.36	0.08	862.98	31.90
07	2.37	1.40	12.38	1.00	961.83	33.70
08	4.17	2.05	9.91	1.24	839.39	22.34
09	2.90	2.68	7.97	1.53	747.18	30.64
10	3.25	1.98	10.56	0.93	788.56	24.08
11	2.57	2.04	9.47	1.39	756.23	26.16
12	0.89	0.14	1.95	0.03	200.32	39.46
13	1.30	0.40	4.05	0.07	286.07	20.39
14	1.52	0.29	2.77	0.03	280.27	36.56
15	1.70	0.26	4.10	0.09	497.98	29.51
16	1.49	0.41	7.32	0.01	474.51	25.36
17	2.81	0.37	7.64	0.07	508.56	33.15
18	3.55	0.30	8.27	0.02	474.88	27.93
19	2.92	0.35	10.30	0.03	572.10	31.60
20	1.30	0.94	7.20	0.30	391.40	39.46

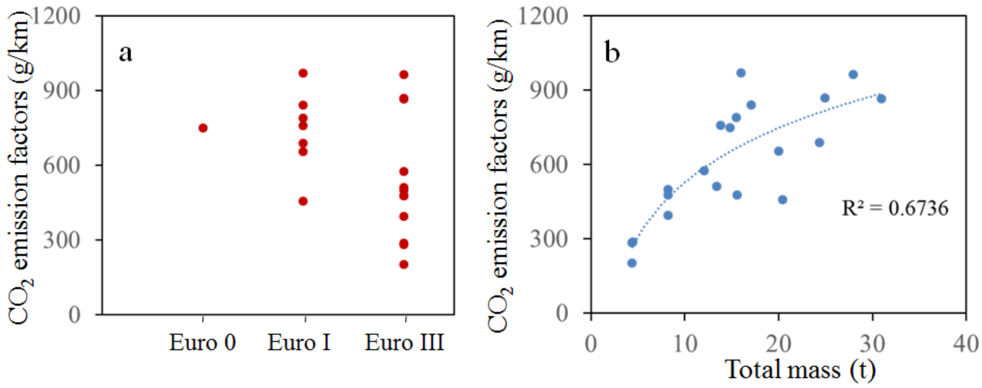

Figure 4-3 The relationships between CO_2 emission factor and emission standard and total mass

5. Comparison and analysis

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

In this part, we analyze the existing data – including the emission factor data measured by other groups in the literature and data from our research team's previous studies (in Chapter 3), and the new measurement data (in Chapter 4) – and compare it against the emission factors determined from the COPERT-China model reported in Cai et al. (2010)'s study as well as emission factors used in the other inventory studies.

5.1 Light duty diesel trucks (LDDTs)

Figures 5-1 to 5-4 present LDDT distance-specific emission factors for CO, HC, NO_X and PM as estimated by different sources. There are few emission factors for Euro IV LDDTs in the literature, and no Euro IV LDDTs were tested in our previous study, so only the COPERT-China model Euro IV LDDT emission factors are shown.

The CO EFs in the literature from measurement studies (Huo et al., 2012; Hou et al., 2010; Sebastian et al., 2007, 2008; Xue, 2010) are much higher than the COPERT-China model (Cai et al., 2010) results. For the three Euro III LDDTs tested in 2012 using PEMS, the average CO EF is 1.24g/km, which is close to the average

EF in our previous study. It should be pointed out that the GVW of LDDTs in the COPERT model is <3500kg, but is defined as <4500kg in our previous study (Huo et al., 2012). The CO emission factors decrease as emissions standards are tightened; the CO emission factors for Euro III LDDTs decreased by 65%, 62% and 82% compared to Euro 0 LDDT in the COPERT-China model, literature, and our previous study, respectively.

For HC, the mean EFs in the literature and in our previous study (Huo et al., 2012) are significantly higher than the COPERT-China model results from Euro 0 to Euro III. The average emission factor of the 3 LDDTs tested in 2012 is 0.28g/km, which is 66% and 54% lower than that in the literature and in our previous study, respectively, but higher than in the COPERT-China model. The on-road HC emission factors decrease as emissions standards are tightened; the HC emission factors for Euro III LDDTs decreased by 60% and 71% compared to Euro 0 LDDT in the literature and our previous study, respectively. However, the HC emission factors for the Euro II and Euro I LDDT in the COPERT-China model were 29% and 33% higher compared to Euro 0 LDDT. The HC emission factors in the COPERT-China model (Cai et al., 2010) are clearly different from the results of on-road tests in the literature. The HC emissions for LDDTs may be significantly underestimated based on COPERT-China model (Cai et al., 2010) results.

For NO_X, the average EFs in the literature and in our previous study (Huo et al., 2012) are significantly higher than the COPERT-China model results from Euro 0 to Euro III. The NO_X emission factors for Euro I and Euro II LDDTs are 53% lower relative to Euro 0 LDDTs in the COPERT-China model (Cai et al., 2010). However, the on-road NO_X emission factors for Euro I and Euro II LDDTs were 22% and 12% higher, respectively, relative to Euro 0 LDDTs in the literature, and 16% and 23% higher than our previous study. The average emission factor of the 3 LDDTs tested in 2012 was 2.92g/km, which is 109% higher than in the COPERT-China model (Cai et al., 2010). The NO_X emissions for LDDTs may be significantly underestimated based on COPERT-China model results.

