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Real-world emissions of construction mobile machines and comparison to a non-road emission model

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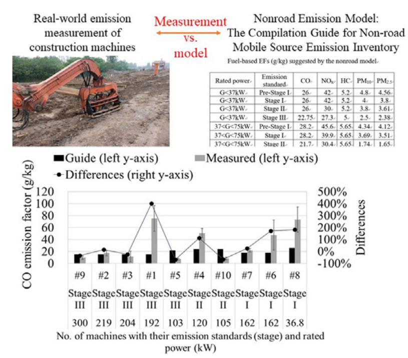
HIGHLIGHTS

- Real-world operation emissions of typical construction machines were measured.
- Emissions during idling have the least variation with higher CO emission factors.
- Emissions during the machine working mode have the highest variation with high EFs.
- Emissions of older machines exceed the non-road emission model by as high as 1066%.
- A stringent machine maintenance strategy is needed to reduce real-world emissions.

GRAPHICAL ABSTRACT



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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 those of 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

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Portable Emission Measurement System (PEMS)
Non-road emission model

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.

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). They also contributed 37% to total non-road emissions in Tianjin, another metropolitan city in the northern China (Zhang et al., 2020b).

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) and 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 7 to Table SI 9), 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 actual emissions of non-road machinery in real-world. Moreover, the uncertainty of emission factors due to different machinery activity modes, varied operations, machine types, and engine deterioration, cannot be captured by a single value provided by the model (Cao et al., 2018; Lewis et al., 2009, 2019; 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 difference between the measured results and those from the model. The novelty of this study is the identification of the gap between emission factors from the commonly adopted model (the Guide) 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. Materials and methods

Emission measurements of non-road construction machines were conducted in the winter of 2018 in Nanjing, China. The type and the number of 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, mobile machinery emissions in three activity modes (idling, moving, and working) were measured by PEMS.

In this study, 20 construction sites were selected from major construction projects in the region of Nanjing city to collect information of construction machines, such as their manufacturers, engine attributes, emission standards, and annual working hours (Fig. 1).

The distribution of the machine types is presented in the SI 1.1. Excavators, cranes, and loaders had the highest occurrence frequency, taking the proportion of total number of machines at 50%, 10%, and 8% respectively. Given the distribution of machine types, as well as restrictions of the permission and access to construction sites, ten construction machines, including three cranes, two loaders, two excavators, one forklift, one concrete pump truck, and one sprinkler, were selected for the operational emission measurement. It should be noted that some most-used machines, such as rollers and bulldozers, were not included in our measurement due to limited permission and access to corresponding construction sites. In addition, generators, which usually operate continuously during the day based on existing research (Desouza et al., 2020), were not used in the surveyed sites because most of the surveyed sites were equipped with plug-in electricity. Therefore, generators were ignored in the experiment.

