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Real-world Emissions of Construction Machines and Comparison to a Non-road Emission Model

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Real-world Emissions of Construction Machines and Comparison to a Non-road Emission Model

ABSTRACT

This study implemented real-world tests in Nanjing, China for measuring emission factors (EFs) of air pollutants, including Carbon Monoxide (CO), Hydrocarbon (HC), Nitrogen Oxides (NO_x), and Particulate Matter (PM) from ten construction machines in three operational modes (idling, moving, and working) with a Portable Emission Measurement System. The idling mode shows the least variation of EFs, and its average CO EFs can be higher than the moving and working modes by 43% and 34%, respectively. The working mode generates the highest emission for all other pollutants with the highest variation. The EFs suggested by the Guide (an official guidebook for developing emission inventory in China) are in general lower than the measured EFs, and the gap becomes larger for older machines. The EFs of CO, NO_x, and PM of China Stage II machines are 24%, 120%, and 66% higher than the Guide, respectively. The differences go up as high as 126%, 1066%, and 559% for China Stage I machines, indicating the upgrade of engine technology from Stage I to Stage II, as well as the effect of machine deterioration. The result of this study reveals the effectiveness of stringent emission standards in controlling emissions from construction machines. High emissions from older machines emphasize the importance of a more rigorous machine replacement policy and a regulated maintenance strategy. The result also stresses the need to update the Guide with differentiated activity modes, region variations, and machine deterioration effects.

Keywords: Non-road mobile machinery (NRMM); construction machinery; air pollutant emissions; Portable Emission Measurement System (PEMS); non-road emission model

1 INTRODUCTION

Non-road mobile machinery (NRMM) is a great contributor to energy consumption as well as air pollution. Most of this type of vehicles are diesel-fueled, which are proved to be a key source for Nitrogen Oxides (NO_x) and Particulate Matter (PM) emissions (Zhao et al., 2015). In 2017, the total NO_x and PM emissions from construction machines reached 3.65 million tonnes in China, which were comparable to the total emissions from on-road diesel vehicles (Huanxing et al., 2020). Similarly, non-road diesel machinery in the US contributed over 35% and 44% to total mobile source NO_x and PM emissions according to statistical data from the U.S. Environmental Protection Agency in 2014. (U.S. Environmental Protection Agency, 2014). In 2016, the construction sector became the largest source to total PM_{10} emissions (34%) and the 5th largest of the total NO_x emissions (7%) in London (Desouza et al., 2020). A strongly positive relationship between total emissions of non-road machines and the level of urbanization has been demonstrated in previous studies (Fan et al., 2018; Guo et al., 2020). Among non-road machinery, construction machines contribute to a large proportion (70%) to total emissions in Sichuan Province, China (Fan et al., 2018). Construction machines also contributed 37% to total non-road emissions in Tianjin, another metropolitan city in the northern China (Y. Zhang et al., 2020).

The estimation of construction machinery emissions in previous studies depends on three major factors, the population, the activity data, and the emission factor (EF) of the machinery. The EFs can be obtained from non-road vehicle emission models such as NONROAD developed by the US Environmental Protection Agency (USEPA) (Marshall et al., 2012; Rasdorf et al., 2012; U.S. Environmental Protection Agency, 2005), the OFFROAD model developed by the California Air Resources Board (CARB) (Lewis et al., 2012; Rasdorf et al., 2010; Shao, 2016.). The modelled EFs are usually derived from engine dynamometer tests through in-lab experiments, where various test conditions with different engine parameters as well as after-treatment equipment can be conveniently implemented (Pirjola et al., 2017; Zhang et al., 2019). Rated power, machine types, and the emission standard of the estimated machine, are commonly used as parameters in non-road emission models. The Compilation Guide for Non-road Mobile Source Emission Inventory (the Guide) developed by the Ministry of Environmental Protection of China (Fan et al., 2018; Guo et al., 2020; Ministry of Environmental Protection of China, 2014) is one of the most commonly used guideline for developing emission inventories in China. The Guide provides three different methods for estimating emissions based on different data availability, with suggested load factor and EFs. The EFs in the Guide are distinguished by the level of rated power and emission standard (Supplemental Information, or SI Table SI 5 to Table SI 7), and the EF values were determined by a Portable Emission Measurement System (PEMS) on 50 typical construction machines (Guo et al., 2020).

However, due to heavy workload, excessive year of usage, and lack of maintenance, EFs provided by models cannot represent the actual emissions of the non-road machinery in real-world. Moreover, the uncertainty of emission factors due to different machinery activity modes, varied operations, machinery types, and engine deterioration, cannot be captured by the single value provided by the model (Cao et al., 2018; Lewis et al., 2019, 2009; Sepasgozar and Blair, 2019). In the study of Frey et al. (2010), a strong positive relationship between the time-based emission rate and engine attributes, such as engine load, power and displacement, was revealed. Time-based emission rates of construction machinery in the working mode and the moving mode are found to be significantly higher than those from the idling mode (Abolhasani et al., 2008; Fu et al., 2012), while in terms of the fuel-based emission factor, decreasing the idling mode ratio in the machine operation can effectively reduce the additional fuel use and excess Carbone Dioxide (CO_2)

emissions (Hu et al., 2019; Lewis et al., 2012). Due to lower combustion efficiency, worse engine wear, and less stringent emission limits, construction machines with older engines lead to higher emission rates in the real-world operation (Desouza et al., 2020; Fu et al., 2012).