Regarding PM, PM_{10} emission factors were calculated by the COPERT-China model

(Cai et al., 2010), but $PM_{2.5}$ emission factors were measured in our previous study (Huo et al., 2012) and in some literatures (Sebastian et al., 2007, 2008; Xue, 2010). In Wang et al. (2001)'s tunnel study, the Euro 0 LDDT PM_{10} emission factor was 2.44g/km; in Hou et al's (2010) study the Euro I, II, and III PM_{10} emission factors were 2.05g/km, 0.76g/km, 0.44g/km, respectively, which were significantly higher than the COPERT-China model (Cai et al., 2010) results. The PM_{10} emission factors for Euro III LDDTs were 60% lower compared to the Euro 0 LDDTs in the COPERT-China model, but are same as the Euro I and Euro II LDDTs. The on-road $PM_{2.5}$ emission factors for Euro I, Euro II and Euro III were 34%, 51% and 97% lower relative to the Euro 0 LDDT in our previous study (Huo et al., 2012), respectively. The $PM_{2.5}$ emission factors for Euro I, Euro II and Euro III were 22%, 65% and 86% lower relative to the Euro 0 LDDT in the literature, respectively. The average $PM_{2.5}$ emission factor of the 3 LDDTs tested in 2012 is 0.04g/km, which is lower than the average emission factor in the literature.

Because of the lack of Euro IV LDDT testing results in the literature and our study, it is important to test more Euro IV LDDTs in the future.

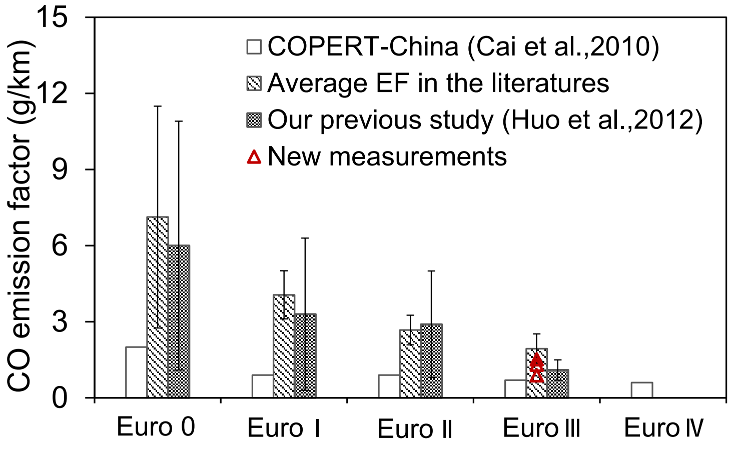

Figure 5-1 CO emission factors for LDDTs (the error bars show standard deviations)

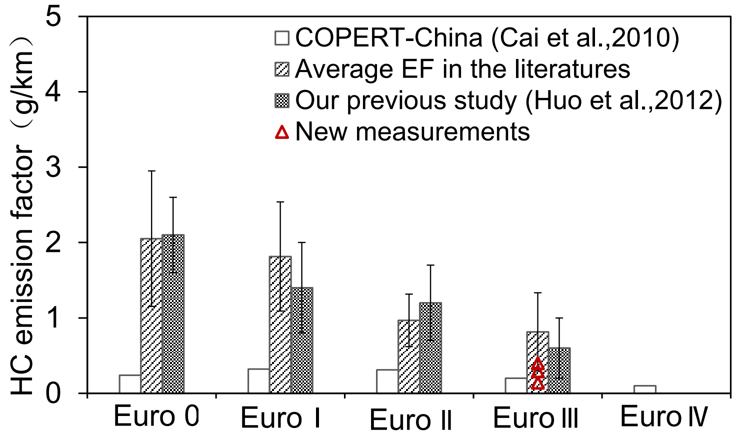

Figure 5-2 HC emission factors for LDDTs (the error bars show standard deviations)

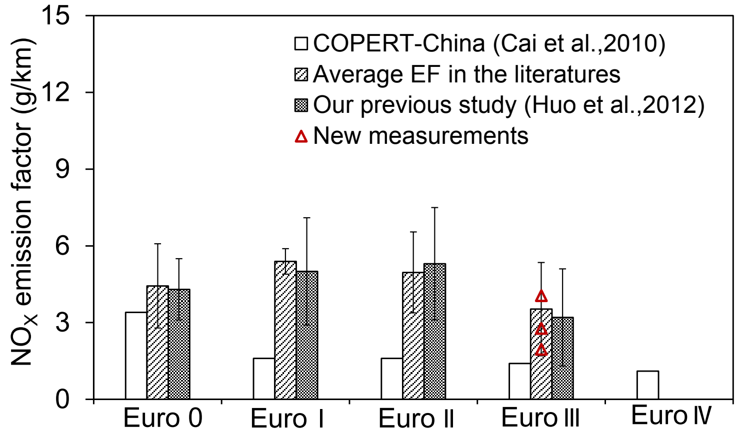

Figure 5-3 NO_X emission factors for LDDTs (the error bars show standard deviations)