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

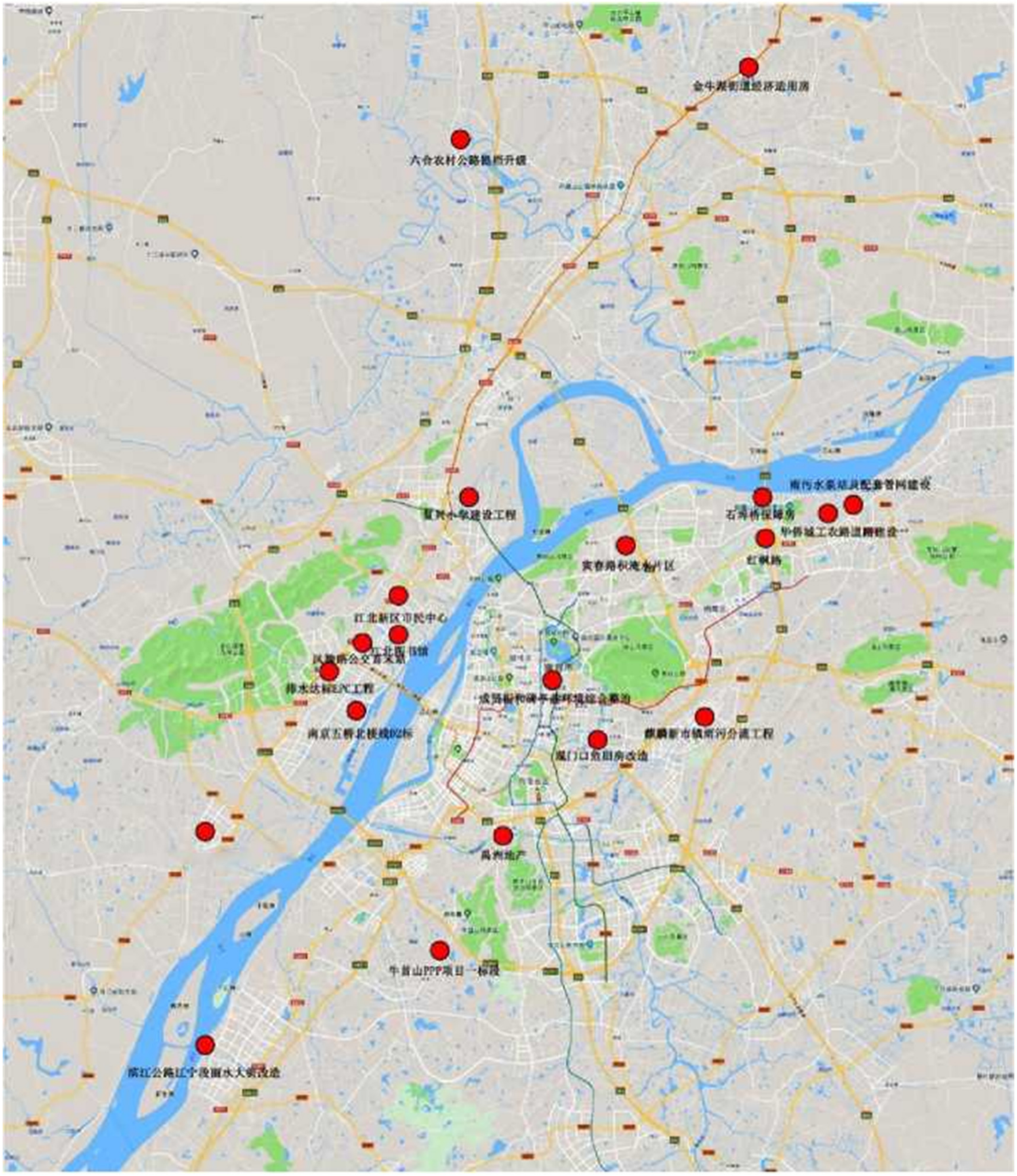

Fig. 1. Map of Nanjing and locations of selected sites (red dots).

2018 and January 2019. The meteorological information of the test, including the temperature and the weather, is listed in the SI 1 Table SI 2. The measurement was implemented in three operational activity modes (idling, moving, and working). 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 m 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. In the experiment, each activity mode was repeatedly tested for 10 to 15 min. The cold-start phase was not included in all the tests.

Two types of PEMS devices were utilized to measure real-world emissions of construction machines. PEMS-1 is developed by Sichuan University (Li et al., 2016). The system consists of a gas analyzer, an engine unit, and a PM unit. The gas analyzer unit can record instantaneous emission rate of CO, CO_2, O_2 (%), HC, and NO_x (ppm). The mass of PM is weighed after each test (g). The fuel rate (g/s) is estimated using the carbon balance method. Emission concentrations measured by PEMS-1 were further converted to fuel-based emission factors (g/kg) using the mole fraction, the molecular weight of each pollutant, and the fuel rate. PEMS-2 is composed of two devices: a PEMS unit (SEMTECH-DS) developed by Sensors. Inc. (Sensors Inc., n.d.), and a PM unit (Dekati eFilter) developed by Dekati Ltd. (Dekati Ltd., n.d.). In PEMS-2, SEMTECH-DS is responsible for measuring the initial fuel rate (gal/s) as well as the rate of exhaust emissions, including CO, HC, and NO_x (g/s). It also records engine parameters such as exhaust temperature and air/fuel ratio. The second-based fuel consumption rate (in kg/s) from SEMTECH-DS is calculated based on the measured initial fuel rate and the carbon concentration (CO, CO_2, and HC measured by the gas analyzer) (Tu et al., 2020). Second-based EFs for CO, HC and NO_x are converted to fuel-based EFs and recorded by SEMTECH-DS, which equals the second-based EFs (g/s) divided by the estimated fuel rate (kg/s). Dekati eFilter records second-by-second PM concentration (#/cm^3). The count