Despite the breadth of emissions modelling and measurements of construction machinery, the variation of real-world machine operational EFs under different working conditions and engine attributes needs to be further discussed to capture the uncertainty in the total emission estimation. In this paper, real-world emissions, including Carbon Monoxide (CO), Hydrocarbon (HC), NO_x, and PM, were measured from different types of construction machines using PEMS. The uncertainty of the EFs is captured from the measured data by differentiating activity modes, emission standards, and rated power of machines. The measured EFs were compared with the values provided by The Compilation Guide for Non-road Mobile Source Emission Inventory (the Guide, an official guidebook for developing non-road machinery emissions in China)(Ministry of Environmental Protection of China, 2014) to illustrate the differences between the measured results and the model. The novelty of this study is the identification of the gap between emission factors from the commonly adopted model and those from the field measurement, with the consideration of machine attributes and activity modes, which can be further used for identifying possible underestimation/overestimation of total emissions when applying the Guide.

2 DATA COLLECTION

Emission measurements of non-road construction machines were conducted in the winter of 2018 in Nanjing, China. The type and the number of the in-use construction machines in the city, as well as their annual operating hours (when the engine is on, including both idling and operating states), were first collected through on-site interview and questionnaire. Second, machinery emissions in three activity modes (idling, moving, and working) were measured by PEMS.

In this study, 20 representative construction sites were selected in the region of the city, considering the spatial distribution and surrounding land use types, to collect information of most common construction machines, such as the manufacturer, engine attributes, emission standard, and annual working hours (see SI Figure SI 1). The results are presented in the SI 1.2. Given the distribution of machine types, ten construction machines, including three cranes, two loaders, two excavators, one forklift, one concrete pump truck, and one sprinkler, representing surveyed machines at 20 construction sites, were selected for the operational emission measurement. The specifications as well as the measurement equipment of these ten machines are listed in Table 1. All the machines are equipped with selective catalytic reduction (SCR) for the emission after-treatment and are powered by diesel under China Stage VI fuel standard with Sulfur content less than 0.001%. The field test was conducted in the winter between November 2018 and January 2019. The meteorological information of the test, including the temperature and the weather, was listed in the SI 1 Table SI 2. The measurement was implemented in three operational activity modes (idling, moving, and working), each repeated for 5 to 15 minutes. The idling mode refers to the state where machines were turned on without any workload or movement; the moving mode was operated by driving machines back and forward for 15 meters without extra workload; and the working mode simulated the real-world construction work of each specific machine type. The moving cycle was excluded from cranes and the concrete pump truck due to their real-world working conditions. Time-based Carbon Monoxide (CO), Hydrocarbon (HC), Nitrogen Oxides (NO_x), and Particulate Matter (PM) emission factors (g/second) were measured by the PEMS. The fuel use rate (kg/hour) was estimated based on the carbon balance of emissions, and the fuel-based emission factors (g/kg) can be further generated. Two types of PEMS (HPC501 and SEMTECH-DS developed by Sensors, Inc.) were utilized to measure emissions from the real-world operation, and Dekati eFilter was added onto SEMTECH-DS for the PM measurement. The frequency of the data record was 1Hz, except for the PM measurement from HPC501, by which only the total value of PM emissions per test was given. In this study, the fuel-based EFs (in g/kg) were adopted due to their less variability compared to the time-based results (in g/second) (Frey et al., 2010). An overall EF of each measured machine can be calculated based on the proportion of three activity modes in the daily use: for idling-moving-working cycle, the time proportion is 0.1, 0.2, 0.7; for idling-working cycle, the time proportion is 0.1, 0.9.

Table 1: Specifications of machines for the emission measurement

ID	Machinery type	Model	Engine model	Registration	Emission standard	PEMS type	Rated power (kW)
1	Crane	Xugong	SC7H260Q5	2017.5	Stage III	HPC	192
2	Crane	XugongXCT50L5	SC9DF300.2Q5	2018.5	Stage III	SEMTECH + Efilter	219
3	Crane	Liugong5301JQZ25	ISD28550	2017.9	Stage III	SEMTECH + eFilter	204
4	Excavator	Xiagong822LG	6BG1TABFD08C2	2010.11	Stage II	HPC	120
5	Excavator	Doushan DX150W0-9C	DL06B-C3	2018.1	Stage III	SEMTECH + eFilter	103
6	Loader	Longgong	WD10G220E11	2010.4	Stage I	HPC	162
7	Loader	W156 Wheel Loader	WD10G220E21	2009	Stage I	SEMTECH + eFilter	162
8	Forklift	Longgong FD35	QC490GP	-	Stage I	SEMTECH + eFilter	36.8
9	Concrete pump truck	ACTROS5041	OM501LA.IV/3	2017.6	Stage III	SEMTECH + eFilter	300
10	Sprinkler	5106GSS	YC4E140-30	2011.05	Stage II	SEMTECH + eFilter	105

