Aerosol and Air Quality Research, 16: 1893–1902, 2016

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2015.09.0534

Real-World Emission from In-Use Construction Equipment in China

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ABSTRACT

In-use emission factors of 11 pieces of construction equipment were collected using a portable emission measurement system. These vehicles include excavators, bulldozers and loaders. Both regulated pollutants and PM carbonaceous compositions were tested. The emission factors of CO, HC, NO_x and PM for these vehicles are 13–91 g kg^{-1}, 12–63 g kg^{-1}, 1.4–27 g kg^{-1}, and 2.5–13 g kg^{-1} respectively. Their fuel consumption rates are also provided. The vehicles in the idling mode are higher in the emission factors of CO and HC than those in the other operating modes. The vehicles certified to different emission standards are significantly different in PM carbonaceous compositions. The analysis by GC-MS shows that the majority of particle-phase PAHs from these vehicles are 2- or 3-ring PAHs, while high-molecular-weight PAHs are seldom detected. There is a great difference in the emission factors of PM and OM between the vehicles at the start-up phase and those in the normal idling mode. Some conclusions and recommendations are made by comparing this study with some others.

Keywords: Portable emission measurement system; Construction equipment; Emission factor; Carbonaceous particle; Particle-phase PAHs.

INTRODUCTION

Construction equipment is an important kind of nonroad mobile emission source. Most construction vehicles are powered by diesel, whose key pollutants include carbon monoxide (CO), total hydrocarbon (THC), nitrogen oxide (NO_x), and particulate matter (PM) (Frey *et al.*, 2008; Fu *et al.*, 2012).

A lot of studies were done to understand the emission from construction equipment. Some calculated the emission inventory using modeling. Li *et al.* (2012) calculated the emission inventory of NO_x and PM from construction equipment in China. The excavators and the loaders in China emit 6.81×10^5 ton of NO_x and 5.31×10^4 ton of PM annually in Li's prediction. Zhang *et al.* (2010) calculated the emission inventory of NO_x, VOC, CO and PM from construction equipment in the Zhujiang River Delta. The widely used model in these studies is the NONROAD model developed by EPA (EPA, 2009), whose emission factors (EFs) are calculated based on engine dynamometer test. It is based on a prescribed cycle which differs from the real-world duty cycle. Remote-sensing and portable emission measurement system (PEMS) are the common methods to obtain real-world EFs. Using PEMS to study real-world emission is thought to be a reliable, accurate and low-cost method (Kousoulidou *et al.*, 2013). It has been frequently used in on-road vehicle emission studies (Huang *et al.*, 2013; May *et al.*, 2014; Vlachos *et al.*, 2014; Yao *et al.*, 2015) and has also been introduced to testing the emission of construction equipment. Frey *et al.* (2008) tested several vehicles fueled with petroleum diesel and biodiesel, and proposed operating mode based method; Frey *et al.* (2010) reported an on-board study of 39 pieces of construction equipment; Adolhasani *et al.* (2012) provided a case study for 3 excavators; Fu *et al.* (2012) firstly provided the on-board emission test result for non-road machinery in China. These studies offered valuable real-world emission test results from construction equipment, and researched on the influence of in-use operating mode. However, results of PM carbonaceous compositions from construction equipment are seldom reported. The start-up emission from construction equipment also needs investigation.

Among the key pollutants from construction equipment, there is a growing attention on PM. In general, PM from diesel

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combustion sources contains carbonaceous compositions, sulfate and ash (Khan *et al.*, 2013). Carbonaceous compositions include organic carbon (OC) and elemental carbon (EC). OC is majorly from unburned fuel, oil and combustion byproducts while EC is from fuel droplet pyrolysis (Shah *et al.*, 2004). They may influence the urban environment, causing visibility impairment (Kim *et al.*, 2006), climate change (Kigoshi *et al.*, 2014) and damage to cultural relics (Bergin *et al.*, 2015). PM carbonaceous compositions also contain carcinogens and mutagens. Polycyclic aromatic hydrocarbons (PAHs) are among the major carcinogens in OC, although they are precious little in mass fraction (Lima *et al.*, 2005). It is found that the mean median diameters of various kinds of PAHs are located in the range of fine particle (Lu *et al.*, 2012) which is more likely to penetrate into human's respiratory system than the coarse one (BéruBé *et al.*, 2007). Therefore, considering the great impact of carbonaceous particle on environment and human's health, it is necessary to investigate the carbonaceous particle from construction equipment.