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	PEMS-1	192
2	Crane	XugongXCT50L5	SC9DF300.2Q5	2018.5	Stage III	PEMS-2	219
3	Crane	Liugong5301JQZ25	ISD28550	2017.9	Stage III	PEMS-2	204
4	Excavator	Xiagong822LG	6BG1TABFD08C2	2010.11	Stage II	PEMS-1	120
5	Excavator	Doushan DX150W0-9C	DL06B-C3	2018.1	Stage III	PEMS-2	103
6	Loader	Longgong	WD10G220E11	2010.4	Stage I	PEMS-1	162
7	Loader	W156 Wheel Loader	WD10G220E21	2009	Stage I	PEMS-2	162
8	Forklift	Longgong FD35	QC490GP	–	Stage I	PEMS-2	36.8
9	Concrete pump truck	ACTROS5041	OM501LA.IV/3	2017.6	Stage III	PEMS-2	300
10	Sprinkler	5106GSS	YC4E140–30	2011.05	Stage II	PEMS-2	105

concentration was converted into mass concentration in mg/L using an experimental factor (#/cm^3 = 10^{-6} mg/L), and further converted to fuel-based emission rate in g/kg using the exhaust volume and the fuel rate. Parameters that can be recorded by two PEMS devices are listed in the SI Table SI 3 and Table SI 4. Due to the limitation and restriction of the access to measured machines, a comparison between the measurements of two devices was not included in the experiment. The specifications and the measurement methods of these ten machines are listed in Table 1.

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/s) (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.

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; Zhang et al., 2020a), 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

Fig. 2 presents 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 Fig. SI 2. EFs are presented by the descending order of the emission standard and the rated power of the measured machines. For every measured machine, EFs between each pair of activity modes are proved to be significantly different (two-tail *t*-test, 95% confidence interval). 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 (rotation per

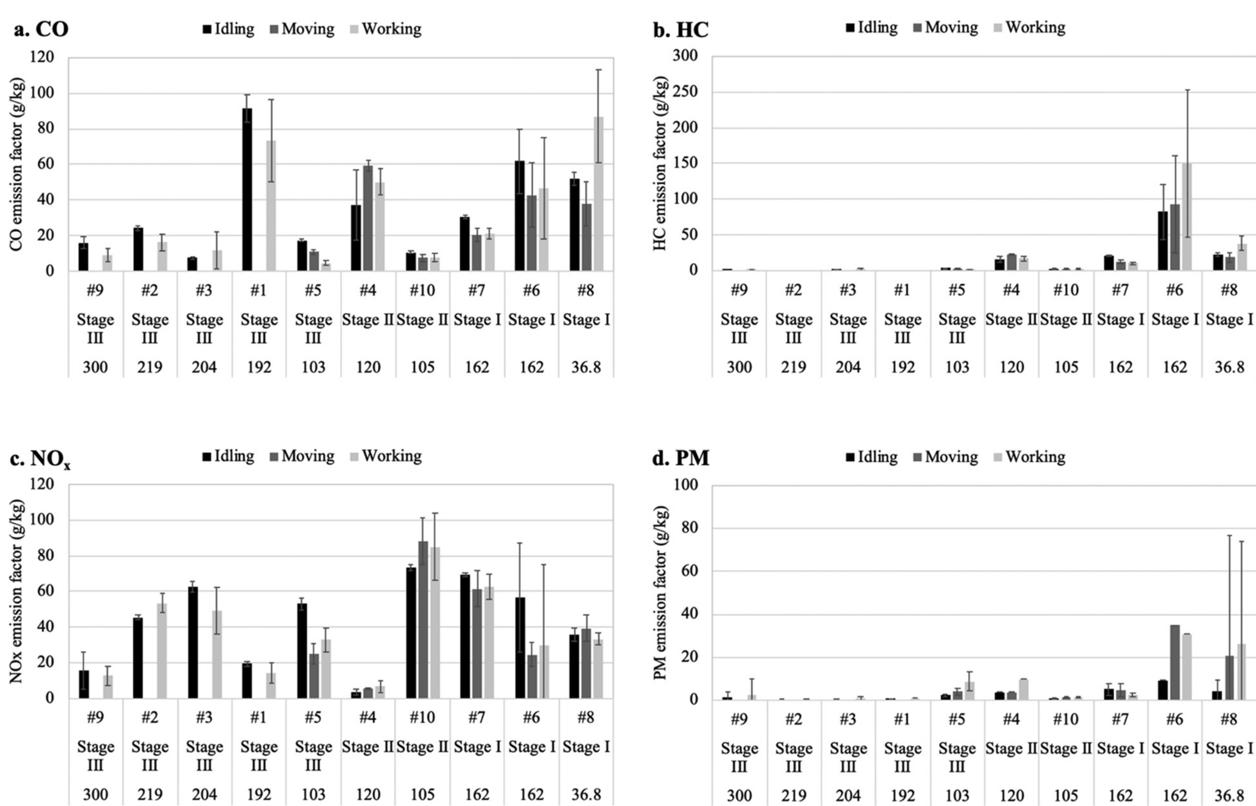

Fig. 2. Mean and standard deviation of CO, NO_x, HC, and PM EFs (g/kg) for ten measured machines under three activity modes (numbers on the bottom of the x-label are the rated power of the corresponding machine).