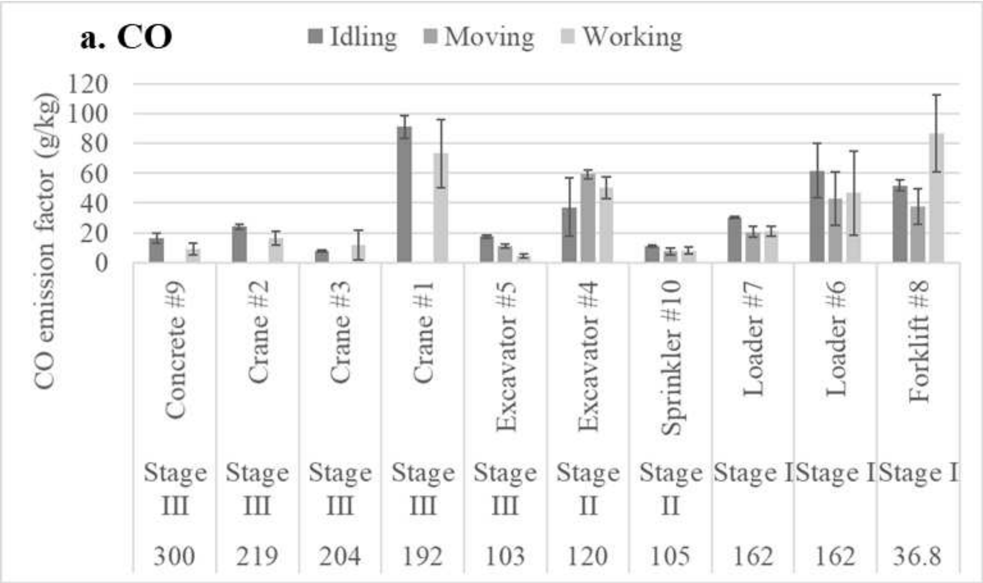
Comparisons of the EFs were implemented from two aspects. First, the measured EFs of this study were compared based on different emission standards and rated power levels. Second, suggested EFs of the same machinery type were extracted from the Guide, which is developed by the Ministry of Environmental Protection of China and is widely applied in the emission inventory development (Fu et al., 2013; Guo et al., 2020; Hou et al., 2019; J. Zhang et al., 2020), to illustrate the gap between the model and the real-world conditions.