The purpose of this paper is to enhance the understanding of emission characteristics of construction equipment. The selected vehicles are of three different types and two different emission standards. This paper provides the EFs of both regulated pollutants and PM carbonaceous compositions under different operating modes and thus enriches the database.

METHODOLOGY

Test Instruments

The measurement system includes a SEMTECH-DS, a particle sampler and some relevant accessories. The SEMTECH-DS was employed to measure gaseous pollutants. It is able to detect CO and CO_2 by non-dispersive infrared (NDIR), NO and NO_2 by non-dispersive ultraviolet (NDUV), and total hydrocarbon (THC) by flame ionization detector (FID). The SEMTECH-DS measures the ambient temperature, humidity and pressure by a weather station to modify the results. The exhaust was sampled by an automatically heated hose and the flow rate was measured by a Pitot tube (SEMTECH-EFM). The particle sampler used to collect PM in the exhaust contained two sampling channels without size-selective inlet. Each channel contained a quartz-fiber filter whose diameter was 47 mm. The sampling volumetric flow rate was set to 10 L min^{-1}. Before entering the sampler, the exhaust was diluted by a two-stage diluter with a constant dilution ratio of 64. The diluted exhaust in the first stage was heated up to 190°C while the second stage was not heated. An air compressor with an air filter was used to supply the air (0.2 MPa) to dilute the exhaust. All these instruments were fastened to the vehicle by iron wire or fastening band. These instruments were powered by external batteries. Three batteries were used, and they weighed approximately 160 kg.

The filters were baked in a muffle furnace whose temperature was set to 850°C for 12 hr before the test. They were weighed by Sartorius Filter Balance CPA2P-F in a constant temperature and humidity machine (25°C and 45%) before and after sampling respectively. Then a part (0.5 cm^2) of the sample was punched, and then analyzed by a Thermal/Optical Analyzer (TOA) to determine the amount of OC and EC using Thermal/Optical Reflectance (TOR) following the IMPROVE-A protocol. According to the protocol, the punched parts were placed in helium which was heated to 140°C, 280°C, 480°C and 580°C, to determine OC1, OC2, OC3 and OC4 respectively. Then the ambiance was switched to 98% helium and 2% oxygen, and heated to 580°C, 740°C and 840°C to determine EC1, EC2 and EC3 respectively. The rest of the sample was analyzed by GC-MS (Agilent 5975-6890) to determine particle-phase PAHs. Before tested by GC-MS, the sample was soaked in dichloromethane for 24 hr to extract particle-phase PAHs. The analysis followed the procedure provided in Chinese environmental standard HJ 646-2013. Sixteen kinds of PAHs are concerned in this study.

Tested Vehicles and Their Operating Modes

The detailed information of the construction equipment is shown in Table 1. They are all in-use vehicles selected at construction sites in the city of Dalian, China. No emission aftertreatment system was employed in these vehicles. As China Stage 2 emission standard is still in force for nonroad machineries, in-use construction equipment is rarely certified to stricter emission standard. Therefore, the selected vehicles are of either China Stage 0 (not certified to any emission standard) or China Stage 2 (equivalent to Euro 2). In all the Stage 2 vehicles, turbocharging system was equipped.

Some points made in this manuscript are based on the comparison between the vehicles certified to the two stages. The comparison is based on fuel-based EFs, which are less affected by vehicle weight and engine power (Fu *et al.*, 2012). Fuel-based EFs are widely used to compare different combustion sources (Zhi *et al.*, 2008; Moldanová *et al.*, 2009; Guo *et al.*, 2014) as it is a good way get rid of the influence of different burners. Therefore, we accept the rationality of this method. As the tested loaders in this study use similar engines, we take the loaders for example to illustrate the relevant points.

This study concerns the three typical operating modes of construction equipment: idling, moving and working (Frey *et al.*, 2008, Adolhasani *et al.*, 2012). Idling refers to the operating mode that the vehicle remains stationary. Moving refers to the mode that the vehicle moves forward or backward, or adjusts its position and direction but its bucket or shovel is not in operation. Working refers to the mode that the vehicle undertakes its designed function with its functioning part (i.e., using bucket or shovel).

Test Procedure

Before the test, all the instruments and hoses were purged and cleaned to ensure that the results are not influenced by the previous test. The SEMTECH-DS needed to warm up for about 30–40 min. To ensure the accuracy, the SEMTECH-DS was sealed and leak-tested before each test. The leak test results showed that the vacuum loss of the sealed system did not exceed 5% within 20 s. After the leak test, the SEMTECH-DS was zeroed and calibrated by calibrating gas.