minute, RPM). The working mode EFs are slightly higher than the moving mode with average relative difference of 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 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 much higher uncertainty for machines under less stringent emission standards (in other words, longer in-use time). Machines under Stage III have relatively lower EFs for all the air pollutants. The coefficient of variation of Stage I machines are higher than those with Stage III standard by 18%, 126%, and 19%, respectively for the idling, moving and operating modes. Among four machines under Stage III, the concrete pump truck (Stage III, 300 kW rated power) generates the lowest EFs: the activity mode weighted average CO, HC, NO_x, and PM EFs were 9.69 g/kg, 13.15 g.kg, 0.58 g/kg and 2.62 g/kg, respectively, which are lower than the other machines with Stage III by 65%, 65%, 35%, and 12%, respectively on average. Statistical tests were implemented, and significant differences among EFs of Stage III machines are depicted. Similarly, CO and NO_x EFs of Loader #7 (Stage I, 162 kW) are also lower than Forklift #8 (Stage I, 36.8 kW) by 235% and 45%, respectively. The trend is consistent with the Guide, which suggests lower EFs for higher rated power with the same emission standard. A large variation of EFs can be observed across machines in the same machine type with the same emission standard and similar rated power, and significant differences are also demonstrated among EFs of machines in the same emission standard (two-tail *t*-test, 95% confidence interval). For example, CO and PM EFs of Crane #1 (Stage III, 192 kW) are significantly higher than other machines under the same emission standard (two-tail t-test with 95% confidence interval), which possibly results from manufacturer and poor maintenance of this 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 Fig. 3. Note that PM_{10} and $PM_{2.5}$, which are distinguished in the Guide, cannot be differentiated by the measurement. Therefore, Suggested PM EFs refer to PM_{10} EFs in the Guide.

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, 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, 162 kW 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. Excess NO_x emissions of the measured Stage III machines are possibly due to reduced efficiency

