

Article



Characterization of Pollutant Emissions from Typical Material Handling Equipment Using a Portable Emission Measurement System

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Abstract: Non-road equipment has been an important source of pollutants that negatively affect air quality in China. An accurate emission inventory for non-road equipment is therefore required to improve air quality. The objective of this paper was to characterize emissions from typical dieselfueled material handling equipment (loaders and cranes) using a portable emission measurement system. Instantaneous, modal, and composite emissions were quantified in this study. Three duty modes (idling, moving, and working) were used. Composite emission factors were estimated using modal emissions and time-fractions for typical duty cycles. Results showed that emissions from loaders and cranes were higher and more variable for the moving and working modes than the idling mode. The estimated fuel-based CO, HC, NO, and PM_{2.5} composite emission factors were 21.7, 2.7, 38.2, and 3.6 g/(kg-fuel), respectively, for loaders, and 8.7, 2.4, 28.3, and 0.3 g/(kg-fuel), respectively, for cranes. NO emissions measured were different from emission factors in the US Environmental Protection Agency NONROAD model and the Chinese National Guideline for Emission Inventory Development for Non-Road Equipment. This indicates that improving emission inventory accuracy for non-road equipment requires more real-world emission measurements.

Keywords: non-road equipment; loader; crane; portable emission measurement system (PEMS); emission factor

1. Introduction

Mobile sources have become important causes of air pollution in major cities around the world [1,2], which make important contributions of particulate matter (PM) and photochemical precursors to the atmosphere [3,4]. Improvements in on-road vehicle emission standards have caused emissions from such vehicles to decrease each year for the past decade [5,6]. The contributions of pollutants from non-road equipment are therefore being paid more attention. It has been found that NO_x, PM, CO, and HC emissions from non-road equipment account for 18–29% of emissions from mobile sources of pollutants around the world [7].

Material handling equipment (e.g., loaders, cranes, and forklifts) is an important type of non-road equipment with a large population. These equipment are mainly diesel powered and emit larger amounts of NO_x and PM than gasoline-powered vehicles. Thus, emissions from material handling equipment need to be quantified before measures and policies for decreasing pollutant emissions can be developed.

The estimation of emission inventory is an effective way of quantifying pollution caused by non-road equipment. An emission inventory would allow policies to be developed to improve air quality by decreasing emissions from non-road equipment. However, it is more challenging to develop an emission inventory for non-road equipment than on-road vehicles because of a lack of relevant data for non-road equipment. Emissions data



Citation: Pang, K.; Meng, X.; Ma, S.; Yin, Z. Characterization of Pollutant Emissions from Typical Material Handling Equipment Using a Portable Emission Measurement System. *Atmosphere* **2021**, *12*, 598. https://doi.org/10.3390/ atmos12050598

Academic Editors: Yuhan Huang, Rafaella Eleni P. Sotiropoulou and Ioannis Sempos (Sebos)

Received: 30 March 2021 Accepted: 26 April 2021 Published: 5 May 2021

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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). used for the development of an emission inventory for non-road equipment have mainly been taken from the NONROAD model [8], the OFFROAD model [9], the EMEP/CRINIR database [10], and a small number of engine dynamometer tests that have been performed in the laboratory but for which the test cycles may not have represented real-world conditions [11,12]. It has been found that emission rates determined under real-world conditions and laboratory conditions may be an order of magnitude different [13,14]. It is therefore essential to characterize real-world pollutant emissions from non-road equipment to improve the accuracy of the non-road equipment emission inventory.

Portable emission measurement systems (PEMSs) are effective instruments for acquiring real-world emission data. A series of PEMSs such as OEM-2100 Montana System (CATI Inc., Leeds, UK), SEMTECH-DS/ECOSTAR (Sensors Inc., Saline, MI, USA), AVL 483/MSS plus Micro-Soot Sensor (AVL Inc., Graz, Austria), and OBS-2000/ONE-GS12 (Horiba Inc., Kyoto, Japan) have been used to measure emissions from non-road equipment during use. A team at North Carolina State University used an OEM-2100 to study the real-time emissions and activity levels of non-road equipment [15–17]. It was found that emissions from non-road equipment had large variability under real-world operating conditions. Similar results have been found in studies of non-road equipment emissions using SEMTECH and AVL series PEMSs [18–20]. Furthermore, the same types of non-road equipment were found to give different emissions in different studies. This was probably caused by the studies being performed in different locations, testing different equipment, and other factors. Even in single studies, markedly different NO_x and PM emissions were found for different types of non-road equipment [17–19]. Therefore, more real-world emission data for non-road equipment of different types and uses and with different powers are required to develop an emission inventory for non-road equipment that is more accurate.

There was 4.8×10^6 material handling equipment in use in China in 2017 [21], accounting for 67.3% of the total population of construction equipment. Emissions from material handling equipment may strongly affect regional air quality. It is therefore important to accurately estimate emissions from material handling equipment to allow policies aimed at decreasing emissions to be developed. However, few measurements of real-world emissions from material handling equipment have been made in China, and there is a distinct lack of data for emissions from material handling equipment during use. Emission factors from the NONROAD model and the Chinese National Guideline for Emission Inventory Development for Non-Road Equipment [22] (later called the National Guideline) have been used to develop an inventory of emissions from material handling equipment in China but may not be representative of emissions under real-world conditions. Few studies have been performed involving real-world measurements of emissions from loaders [20], forklifts [23], and cranes. In these studies, it was found that emissions from material handling equipment during use are very variable because of variability in engine attributes, tasks, working conditions, and driver operating habits. Emissions from material handling equipment under real-world conditions in China need to be characterized to improve the understanding of variability in these factors and improve the accuracy of the inventory of emissions from material handling equipment. The aim of this study was to characterize real-world emissions from material handling equipment to provide data for improving equipment management protocols, air quality management plans, and policies. This study is part of a larger project in which real-world emissions from non-road equipment are being quantified. Part of the project is aimed at quantifying emissions from forklifts [23]. The study described here was mainly focused on quantifying emissions from loaders and cranes.