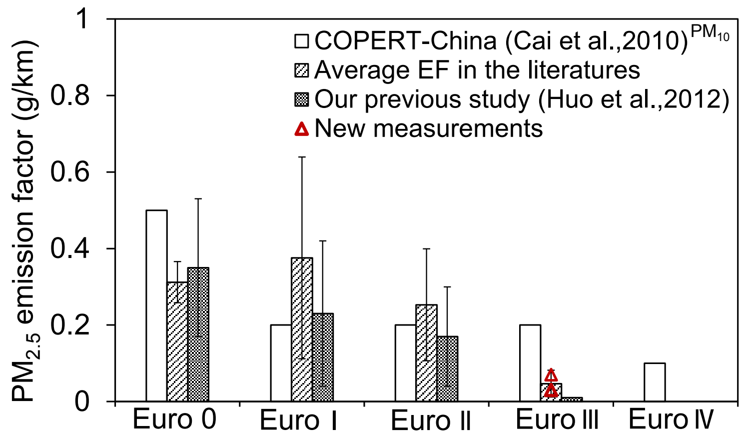

Figure 5-4 $PM_{2.5}$ emission factors for LDDTs (the error bars show standard deviations)

Table 5-1 summarizes the differences between on-road LDDT test results and emission factors estimated in by the COPERT-China model. The table highlights the dramatic underestimation of emission factors by the COPERT-China model.

Table 5-1 Comparison of LDDT distance-specific emission factors for CO, HC, NO_X and $PM_{2.5}$ from different sources. Numbers show percentage difference higher (+) or lower (-) of mean EFs in the literature (1) or our previous study (2) (Huo at al., 2010) as compared with the COPERT-China model (Cai et al., 2010).

	CO		HC		NO_X		$PM_{2.5}$	
	1	2	1	2	1	2	1	2
Euro 0	155%	200%	596%	775%	48%	26%	-38%	-30%
Euro I	351%	267%	467%	338%	237%	213%	88%	15%
Euro II	197%	222%	212%	287%	210%	231%	27%	-15%
Euro III	177%	57%	308%	200%	152%	129%	-77%	-95%

5.2 Heavy duty diesel trucks (HDDTs)

Figures 5-5 to 5-8 show the HDDT distance-specific emission factors of CO, HC, NO_X and PM from different sources.

For CO, the average EFs in the literature as well as in our previous study (Huo et al., 2012) are higher than the results in the COPERT-China model (Cai et al., 2010) for Euro 0, Euro I, Euro II and Euro IV HDDTs. The HDDT CO emission factors increased by 18% from Euro II to Euro III in the COPERT-China model (Cai et al., 2010). Conversely, our previous study showed that CO emission factors decreased by 75% during the same transition. The average CO emission factors for heavy duty diesel trucks tested in 2012 are 2.9g/km, 3.24g/km and 2.76g/km for Euro 0, Euro Ⅰ and Euro III, respectively.

For HC, the average EFs in the literature and in our previous study (Huo et al., 2012) are higher than the COPERT-China model (Cai et al., 2010) results for Euro 0 and Euro III HDDTs, but lower for Euro I and Euro II HDDTs. The on-road HC emission factors decrease as emission standards are tightened. The HC emission factors decrease by more 75% from Euro 0 to Euro III for HDDVs both in the literature and in the COPERT-China model. The average emission factors of the vehicles tested in 2012 are 2.68g/km and 1.68g/km for Euro 0 and Euro I HDDTs, respectively, which are close to the average emission factors in the literatures and our previous study. However, the average emission factor of the six Euro III HDDTs is 0.86g/km, which is 72%, 76% and 187% higher than in the COPERT-China model, the average emission factors in the literatures and our previous study, respectively. But we cannot definitively conclude that the previous studies underestimate the HC emission factor, because there are only 6 Euro III HDDT new tested samples, the other factors such as average speed, and fierce driving habits also may cause this result.

The difference of NO_X emission factors between the literature, in our previous study, and in the COPERT-China model (Cai et al., 2010) results are shown in Table 5-2 and illustrated in Figure 5-7. The NO_X emission factors are not clearly reduced from Euro I to Euro III. The average emission factors of vehicles tested in 2012 are 7.97g/km, 11.42g/km and 10.87g/km for Euro 0, Euro I and Euro III HDDTs, respectively. Previous policy evaluations (Wu et al., 2011; Zhou et al., 2010) have widely assumed a continuous decrease in NO_X emission factors as emission standards for HDDTs were tightened. Thus, NO_X emissions for China's diesel truck fleet may be significantly underestimated based on these new NO_X results.

For PM, the average $PM_{2.5}$ EFs in the literature and in our previous study (Huo et al., 2012) are lower than the PM_{10} emission factors in the COPERT-China model (Cai et al., 2010) results from Euro I to Euro IV HDDTs, as shown in Table 5-2. 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}. Many cities including Beijing were under the strong influence of continual "hazy days" in the past five years, which were characterized by high concentration 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. It is very important for us to understand the $PM_{2.5}$ emissions. But PM_{10} emission factor were calculated in some models, while the $PM_{2.5}$ emission factors were measured by PEMS, therefore the PM emission factor in model and measurement should be unified.