Table 1. Detailed Information about the Tested Vehicles.

No.	Type	Model	Rated Power	Rated Speed	Displacement	Gross Weight	Number of Cylinders	Model Year	Engine Type	Emission Standard
			kW	rpm	L	ton				
1	Excavator	H330	185	2000	7.8	30	6	2005	Naturally Aspirated	Stage 0
2	Excavator	DH300LC7	147	1900	8	30	6	2011	Turbocharged	Stage 2
3	Excavator	JS-370LC	212	1900	7.8	38	6	2014	Turbocharged	Stage 2
4	Bulldozer	T140	140	1800	12	17	6	2000	Naturally Aspirated	Stage 0
5	Bulldozer	TY220	175	1800	14	32	6	1999	Naturally Aspirated	Stage 0
6	Bulldozer	60W-2	175	2200	10	32	6	2013	Turbocharged	Stage 2
7	Loader	ZL50D	162	2200	9	16	6	2006	Naturally Aspirated	Stage 0
8	Loader	ZL50DM	162	2200	9	16	6	2006	Naturally Aspirated	Stage 0
9	Loader	LG850	162	2200	9	16	6	2006	Naturally Aspirated	Stage 0
10	Loader	ZL50G	162	2200	9	17	6	2010	Turbocharged	Stage 2
11	Loader	XG955	162	2200	9	16	6	2010	Turbocharged	Stage 2

The operating modes were tested in series. A start-up idling test was done for 1 min. Before the start-up idling test, the vehicle remained engine-off for at least 6hr in the open air. Then the vehicle continued warming up. After the variation of the exhaust temperature was within ±2°C, the idling test began, followed by the moving test, followed by the working test, and then these tests were repeated. The moving test was done on an unpaved road whose length was approximately 100 m, and the vehicle moved forward and backward. The working test was done inside the construction site, and the vehicle was requested to do a prescribed task such as soil excavation or material handling. For the vehicles belong to the same type, the requested tasks are similar. Each test lasted for 10 min. The recording frequency of the test instrument was 1Hz. Therefore, for each operating mode, 1200 pieces of data were collected. During the intervals between the tests, the filters were switched manually.

During the test, a laptop computer was connected to the instruments to ensure that they were functioning properly. If any potential error such as abnormally low level of exhaust flow rate or consecutive negative value of emission concentration appeared, we could only discard the result and redo the test.

Data Processing

The fuel-based EF is defined as:

$$EF_{fuel,i} = \sum m_i / \sum \left(\rho_{diesel} \times FC\right) \quad (1)$$

where $EF_{fuel,i}$ is the fuel-based EF of the i^{th} pollutant, g kg^{-1}
m_i is the instantaneous emission rate, g s^{-1}
ρ_{diesel} is the density of the fuel, g m^{-3}
FC is the fuel consumption rate, L s^{-1}

The overall EFs of the regulated pollutants can be calculated using the weighted mean value of the operating mode based EFs. The weight for each operating mode is listed in Fu *et al.* (2012). For excavators, the weights for idling, moving and working used in this study are 0.05, 0.15, and 0.80, respectively. For loaders, the weights for idling, moving used in this study are 0.05, 0.40, and 0.55, respectively. For bulldozers, we use the same weight as what we use for loaders.

For gaseous pollutants, the emission rates are obtained by integrating the instantaneous mass emission rates, while for PM, it is obtained by weighing the quartz-fiber filters. The fuel consumption rates are determined by carbon balance method. It is assumed that CO_2, CO and HC from the engine are derived from the fuel, and the chemical formulas for both HC and diesel are $CH_{1.85}$. The equation is (Fang and Zheng, 2005):

$$FC = \frac{0.866 \times m_{HC} + 0.429 \times m_{CO} + 0.272 \times m_{CO_2}}{1000 \times 0.866 \times \rho_{diesel}} \quad (2)$$

T-test is employed to determine whether a difference among the vehicles is significant. If the word "significant" or "significantly" is used in the next section, the confidential level is at least 90%.