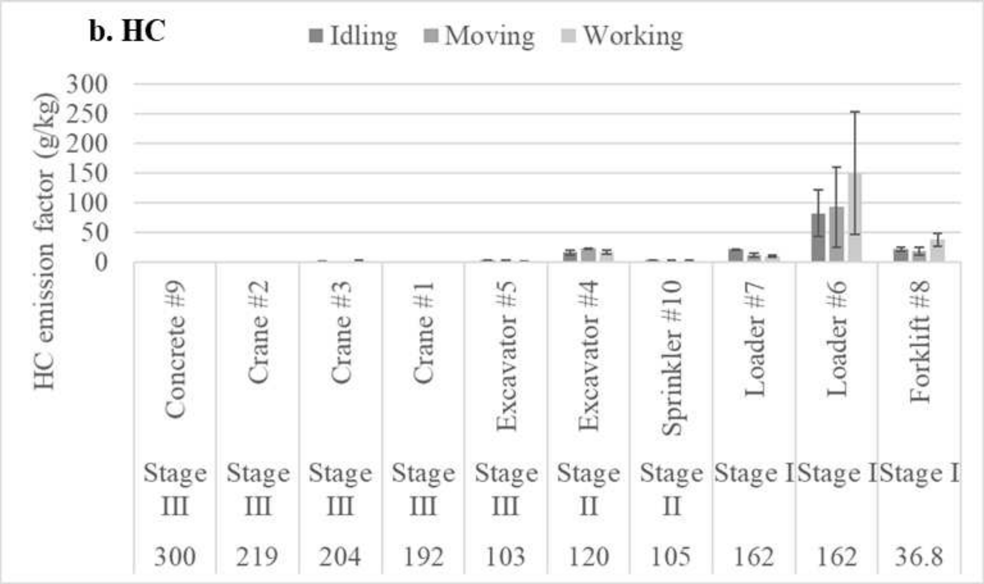
3 RESULTS AND ANALYSIS

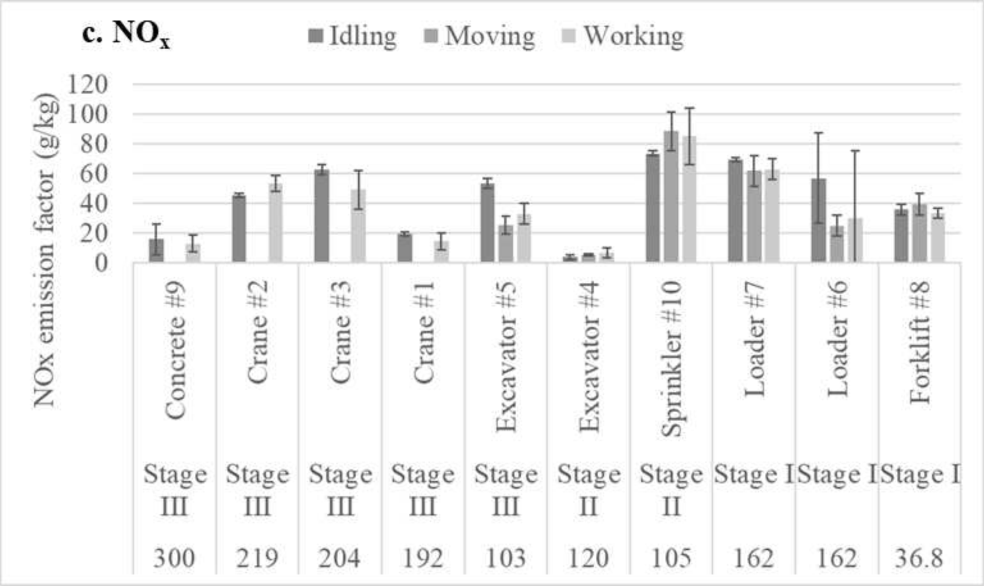
3.1 Comparison of emission factors among different machine specifications

Figure 1 present average EFs of ten measured machines under three activity modes, error bars indicating the standard deviation. Values of the Coefficient of Variation (CV), which equals the standard deviation divided by the mean, are illustrated in the SI 2 Figure SI 3. EFs are presented by the descending order of the emission standard and the rated power of the measured machines. On average, CO EFs of idling mode are higher than the moving and working mode by 43% and 34%, respectively. It is possibly due to the incomplete combustion of the fuel during idling. While the variance of idling EFs is lower than that of the other two activity modes for all the pollutants due to stable engine speed (or rotation per minute, RPM). The working mode EFs are slightly higher than the moving mode with average relative difference 4%, 9%, 14% and 40% for CO, HC, NO_x and PM, respectively. Due to varied workload during the working mode, the CV of the working mode EFs is also higher than the moving mode by 58% and 122% on average for CO and NO_x EFs, respectively. PM EFs from working and moving modes are significantly higher than those from the idling mode by as much as 576%, which is different to the trend of CO EFs. In addition, PM emissions reach the highest variation during all three activity modes for every measured machine.

Comparing among different machines, EFs of each activity mode present an increasing trend with less stringent emission standard (or longer in-use time). Machines under Stage III have relatively lower EFs for all the air pollutants. In contrast, machines under lower emission standard emit more emissions in all activity modes, and their EFs are constantly high as the variations are lower than those with Stage III standard. Among four machines under Stage III, the concrete pump truck generates the lowest EFs, possibly due to higher rated power and higher energy efficiency. The trend is consistent with the Guide, which suggests lower EFs for higher rated power or more stringent emission standards. However, this does not apply to all pollutants. For example, Crane #3 (with Stage III and 204kW rated power) shows higher NO_x EFs than Excavator #5 (with Stage III and 103kW rated power). Similarly, Loader #7 (Stage I, 162kW) also generates higher NO_x EFs than Forklift #8 (Stage I, 36.8kW). In addition, CO EFs of Crane #1 (Stage III, 192kW) are significantly higher than other machines under the same emission standard, which possibly results from the manufacturer and poor maintenance of this machine.




b. HC
Idling
Moving
Working
HC emission factor (g/kg)
300
250
200
150
100
50
0
Concrete #9
Crane #2
Crane #3
Crane #1
Excavator #5
Excavator #4
Sprinkler #10
Loader #7
Loader #6
Forklift #8
Stage III
Stage III
Stage III
Stage III
Stage III
Stage II
Stage II
Stage I
Stage I
Stage I
300
219
204
192
103
120
105
162
162
36.8


c. NO$_x$
Idling
Moving
Working
NOx emission factor (g/kg)
120
100
80
60
40
20
0
Concrete #9
Crane #2
Crane #3
Crane #1
Excavator #5
Excavator #4
Sprinkler #10
Loader #7
Loader #6
Forklift #8
Stage III
Stage III
Stage III
Stage III
Stage III
Stage II
Stage II
Stage I
Stage I
Stage I
300
219
204
192
103
120
105
162
162
36.8