The on-road $PM_{2.5}$ emission factors decrease as emission standards were tightened. The $PM_{2.5}$ emission factors for Euro IV HDDTs decreased by 98%, 89% and 98%

compared to Euro 0 HDDTs in the literature, in the COPERT-China model (Cai et al., 2010) results, and in our previous study (Huo et al., 2012), respectively. The average emission factors of trucks tested in 2012 are 1.53g/km, 0.68g/km and 0.25g/km for Euro 0, Euro I and Euro III HDDTs, respectively. These are higher than the results in our previous study and the average EFs in the literatures.

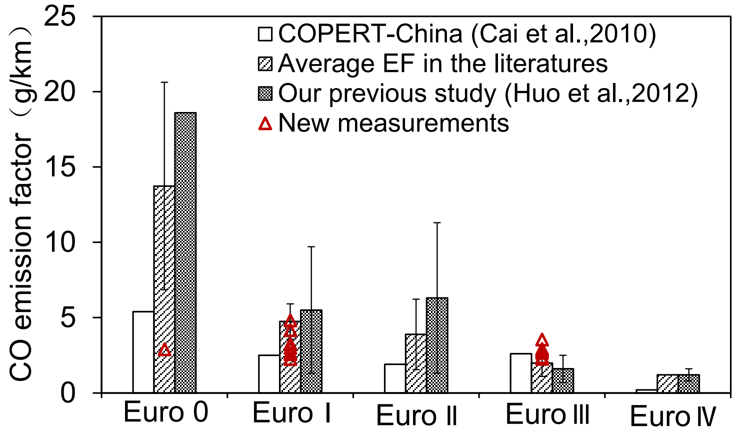

Figure 5-5 CO emission factors for HDDTs (the error bars show standard deviations)

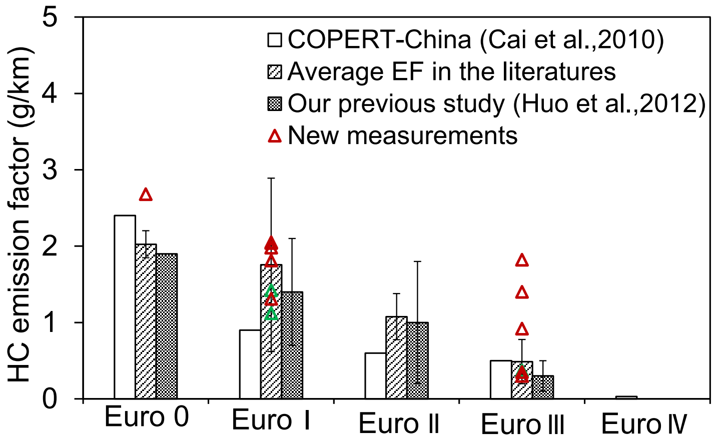

Figure 5-6 HC emission factors for HDDTs (the error bars show standard deviations)

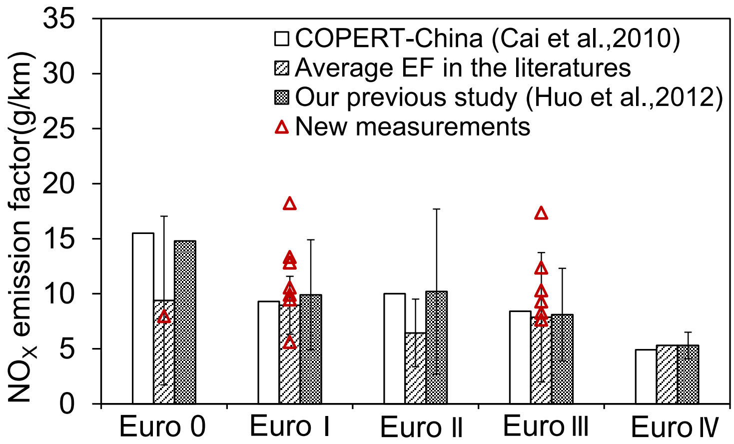

Figure 5-7 NO_X emission factors for HDDTs (the error bars show standard deviations)

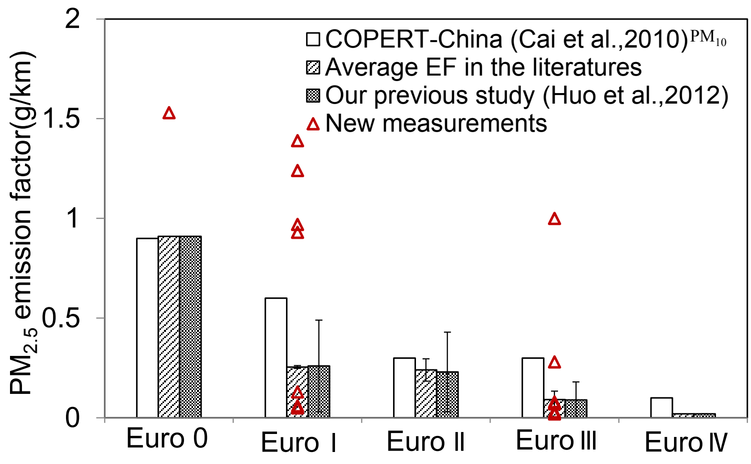

Figure 5-8 $PM_{2.5}$ emission factors for HDDTs (the error bars show standard deviations)

Table 5-2 summarizes the differences between on-road HDDT test results and emission factors estimated by the COPERT-China model.