RESULTS AND DISCUSSION

Emission Factors

The EFs of the tested pollutants are listed in Table 2. As is listed in the table, the EFs of CO, NO_x, HC and PM for the vehicles in the idling mode are 37–81 g kg^{-1}, 12–45 g kg^{-1}, 3.9–27 g kg^{-1} and 2.5–13 g kg^{-1}, respectively, while those for the vehicles in the moving or working mode are 13–58 g kg^{-1}, 21–63 g kg^{-1}, 1.4–15 g kg^{-1} and 2.6–11 g kg^{-1}, respectively. The vehicles in the idling mode are significantly high in EF_{CO} and EF_{HC}, while slightly low in EF_{NOx} compared with those in the other two operating modes. This may be due to the low combustion temperature caused by the low engine load in the idling mode. Since turbocharged engines are equipped in all the Stage 2 vehicles, the EFs of CO and HC for the Stage 2 vehicles decrease significantly compared with those for the Stage 0 vehicles. For EF_{NOx}, the difference between the vehicles certified to the two stages is minor. For example, the EFs of CO, NO_x and HC for the Stage 0 loaders are 46–81 g kg^{-1}, 45–63 g kg^{-1} and 9.7–16 g kg^{-1}, respectively, while those of the Stage 2 loaders are 14–37 g kg^{-1}, 35–54 g kg^{-1} and 3.4–6.8 g kg^{-1}, respectively.

NO_x from construction equipment usually contains NO and NO_2. The majority of NO_x is NO, whose fractions are 0.71–0.87, 0.84–0.92 and 0.91–0.94 in the idling, moving and working mode respectively. As low temperature favors the conversion from NO to NO_2, the fraction in the idling mode is the lowest one.

For construction equipment, the EFs of OM and EC are 0.14–1.1 g kg^{-1} and 0.10–7.8 g kg^{-1} respectively. Although the number of the tested vehicles is not statistically large, the results suggest that the vehicles certified to the two stages differ greatly in PM carbonaceous composition. The TCA/PMs for the Stage 0 excavator, bulldozers and loaders are 0.39–0.65, 0.30–0.67 and 0.53–0.66, respectively, while those for the Stage 2 excavators, bulldozer and loaders are 0.12–0.13, 0.12–0.15 and 0.11–0.17, respectively. This may indicate that for the Stage 2 vehicles, the major composition of PM is inorganic constitutes, which are thought to originate from fuel addictive and lubricant oil. Besides TCA/PM, the OC/ECs for the vehicles certified to the two stages are also different. The OC/ECs for the Stage 0 excavator, bulldozers and loaders are 0.13–0.25, 0.22–0.32 and 0.08–0.19, respectively, while those for the Stage 2 excavators, bulldozer and loaders are 1.5–3.3, 1.0–1.2 and 0.83–2.0, respectively. The high OC/EC for the Stage 2 vehicles may be attributed to the employment of turbocharging system, which provides more homogeneous air-fuel mixture and thus greatly suppresses the formation of EC (Li *et al.*, 2014), and leads to the increase of OC/EC. For particle-phase PAHs, the EFs for the Stage 2 vehicles decrease significantly compared with those for the Stage 0 vehicles. For example, the EFs of particle-phase PAHs for the Stage 2 loaders are 1.2–3.7 mg kg^{-1}, which are only 14.4%–58.9% of those for the Stage 0 loaders.

The sixteen compositions of particle-phase PAHs are shown in Fig. 1, and their chemical properties are provided in Table 3. The error bars represent the standard deviations. To summarize, the particle-phase PAHs are dominated by 2- or 3-ring PAHs, which are largely derived from unburned fuel (Marr *et al.*, 1999). Their mass fractions are 71%–81%. Among all the 2- or 3-ring PAHs, ANA is much less than the others, and is only detected in the Stage 0 vehicles. Besides 2- or 3-ring PAHs, the rest are mainly 4-ring PAHs with stable chemical structure, such as FLT and PYR. BaA, CHR, BbF, BaP, IPY and BPE are occasionally detected in the samples while BkF and DBA in none of the samples exceed the detection limits.

Fuel Consumption

The fuel consumption rates of the vehicles are shown in Fig. 2. The error bars represent the standard deviations. Previous study (Fu *et al.*, 2012) has indicated that the factors influencing fuel consumption rate are operating mode and rated power. Therefore, the vehicles are categorized into 2 groups according to their rated power: 140–162 kW and 175–212 kW. The vehicles in the idling mode consume the least amount of fuel while those in the working mode consume the most amount. This difference is statistically significant for both groups. This conclusion is similar with that in Fu's study.

Start-up Emission

The comparison between the EFs at the start-up phase and those in the normal idling mode for all the vehicles is shown in Fig. 3. The error bars represent the standard deviations. For the vehicles at the start-up phase, EF_{CO} increases by 45% respectively while EF_{NOx} decreases by 27%, compared with the EFs for the vehicles in the normal idling mode. However, the increase or the decrease is not statistically significant. For PM, since the low temperature does not favors the oxidation of formed particle, the EFs for vehicles at the start-up phase significantly increase compared with those in the normal idling mode. These results for real-world start-up emission test are generally similar with what was reported in bench test (Bielaczyc *et al.*, 2001). For PM carbonaceous compositions, EF_{OM} significantly increases by 237% while EF_{EC} slightly increases by 39%.