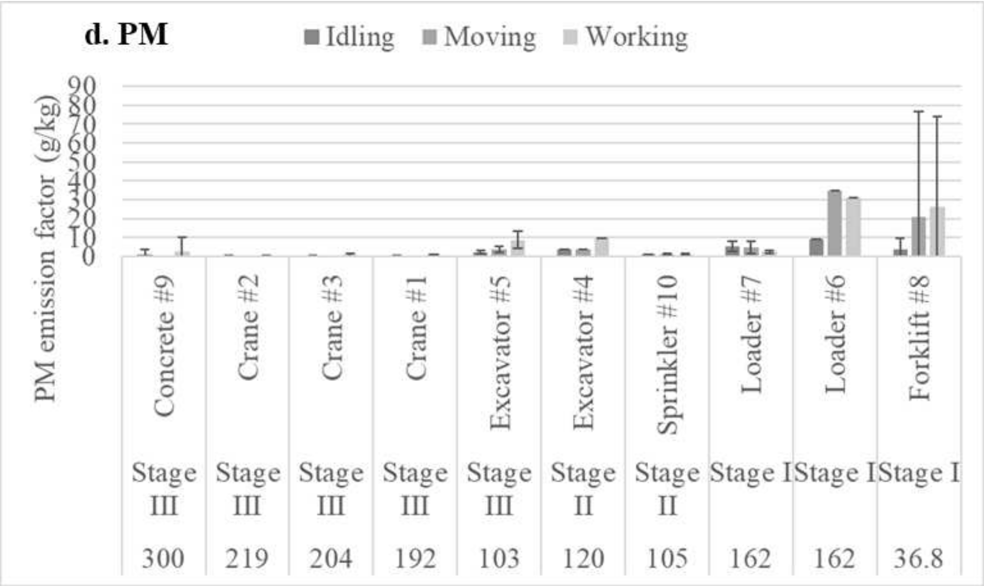


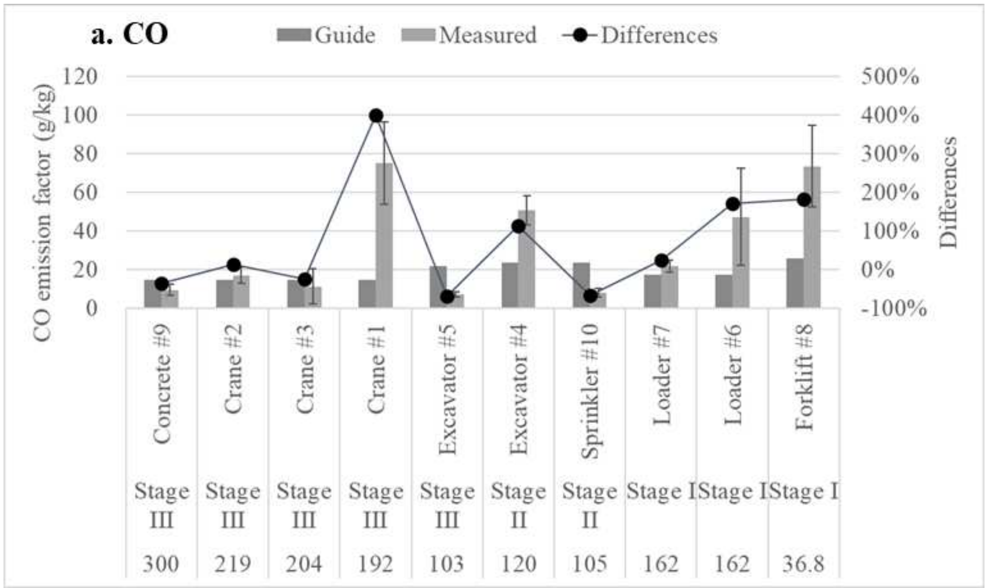
Figure 1: Mean and standard deviation of CO, NO_x, HC, and PM EFs (g/kg) for ten measured machines under three activity modes (numbers on the bottom of the x-label are the rated power of the corresponding machine)

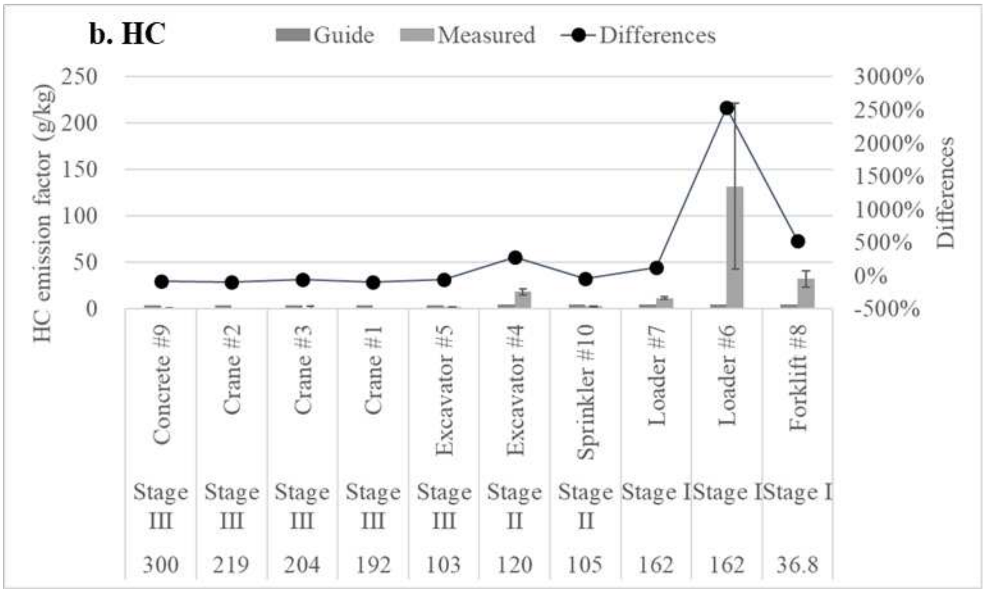
3.2 Comparison between measured EFs and the Guide EFs