Table 5-2 Comparison of HDDT distance-specific emission factors for CO, HC, NO_X and $PM_{2.5}$ from different sources. Numbers show percentage difference higher (+) or lower (-) of mean EFs in the literature (1) or our previous study (2) (Huo at al., 2010) as compared with the COPERT-China model (Cai et al., 2010).

	CO		HC		NO_X		$PM_{2.5}$	
	1	2	1	2	1	2	1	2
Euro 0	154%	244%	-16%	-21%	-39%	-5%	1%	1%
Euro I	90%	120%	95%	56%	-4%	6%	-58%	-57%
Euro II	105%	232%	79%	67%	-36%	2%	-20%	-23%
Euro III	-24%	-38%	-3%	-40%	-6%	-4%	-69%	-70%
Euro IV	500%	500%			8%	8%	-80%	-80%

5.3 Diesel buses

Figures 5-9 to 5-12 compare the diesel bus distance-specific emission factors for CO, HC, NO_X and PM in the COPERT-China model (Cai et al., 2010) and in the literature. The mean CO and PM emission factors in the literature are significantly higher than the COPERT-China model for Euro I to Euro IV. The differences in HC and NO_X emission factors between the COPERT-China model and means in the literatures are smaller than for CO and PM. The NO_X emission factors in the COPERT model were highly similar to the means in the literature; neither of them have a deceasing trend from Euro I to Euro III.

Diesel buses may be a major PM source in urban areas, because diesel trucks in China 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 clearly understand the emission factors of diesel buses. Because the existing samples of tested diesel buses are limited, more diesel buses should be tested.

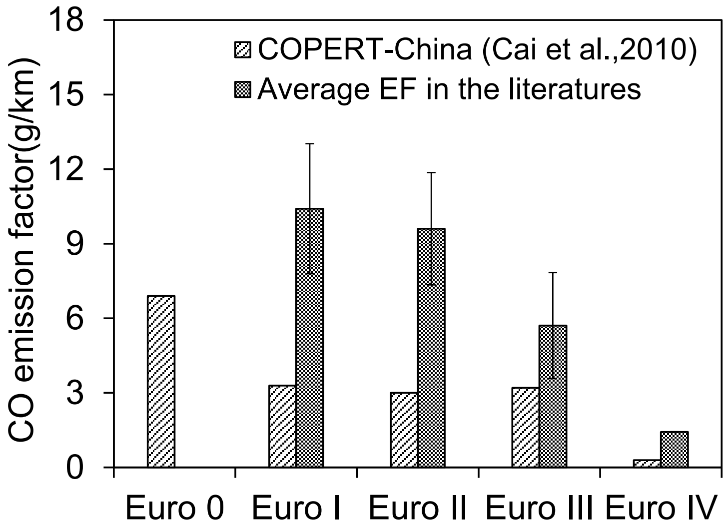

Figure 5-9 CO emission factors for diesel buses (the error bars show standard deviations)

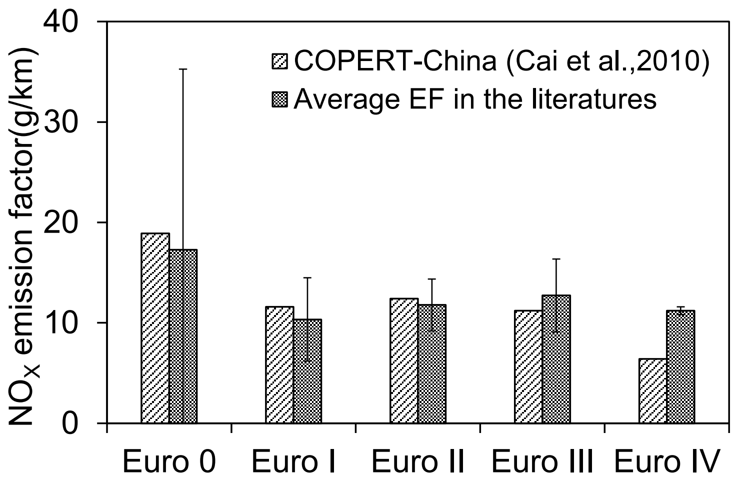

Figure 5-10 HC emission factors for diesel buses (the error bars show standard

deviations)

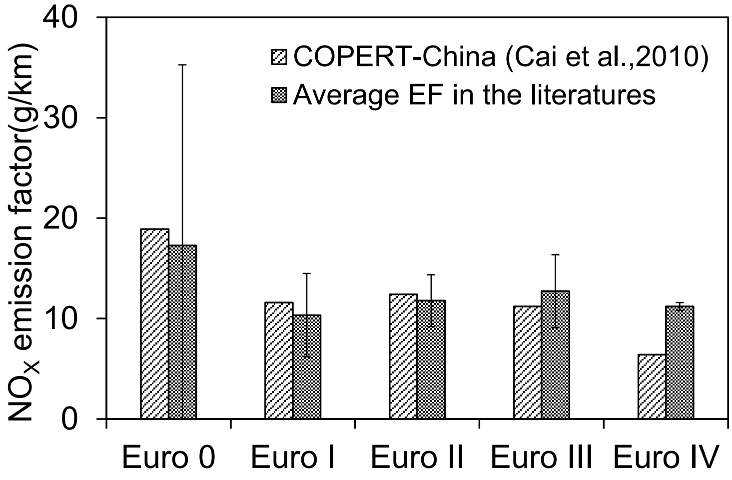

Figure 5-11 NO_X emission factors for diesel buses (the error bars show standard deviations)