Comparison with Other Studies

A summary of the overall EFs in this study and those obtained from other studies are listed in Table 4. The table also includes a study reporting the real-world EFs for heavy-duty on-road vehicles (Huo *et al.*, 2012). As currently, most in-use on-road vehicles in China only comply with China III, the real-world EFs for China III heavy-duty diesel vehicles are listed here. For CO and HC, the EFs of the Stage 0 vehicles in this study are much higher than those in the other studies, while those of the Stage 2 vehicles are lower than or similar to those in the other studies. The EF_{PM} in this study is extremely high compared with those in the other studies. This may be due to the difference in the method. The method to determine EF_{PM} in the other studies is opacity-based method, while in this study, EF_{PM} is determined by weighting filters. For NO_x, These studies reported similar EFs for excavators. However, the difference of EF_{NOx} is larger for loaders. Most of the EFs of CO and HC for construction equipment are much larger than those for China III vehicles, while the EFs of NO_x are lower. As

Table 2. Emission Factors.

Type	Emission Standard	Operating Mode	CO	NO_x	HC	PM	OM[a]	EC	OC/EC	TCA/PM	Total PAHs[c]
			g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}			mg kg^{-1}
Excavator	Stage 0	Idling	52	19	12	4.4	0.40	2.5	0.13	0.65	n.a.[d]
		Moving	34	31	7.1	5.3	0.34	1.8	0.16	0.40	n.a.
		Working	23	32	8.7	5.4	0.49	1.6	0.25	0.39	n.a.
	Stage 2	Idling	44 ± 8[e]	17 ± 3	3.9 ± 2.3	3.9 ± 1.6	0.29 ± 0.09	0.16 ± 0.02	1.5	0.12	1.9 ± 0.6
		Moving	14 ± 4	27 ± 3	2.3 ± 1.4	4.8 ± 0.6	0.41 ± 0.13	0.23 ± 0.04	1.5	0.13	1.3 ± 0.2
		Working	13 ± 2	29 ± 4	1.4 ± 0.7	4.1 ± 0.4	0.39 ± 0.11	0.10 ± 0.03	3.3	0.12	1.7 ± 0.7
Bulldozer	Stage 0	Idling	60 ± 23	18 ± 6	27 ± 5	5.8 ± 0.4	0.82 ± 0.24	3.1 ± 0.5	0.22	0.67	5.8 ± 2.2
		Moving	48 ± 17	24 ± 7	12 ± 2	6.8 ± 0.8	0.74 ± 0.21	1.9 ± 0.4	0.32	0.39	5.5 ± 1.4
		Working	46 ± 13	27 ± 6	15 ± 8	7.0 ± 1.2	0.46 ± 0.06	1.6 ± 0.5	0.25	0.30	4.9 ± 1.2
	Stage 2	Idling	39	12	6.5	3.7	0.24	0.20	1.0	0.12	0.7
		Moving	18	21	4.5	3.5	0.31	0.22	1.2	0.15	0.6
		Working	15	24	5.3	4.9	0.43	0.30	1.2	0.15	1.2
Loader	Stage 0	Idling	81 ± 21	45 ± 13	16 ± 9	13 ± 1.6	0.75 ± 0.37	7.8 ± 3.6	0.08	0.66	8.3 ± 2.9
		Moving	46 ± 9	59 ± 11	10 ± 5	11 ± 1.2	1.1 ± 0.4	4.7 ± 1.7	0.19	0.53	6.1 ± 2.5
		Working	58 ± 14	63 ± 4	9.7 ± 4.3	11 ± 2.4	0.58 ± 0.13	6.0 ± 2.4	0.08	0.60	5.6 ± 0.6
	Stage 2	Idling	37 ± 2	35 ± 24	6.8 ± 2.6	2.5 ± 1.8	0.14 ± 0.05	0.14 ± 0.03	0.83	0.11	1.2 ± 0.2
		Moving	27 ± 2	49 ± 20	4.7 ± 1.0	2.6 ± 1.4	0.20 ± 0.06	0.16 ± 0.05	1.0	0.14	3.7 ± 1.0
		Working	14 ± 1	54 ± 25	3.4 ± 1.2	3.1 ± 1.7	0.32 ± 0.03	0.13 ± 0.08	2.0	0.17	3.3 ± 1.5

[a] Organic matter, calculated by OC × 1.2 for diesel combustion source (Shi *et al.*, 2000); [b] Total carbonaceous aerosol, calculated by OM + EC; [c] the sum of the sixteen kinds of PAHs in Fig. 1; [d] not tested; [e] Average ± Standard Deviation.