A weighted average EF is calculated for each tested machine based on the activity mode proportion. The comparison between the PEMS-based weighted average EFs and the Guide-based EFs is illustrated in Figure 2. Note that PM_{10} and $PM_{2.5}$, that are distinguished in the Guide, cannot be differentiated by the measurement. Therefore, PM EFs from the Guide refer to the sum of PM_{10} and $PM_{2.5}$.

The result shows that measured EFs are higher than the suggested values in general, and the relative difference between the Guide and the measured result increases for machines under lower emission standards. For older machines under Stage I, the relative difference between the measurement and the Guide for CO, HC, NO_x, and PM is 126%, 33%, 1066%, and 559% on average, respectively; while for Stage II machines, the average relative difference is 24%, 58%, 120%, and 66% respectively.

For CO and PM emissions, the relative difference of machines with Stage III standard lead to similar or lower EFs than the suggested values, except Crane #1, of which the average CO EF is higher than the suggested EF by 400%. Machines with Stage I standard generate higher EFs for almost all the pollutants. Especially for Loader #6 (Stage I, 162kW rated power), from which the EFs of CO, HC, and PM exceed the value provided by the Guide by 171%, 2543%, and 1417%, respectively. The comparison of NO_x emissions between measured and the Guide shows inconsistent trend to other pollutants. Crane #2 and Crane #3 under Stage III lead to the highest difference on the NO_x EFs, exceeding the Guide by 275% and 261%, respectively. The CO, HC, and PM EFs for forklift #8 (Stage I) exceed the Guide by 183%, 523%, and 196%, respectively, while it has lower NO_x EFs than the suggested value.




b. HC
Guide
Measured
Differences
HC emission factor (g/kg)
250
200
150
100
50
0
3000%
2500%
2000%
1500%
1000%
500%
0%
-500%
Differences
Concrete #9
Crane #2
Crane #3
Crane #1
Excavator #5
Excavator #4
Sprinkler #10
Loader #7
Loader #6
Forklift #8
Stage III
Stage III
Stage III
Stage III
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Stage II
Stage II
Stage I
Stage I
Stage I
300
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204
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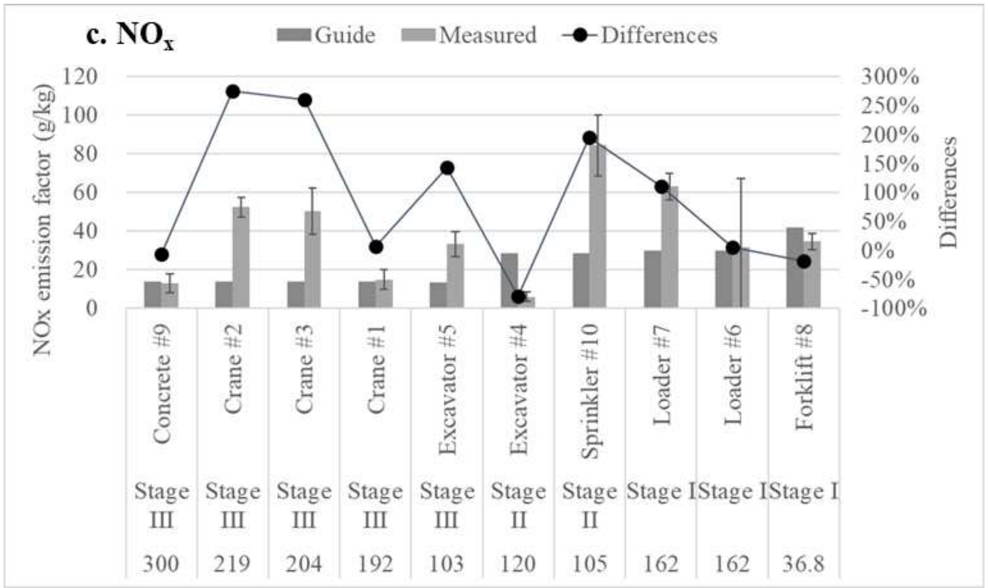
162
162
36.8


c. NO$_x$
Guide
Measured
Differences
NOx emission factor (g/kg)
120
100
80
60
40
20
0
300%
250%
200%
150%
100%
50%
0%
-50%
-100%
Differences
Concrete #9
Crane #2
Crane #3
Crane #1
Excavator #5
Excavator #4
Sprinkler #10
Loader #7
Loader #6
Forklift #8
Stage III
Stage III
Stage III
Stage III
Stage III
Stage II
Stage II
Stage I
Stage I
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120
105
162
162
36.8