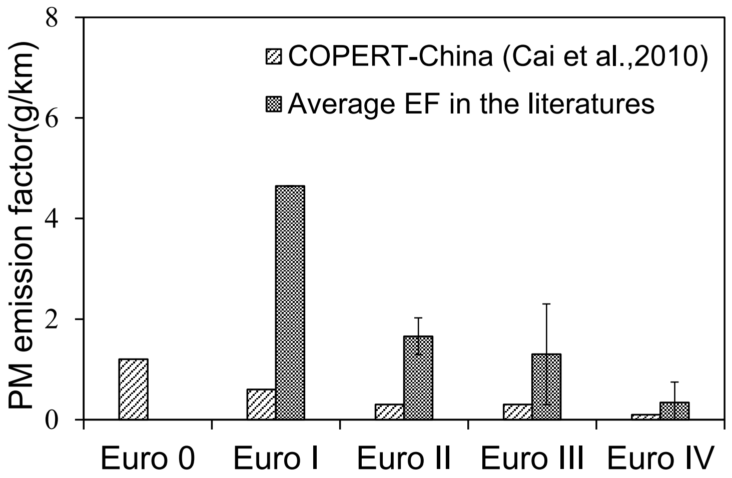

Figure 5-12 PM emission factors for diesel buses (the error bars show standard deviations)

5.4 Evaluation of emission factors used in recent emissions inventory studies

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

Figures 5-13 to 5-16 summarize the on-road CO, HC, NO_X and $PM_{2.5}$ emission factors (in g/km) utilized in recent inventory studies, and the average emission factors in the literature. It should be pointed out that the emission factors used in the inventories are the average fleet emission factors, so 1994, 1995, and 1999-2010 HDDTs fleet average emission factors were calculated based on measured emission factors according to different emission standards and data of technology distribution in Beijing, Shanghai and other cities in China.

The CO, HC, NO_X 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 (Wang et al., 2005; Wu et al., 2011; Wang et al., 2008; Wang et al., 2010a) are higher than the fleet average emission factors derived from measurements, especially in Wang's (2008, 2010a) studies, in which the CO EFs are 7 times higher than fleet average emission factors in the literature. But the CO emission factors used in some other inventory studies (Guo et al., 2009; Liao et al., 2010) are lower than the fleet average emission factors derived from measurement. The CO emission factors used in Wang et al., (2010a) study also come from COPERT model, but have an order of magnitude difference with the COPERT-China model (Cai et al., 2010) results.

For HC, the emission factors used in some inventory studies (Wu et al., 2011; Wang et al., 2008) are higher than the average emission factors in the literature. For NO_X, the emission factors used in some inventory studies (Wu et al., 2011; Zhang et al., 2007) are higher than the average emission factors in the literature for the period 1995 to 2001. For $PM_{2.5}$, the EFs 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 lower than the emission factors used in Lang's (2012) study for Euro I to Euro IV.

The emission factors used in the Guo et al. (2009) and Liao et al. (2012) studies were derived from the MOBILE5 and COPERT IV models, respectively; both are lower than the measurement data. The emission factors in the Wu et al. (2010) study, derived from the COPERT and PART models and updated by the measurement in China, are higher than the fleet average emission factors in this study. The Wang et al., (2010a) study obviously overestimated the CO emission factors, but underestimated the PM emission factors. Above all, the emission factors derived from COPERT and MOBILE both may underestimate the real emission factors, and updated models also may overestimate the emission factors in China. The real world measurement results and emission factors used in recent emission inventory studies are not consistent, which will lead to inaccurate estimates of emissions from diesel trucks and buses for recent years. The best case scenario is to develop an emission inventory based on the local real world measurements in China.