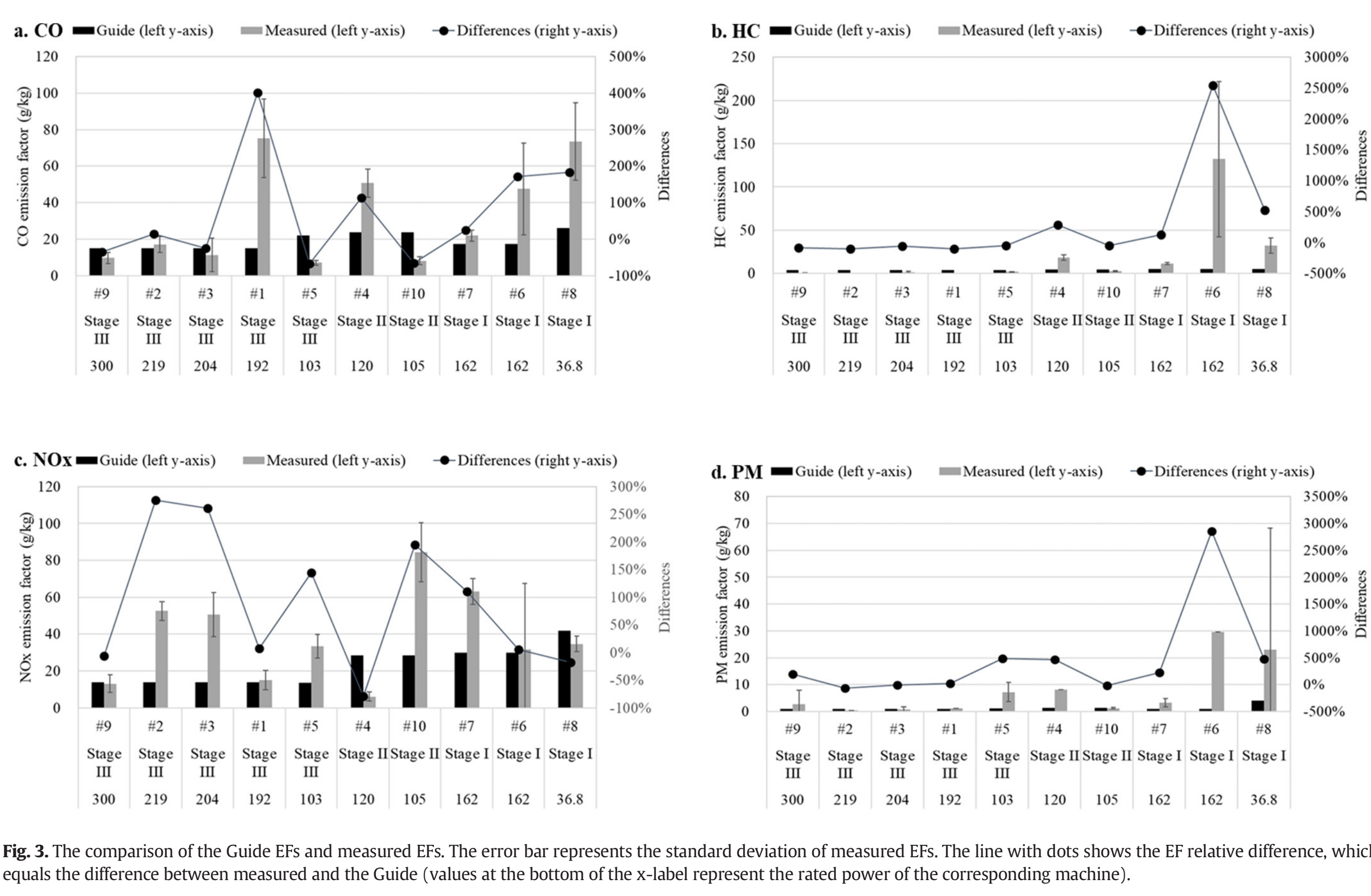

Fig. 3. The comparison of the Guide EFs and measured EFs. The error bar represents the standard deviation of measured EFs. The line with dots shows the EF relative difference, which equals the difference between measured and the Guide (values at the bottom of the x-label represent the rated power of the corresponding machine).

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 $\left(\frac{surveyed-Guide}{Guide}\right)$
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	–	–

of the emission after-treatment, SCR, which can be the result of improper machine maintenance.

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 mobile 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 mobile 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 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 (SCR) of the measured machines than those tested in the Guide. Working conditions of the SCR in the real-world should be further explored in order to effectively reduce tailpipe NO_x emissions from non-road mobile machines. In addition, more stringent controls from local authorities should be implemented for non-road machines in terms of their NO_x emissions.

Besides 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 3 compares the measured EFs of this study with the result of existing research on the real-world non-road mobile 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

Table 3
Comparison with previous research on real-world non-road mobile 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, 105 kW	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, 120 kW	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.

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.

5. Conclusion

In this study, emission factors of air pollutants, including CO, HC, NO_x, and PM, of non-road construction mobile machinery were measured in the real-world working condition. Fuel-based emission factors (EFs, in g/kg) of ten typical construction machines with six mobile 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 among ten machines, EFs become higher with lower rated powers or less stringent emission standards, 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 conditions, and different engine technologies adopted by manufacturers. Comparing the measured EFs to the Guide EFs, 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 standards. 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 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 comparison of NO_x EFs shows different trend to other emissions, and machines under Stage III exhibit the highest relative difference to the Guide. This is possibly due to improper working condition of the Selective Catalytic Reduction (SCR). However, due to limited access to the machine inspection, parameters related to the SCR were not recorded in the experiment, which is the weakness of this study, and the reason for the excess NO_x emissions needs a further investigation.

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, the comparison between the measured EFs and the Guide EFs suggest a significant impact of the machine age on its emissions. Given the heavy workload and strong deterioration of construction machines, an official Guide developed six years ago is no longer suitable for estimating emissions in the real-world. 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.

CRediT authorship contribution statement

Ran Tu: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Tiezhu Li:** Conceptualization, Project administration, Supervision, Writing – review & editing. **Chunsheng Meng:** Investigation, Resources, Data curation. **Jinyi Chen:** Investigation, Data curation. **Zhen Sheng:** Data curation. **Yisong Xie:** Investigation, Resources, Data curation. **Fangjian Xie:** Investigation, Resources, Data curation. **Feng Yang:** Investigation, Resources, Data curation. **Haibo Chen:** Writing – review & editing. **Ying Li:** Writing – review & editing. **Jianbing Gao:** Writing – review & editing. **Ye Liu:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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