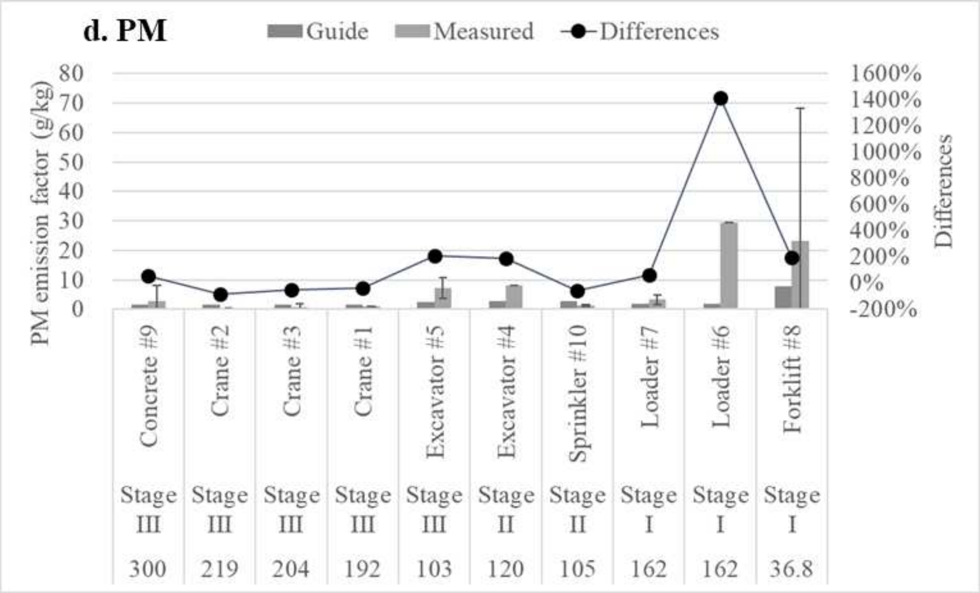

Figure 2: The comparison of the Guide EFs and measured EFs. The error bar represents the standard deviation of measured EFs. The line with dots shows the EF relative difference, which equals the difference between measured and the Guide (values at the bottom of the x-label represent the rated power of the corresponding machine)

4 DISCUSSION

The result in this study illustrates the effectiveness of stringent emission standard for remarkedly reducing non-road machine emissions in general, particularly for CO, PM, and HC emissions. However, this trend cannot apply to all machines, and the variation of the emissions is also not neglectable. From the activity mode perspective, EFs generated from the idling mode are relatively less varied, due to stable engine RPM. Moving EFs are slightly lower than working EFs, while EFs have higher variation during the working mode, which may result from varied load during the working mode. To estimate total emissions from non-road machinery more accurately, it is essential to differentiate EFs from different activity modes, and that requires investigations on the proportion of activity modes in the operational hours during on-site surveys. Comparing across three stages of emission standards, EFs of machines with Stage I show higher variations, introducing more uncertainties to EFs. These machines have usually been used for over ten years. Given their high EFs with large uncertainties, management should be taken into effect for replacing these machines with newer ones.

Comparing the measurement of this study with the Guide, the result shows a large gap of EFs between the real-world measurement and the suggested values. Overall, the measured EFs are higher than those suggested in the Guide, and the relative differences between the measured EFs and the suggested values increase with older machines for CO, HC, and PM emissions. This is expected since the Guide was released six years ago, while Stage I machines are still in use till now. Therefore, engines of these older machines have deteriorated significantly, leading to higher emissions than the Guide values. The comparison stresses the need to update the Guide for the non-road machinery emission estimation, due to a highly possible underestimation of total emissions using the EFs suggested by the current version. For NO_x emissions, however, the trend is completely different to the other three emissions: the NO_x EF of newer machines can be up to 275% higher than those of the Guide EFs, indicating much worse NO_x after-treatment of the measured machines than those tested in the Guide. More stringent controls from local authorities should be implemented for non-road machines in terms of their NO_x emissions.

In addition to the EFs, the annual working hours of each machine type is also recommended by the Guide for the calculation of total emissions. Table 2 shows the comparison between suggested working hours from the Guide and those of the surveyed construction sites in this study. The average working hours of the construction sites in Nanjing are higher than the national average level (which is suggested in the Guide) by 192% to 319%. The overloaded work fastens the engine deterioration, lowering the efficiency of after-treatment equipment, which explains the higher EFs measured in this study compared to the Guide. The comparison also demonstrates the importance of on-site surveys. Local working conditions of construction machines should be considered when developing regional emission inventories, instead of using the value recommended by the Guide.