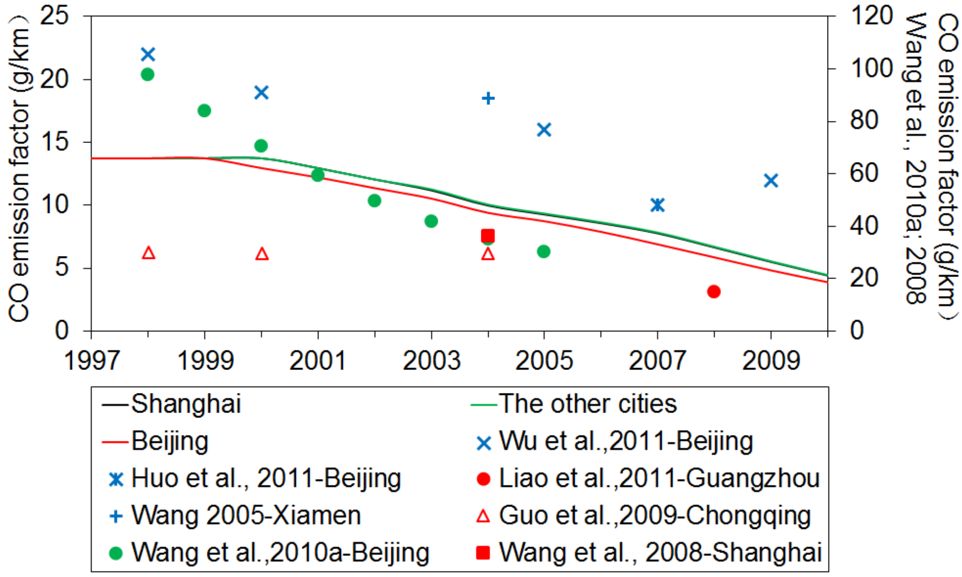

Figure 5-13 Comparison of CO emission factors of HDDTs in inventory studies (points) and from measurements (lines). Measurements mean the fleet average emission factors in Beijing, Shanghai and the other cities in China derived from the average emission factors in the literatures.

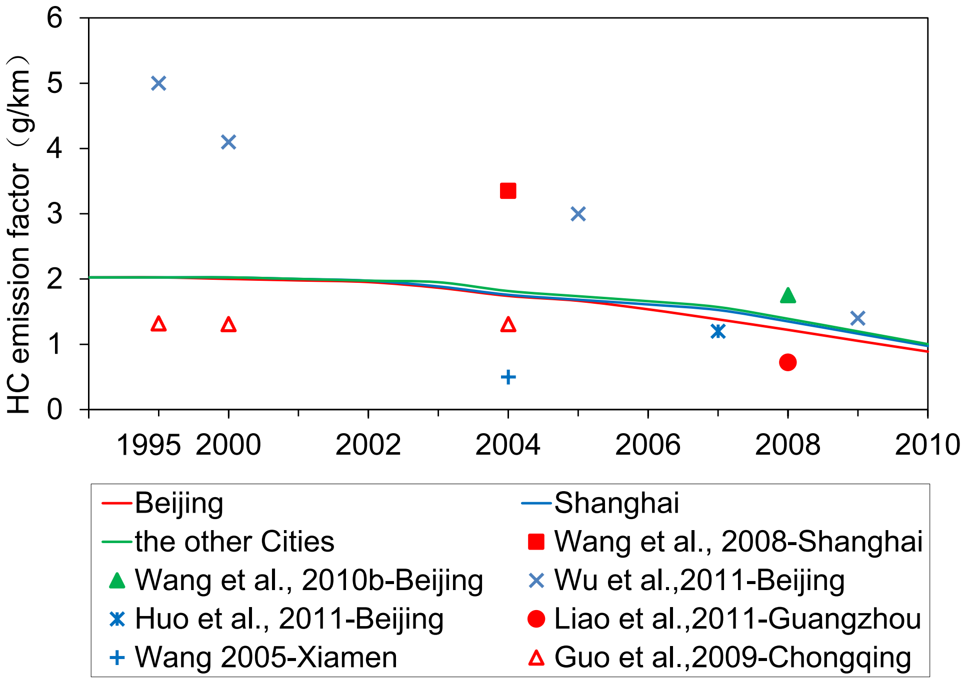

Figure 5-14 Comparison of HC emission factors of HDDTs in inventory studies (points) and from measurements (lines). Measurements mean the fleet average emission factors in Beijing, Shanghai and the other cities in China derived from the average emission factors in the literature.