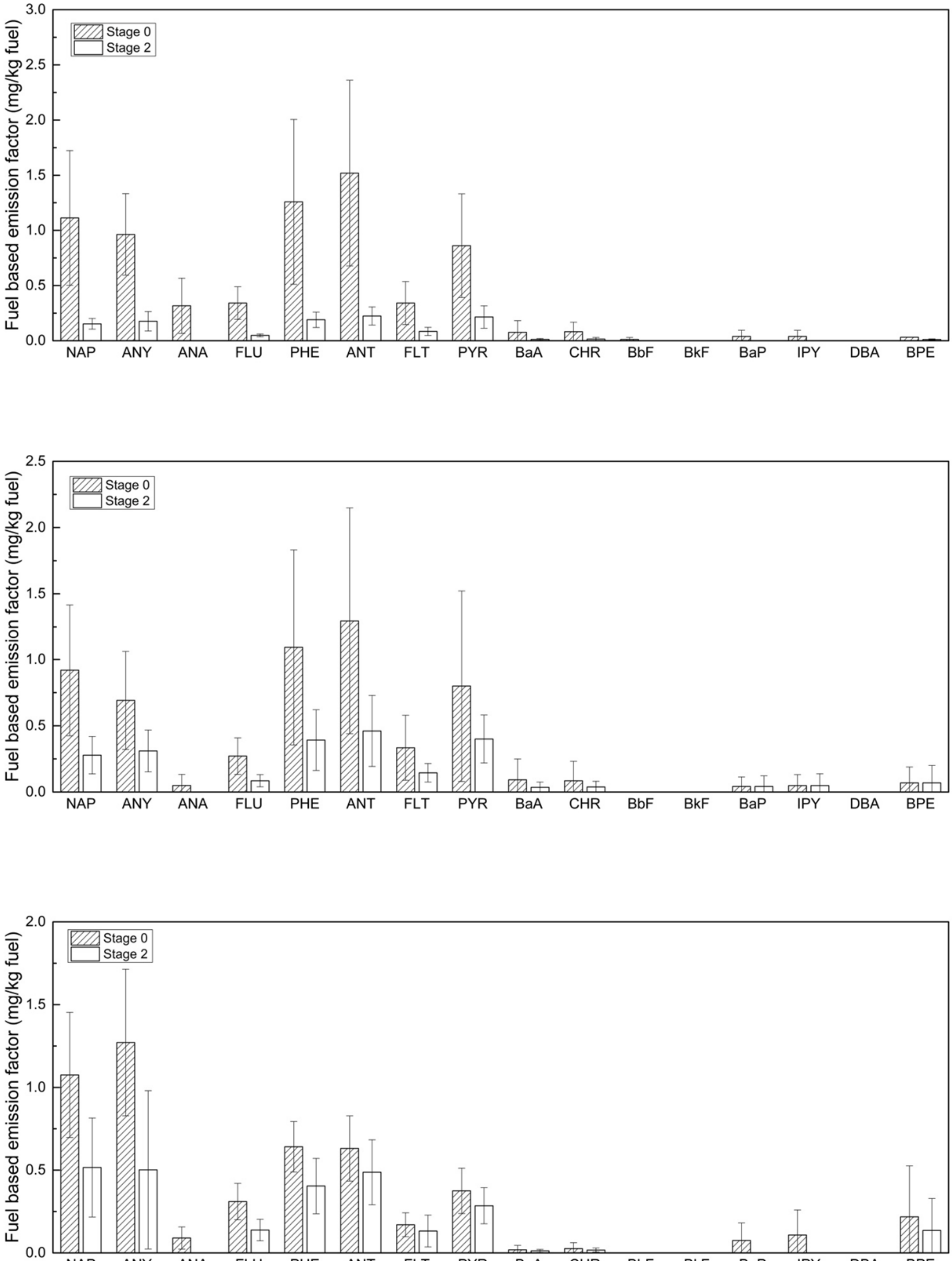

Fig. 1. The PAHs in different operating modes (the upper one is for the idling mode, followed by the one for the moving mode, followed by the one for the working mode).

Table 3. The Tested Particle-phase PAHs.