Table 2: Average annual working hours of the surveyed sites and the Guide

	Average annual working hours at 20 construction sites	Average annual working hours suggested by the Guide	Differences $(\frac{surveyed-Guide}{Guide})$
Loader	3225	770	319%
Concrete pump truck	2535.7	-	-
Excavator	2578.1	770	235%
Crane	2317.3	770	201%
Forklift	2250	770	192%
Sprinkler	2416.7	-	-

Table 3 compares the measured EFs of this study with the result of existing research on the real-world non-road machinery emission measurement. Similar to this study, working and moving PM EFs are also found to be higher than those of the idling mode in Yu et al. (2020), with similar PM EFs for machines under China Stage III. Compared to Yu et al. (2020) and Fu et al. (2013) for Stage I and Stage II machines, the EFs of this study are much higher, which could result from the overloaded work of measured machines. The annual working hours in this study are over 2000, while in Hou et al. (2019), the working hours of these two types of machines are 500 and 150, respectively. Due to the lack of data, US Tier 1and Tier 2, which correspond to China Pre-Stage I, cannot be compared with this study. The comparison emphasizes a strong deterioration effect on non-road machinery, demonstrating an urgent need for a more stringent control on the machine replacement and a more efficient working organization of construction machines.

Table 3: Comparison with previous research on real-world non-road machinery emission factors (g/kg)

Previous research							This study				
	Activity mode	Machine type or emission standard	CO	HC	NO_x	PM	Machine type and emission standard	CO	HC	NO_x	PM
Yu et al. (2020)[1]	Idling	China Stage I	-	-	-	3.27	China Stage I	-	-	-	6.15
	Working		-	-	-	7.78		-	-	-	19.96
	Idling	China Stage II	-	-	-	1.87	China Stage II	-	-	-	2.40
	Working		-	-	-	2.50		-	-	-	5.53
	Idling	China Stage III	-	-	-	1.29	China Stage III	-	-	-	1.02
	Working		-	-	-	2.94		-	-	-	2.76
Hou et al. (2019)[2]	Idling	China Stage II, 37-75 kW	1.62	0.22	2.21	0.13	Stage II, 105kW	10.77	2.82	73.26	0.99
	Moving		2.51	0.41	2.76	0.16		7.56	2.54	88.18	1.31
	Working		5.56	1.29	8.06	0.49		7.88	2.62	84.95	1.21
	Idling	China Stage II, 75-135 kW	1.88	0.25	2.06	0.04	Stage II, 120kW	37.13	16.53	3.74	3.81
	Moving		2.96	0.47	4.86	0.21		59.42	23.09	5.57	3.77
	Working		5.80	1.12	6.36	0.35		50.17	17.28	6.58	9.85
Frey et al. (2008)[3]	Working	US Tier 1	67.59	76.60	482.14	3.79	Pre-stage I	-	-	-	-
	Working	US Tier 2	54.07	54.07	432.57	3.79		-	-	-	-
	Working	US Tier 3	39.65	27.94	292.89	2.57	China Stage I	48.00	41.87	53.89	6.15
Muresan et al. (2015)[4]	Working	EURO Stage III	3.15	0.49	12.80	-	China Stage I	48.00	41.87	53.89	

Note: 1, 3, 4: Emission factors of the study presented in this paper are the average value under each corresponding emission standard; 2: Measured machines with the same rated power category and the emission standard are selected for the comparison; 3: the unit is converted from g/gal to g/kg; 4: the unit is converted from g/L to g/kg.

5 CONCLUSION

In this study, emission factors of air pollutants, including CO, HC, NO_x, and PM, of non-road construction machinery were measured in the real-world working condition. Fuel-based emission factors (EFs, in g/kg) of ten typical construction machines with six machinery types and three activity modes (idling, moving, working) were summarized. EFs from the idling activity mode generally have smaller variations, while the working mode leads to the highest variation with relatively higher EFs. From the comparison of EFs among ten machines, EFs become higher with lower rated power or less stringent emission standard, which is consistent with the trend of the EFs suggested by the Guide. Given similar engine attributes, EFs are varied among different machine types, which possibly results from different working operations, varied maintenance condition, and different engine technologies adopted by manufacturers. Comparing the measured EFs to the Guide ones, it is found that in general, the measured EFs are higher than those from the Guide, and the relative difference between the measured EFs and the Guide increases for machines under lower emission standard. For older machines under Stage I, average relative difference can be as high as 1066% (HC EFs); while for Stage II machines, the average relative difference is at most 120% (HC EFs). The comparison of NO_x EFs shows different trend to other emissions, and machines under Stage III exhibit the highest relative difference to the Guide. The high EFs from the measurement is possibly due to the engine deterioration of tested machines. This may result from overloaded annual working hours, which can be more than 300% higher than the suggested working hours in the Guide.

The measurement of this study covers representative construction machines utilized in the real-world construction sites, which include all the emission standards in effect. The deterioration of old machines shows strong impacts on emissions, suggesting a more stringent machine replacement strategy that should be applied by the local authority. An efficient working organization of non-road machines and regulated maintenance should also be implemented to keep an appropriate working condition of construction machines, especially for urban regions, where the construction demand is high. In addition, in order to develop emission inventories more accurately, an urgent need for an updated Guide is revealed, in which the demographical and geographical variation of estimated areas, emission factor differences among various activity modes, and the engine deterioration effect should be considered.

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