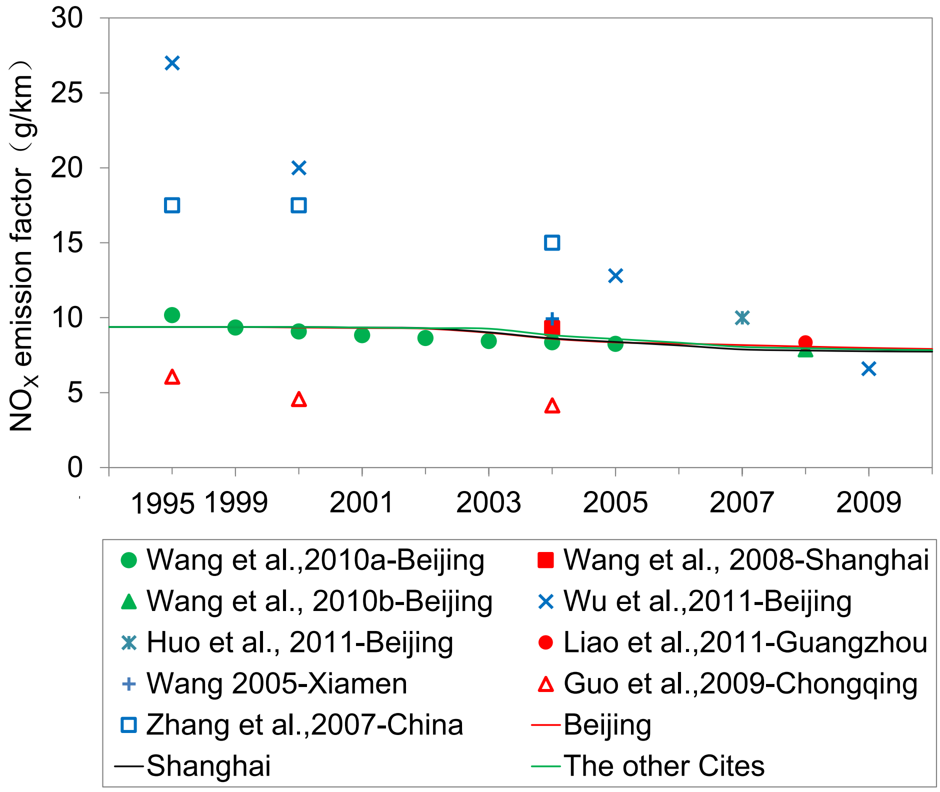

Figure 5-15 Comparison of NO_X emission factors of HDDTs in inventory studies (points) and from measurements (lines). Measurements mean the fleet average emission factors in Beijing, Shanghai and the other cities in China derived from the average emission factors in the literature.

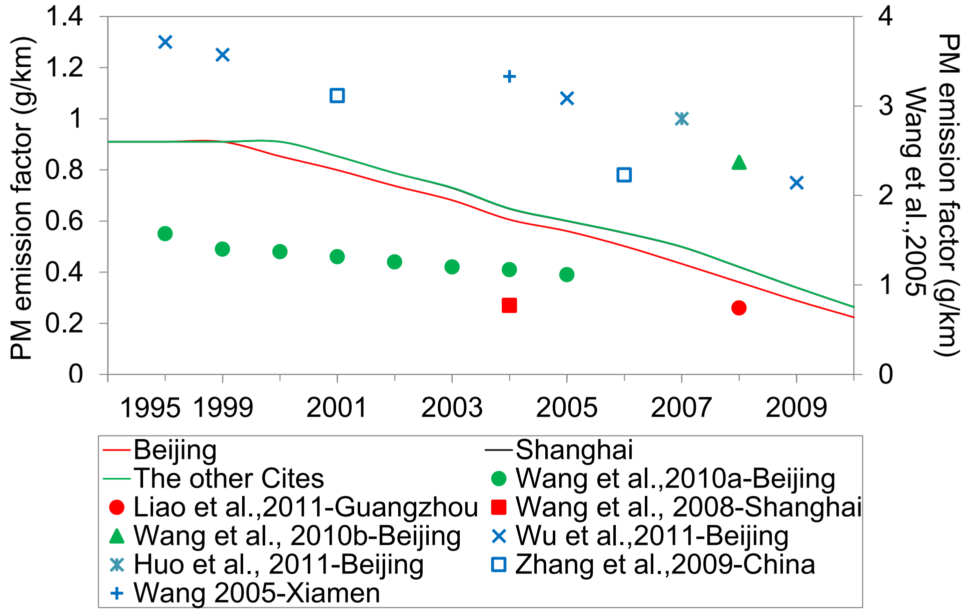

Figure 5-16 Comparison of $PM_{2.5}$ emission factors of HDDTs in inventory studies (points) and from measurements (lines). Measurements mean the fleet average emission factors in Beijing, Shanghai and the other cities in China derived from the average emission factors in the literature.

6. Conclusions and Suggestions

Diesel trucks are a significant source of NO_X and other pollutants such as particulate matter in China (Zhang et al., 2009b). Over the past few years, on-board emissions 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, NO_X and PM emission factors of LDDTs, HDDTs and buses 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 emission standards have become more stringent from Euro 0 to Euro III. However, the same trend is not true for NO_X. Euro II and Euro III trucks and buses failed to show a reduction in NO_x as regulated by the standards compared to Euro 0 trucks and buses. Therefore, it appears that the existing regulations are not sufficient to fulfill the national target of reducing NO_X emissions by 10% by 2015 as compared with 2010. This trend is exasperated when considering the future growth in the truck population and annual driving distance of individual trucks, which are projected to grow by 20% and 10%, respectively, from 2010 to 2015 (Huo et al, 2012). More stringent NO_X requirements (e.g. Euro IV and Euro V) need to be considered to mitigate this problem. Euro IV control technologies can achieve a reduction in NO_X emissions of 12-40% compared to Euro III technologies. The Euro IV requirements were delayed by two and a half years in China due to fuel quality problems, and only finally became effective in July 2013.

There are significant differences in emission factors of LDDTs, HDDTs and diesel buses between measured results, those reported in various literature sources, and those estimated by the COPERT-China model (Cai et al., 2010). This suggests that inventory model results based on European or US vehicle emission databases will be unrepresentative of the real-world emissions conditions in China. Therefore, it is useful and necessary to conduct vehicle emission measurements in China for direct input into emissions inventory models. In addition, it is necessary to develop vehicle emissions models themselves 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: Euro 0 and Euro IV LDDTs, MDDTs, Euro IV HDDTs, and Euro 0 and Euro I diesel buses.

It has been found that the emission factors being utilized as inputs into 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., 2012) use emission factors derived from model results based on European databases. Others (Wang et al., 2008; Huo et al., 2011; Zhang et al, 2009b; Guo et al., 2009) use US vehicle emissions databases. It has been shown in this study that real world measurement results and emission factors used in recent emission inventory studies are not consistent, which will lead to inaccurate estimates of emissions from diesel trucks and buses for recent years. The best case scenario is to develop an emission inventory based on the local real-world measurements in 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 consistently defined. 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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