CAS No.	Abbreviation	Full Name	Molecular Formula	Molecular Weight	CAS No.	Abbreviation	Full Name	Molecular Formula	Molecular Weight
91-20-3	NAP	Naphthalene	$C_{10}H_8$	128.18	56-55-3	BaA	Benzo[a]anthracene	$C_{18}H_{12}$	228.29
208-96-8	ANY	Acenaphthylene	$C_{12}H_8$	152.20	218-01-9	CHR	Chrysene	$C_{18}H_{12}$	228.29
83-32-9	ANA	Acenaphthene	$C_{12}H_{10}$	154.21	205-99-2	BbF	Benzo[b]fluoranthene	$C_{20}H_{12}$	252.30
86-73-7	FLU	Fluorene	$C_{13}H_{10}$	166.22	207-08-9	BkF	Benzo[k]fluoranthene	$C_{20}H_{12}$	252.30
85-01-8	PHE	Phenanthrene	$C_{14}H_{10}$	178.23	50-32-8	BaP	Benzo[a]pyrene	$C_{20}H_{12}$	252.30
120-12-7	ANT	Anthracene	$C_{14}H_{10}$	178.23	193-39-5	IPY	Indeno[1,2,3-c,d]pyrene	$C_{22}H_{12}$	276.33
206-44-0	FLT	Fluoranthene	$C_{16}H_{10}$	202.26	53-70-3	DBA	Dibenz[a,h]anthracene	$C_{22}H_{14}$	278.35
129-00-0	PYR	Pyrene	$C_{16}H_{10}$	202.26	191-24-2	BPE	Benzo[g,h,i]perylene	$C_{22}H_{12}$	276.33

the number of construction equipment is much less than that of on-road vehicles, it can be concluded that construction vehicles are not among the major emission sources of NO_x.

The Stage 2 vehicles, after put into operation, do not definitely emit less amount of pollutants than the emission limits. For example, if we assume a brake specific fuel consumption (BSFC) of 190 g kW^{-1} h^{-1} (Wolf and Eilts, 2014), the estimated Stage 2 emission limits for CO, NO_x, HC and PM are 18.5 g kg^{-1}, 31.6 g kg^{-1}, 5.3 g kg^{-1} and 1.1 g kg^{-1} respectively. Several EFs for the Stage 2 vehicles in Table 4 exceed the limits, especially for PM. The EFs of PM from Stage 2 vehicles are 2.6–3.9 times the limits. The reasons may include the difference of duty cycles, and the poor maintenance of the vehicles. As the certification of construction equipment is done using engine dynamometer test, these results demonstrate that the employment of the EFs from engine dynamometer test to calculate emission inventory may sometimes results in a large deviation from the actual emission amount.

CONCLUSION

In this study, emission from 11 pieces of construction equipment were measured by portable emission measurement system. The emission factors of regulated pollutants, OC, EC and particle-phase PAHs are provided in this study. The vehicles in the idling mode are significantly high in EF_{CO} and EF_{HC} while low in fuel consumption. There are some statistically great differences in EF_{CO}, EF_{HC}, OC/EC, and TCA/PM between the vehicles certified to different emission standards. Although the number of the tested vehicles is not statistically large, the Stage 2 vehicles do emit less amount of some pollutants than the Stage 0 vehicles when they are put into operation. The analysis of particle-phase PAHs shows that 2- or 3-ring PAHs are the major PAHs. For the vehicles at the start-up phase, the EFs of PM and OM increase significantly.

The comparison between construction equipment and on-road vehicle shows that for construction equipment, the emission issue of CO and HC is more severe while that of NO_x is much less. This implies that the current regulation for NO_x is stringent enough while that for CO and HC needs to be stricter. The Stage 2 vehicles do not emit less amount of pollutants than the amount they are expected to emit. Therefore, it is strongly recommended that the calculation of emission inventory should be based on massive real-world emission results. More emission tests on construction equipment are thus needed.

There are some recommendations for future researchers on real-world emission test of construction equipment. Dilution tunnel is recommended for the researchers who are interested in TOA. If it is not used, the analysis may fail due to final FID check failure. However, for the researchers who need to accurately determine high-molecular-weight (HMW) PAHs, it is not recommended. As the mass fraction of HMW PAHs is minor, the employment of dilution tunnel may lead to an undetectable amount of HMW PAHs. Except for a further collection of the EFs and a further study on HMW PAHs, future study may concentrate on the research of activity

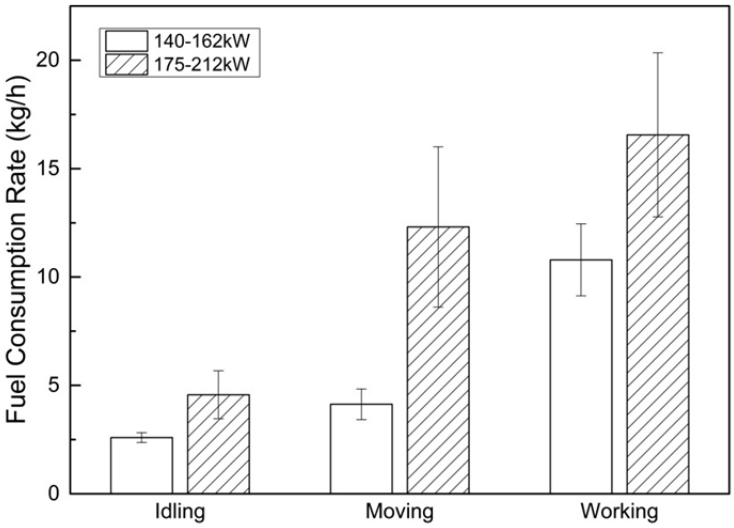

Fig. 2. The fuel consumption rate in different operating modes.

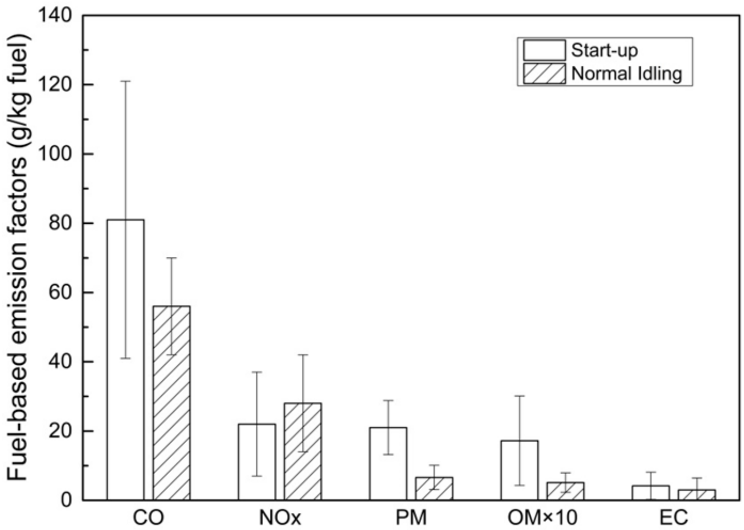

Fig. 3. Comparison between the EFs at start-up phase and those in normal idling mode.

Table 4. Overall Emission Factors and Comparison with Other Studies.

Vehicle Type	Source literature	CO	NO_x	HC	PM
		g kg^{-1}	g kg^{-1}	g kg^{-1}	g kg^{-1}
Excavator	This study (Stage 0)	26	31	8.6	5.3
	This study (Stage 2)	15	28	1.7	4.2
	Fu *et al.* (2012)	~12	~31	~3.3	~1.4
	Frey *et al.* (2008)[a]	~13	~32	~3.8	~0.3
	Frey *et al.* (2010)	~7.9	~37[b]	~3.5	~0.3
Bulldozer	This study (Stage 0)	48	25	14	6.9
	This study (Stage 2)	17	22	5.0	4.3
Loader	This study (Stage 0)	54	61	10	11
	This study (Stage 2)	20	51	4.1	2.9
	Fu *et al.* (2012)	~17	~83	~7.6	~1.5
	Frey *et al.* (2008)	~4.4	~36	~3.3	~0.24
	Frey *et al.* (2010)	~11	~43	~6.0	~0.3
China III vehicles[c]	Huo *et al.* (2012)	~10	~51	~2.1	n.a.[d]

[a] the EFs are given in g $gallon^{-1}$, we assume the density of diesel is 0.848 kg L^{-1} to estimated the EFs in g kg^{-1}; [b] The literature reported NO; [c] Heavy duty diesel vehicles; [d] The literature reported $PM_{2.5}$ which is greatly different from PM_{10}.

value, or the investigation into other major unregulated pollutants such as ammonia, ketone and aldehyde.

ACKNOWLEDGEMENT

This study is funded by the National Science Foundation of China (No. 41275133). The authors appreciate the great support from Vehicular Emission Control Center, the Ministry of Environmental Protection of China.

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Received for review, September 4, 2015
Revised, January 31, 2016
Accepted, May 17, 2016