2. Materials and Methods

The method used in this study had three parts: (1) Experimental design for emission measurement; (2) Real-world emission measurements; (3) Data quality control and analysis. These parts are described in detail below:

2.1. Experimental Design for Emission Measurement

The experimental design was in order to measure the gaseous pollutant and $PM_{2.5}$ emissions from loaders and cranes using a PEMS. This section includes: (1) selection of PEMS; (2) selection of the material handling equipment to be tested; (3) testing duty modes.

2.1.1. Description of the PEMS Used in This Study

The PEMS that was used has been used in previous studies of real-world emissions from other types of construction equipment, including rollers and pavers [24] and excavators [25], and has been shown to give relatively accurate results [23–25]. As shown in Figure 1, the system contained five units: a gaseous pollutant emission measurement unit, a PM_{2.5} sampling unit, an engine parameter measurement unit, a power supply unit, and a data collection unit.



Figure 1. Schematic of the portable emission measurement system (PEMS) used in the study.

The gaseous pollutant emission measurement unit measured CO, CO₂, and HC emissions using non-dispersive infrared sensors. These sensors work on the principle that each compound of interest absorbs infrared light at a particular wavelength that allows the concentration of the compound to be selectively determined in the presence of other compounds. NO and O₂ emissions were measured using electrochemical sensors. A change in electrical current caused by a redox reaction of NO on an electrode surface allowed the NO and O₂ concentrations to be determined.

A gravimetric method [26] was used to measure $PM_{2.5}$ emissions. The $PM_{2.5}$ sampling unit contained a sampling pipe, a dilution system, a gas supply system, an air extraction system, and a sampling system. The sampling pump extracted exhaust gases from the exhaust pipe of the equipment at a constant flow rate. The gases entered the dilution system through the sampling pipe. The dilution system diluted the gases at a dilution ratio of between 15 and 20. The valve was used to adjust the flow rate of the gases passing through the $PM_{2.5}$ cutting head to 10 L/min. $PM_{2.5}$ was collected on a polytetrafluoroethylene membrane with a known mass.

The engine parameter measurement unit contained a temperature sensor, a pressure sensor, an engine revolution sensor, and an exhaust temperature sensor, which measured the intake air temperature (IAT), manifold absolute pressure (MAP), engine revolutions per minute (RPM), and exhaust temperature (ET), respectively.

A battery powered the whole system. Data were transmitted using a wireless system (maximum transmission distance: 200 m).

Second-by-second time-based and fuel-based emission rates (for gases) were determined using the PEMS using a mass-balance approach and the ideal gas law, as described in previous publications [27,28]. The PM_{2.5} emission rate is given as the mean mass emission rate determined from the changes of filter membrane weight.

The PEMS precision was 3 ppm for NO, 0.01% for CO and CO₂, and 1 ppm for HC. The instrument was calibrated before and after each measurement using standard gases, one containing high concentrations of the analytes (8.02% CO, 20.06% CO₂, 1603 ppm C_3H_8 ,

and 2950 ppm NO) and the other containing low concentrations of the analytes (0.50% CO, 5.87% CO₂, 200.8 ppm C₃H₈, and 312.5 ppm NO). Furthermore, the data reported by the PEMS were compared with data reported by a HORIBA OBS-2000 system for an engine dynamometer, and the correlation coefficients R² for the relationships between the time-based emission rates for all of the pollutants of interest were >0.98.

2.1.2. Selection of the Equipment for Testing

It is difficult to obtain real-world measurements of emissions from non-road equipment, unlike light-duty gasoline vehicles. After assessing the implications for safety at the construction sites and the experiment permit, four loaders and five cranes at three construction sites in Chengdu City in Sichuan Province, China, were selected for emission measurements to be made. Information on the loaders and cranes is shown in Table 1. The selected equipment complied with either stage I or II Chinese emission standards and had power ratings between 86 and 170 kW.

Test Count	Equipment Type	Equipment Model	Engine Model	MY ¹	EP ² (kW)	ESC ³ (Stage)
1		CG ⁴ ZL50E-3	WD10G22CE23	2013	162	II
2	Taadaa	CG ⁴ ZL30B-2	6110/125G-18	2007	86	Ι
3	Loader	CG ⁴ ZL30B	6110/125G-18	2008	86	Ι
4		CG ⁴ ZL30B	6110/125G-18	2008	86	Ι
5		XG ⁵ XZJ5160JQZ12	D6114ZQ33A	2003	152	Ι
6		XG ⁵ XAJ5164JQZ12	SC8DK230Q3	2009	170	Ι
7	Crane	XG ⁵ XZJ5164JQZ12	SC8DK230Q3	2010	170	II
8		XG ⁵ XZJ5164JQZ12	SC8DK230Q3	2011	170	II
9		CJ ⁶ QZC5102JQZQY8F	YC4E140-30	2008	105	Ι

¹ Manufacture year; ² engine power; ³ emission standards compliance; ⁴ Chengdu Chenggong Construction Equipment Co., Ltd.; ⁵ Xuzhou Construction Equipment Co., Ltd.; ⁶ Sichuan Changjiang Crane Co., Ltd.

2.1.3. Testing Duty Modes

Emissions from non-road equipment will be different at different operating conditions. Thus, different duty modes were designed for loaders and cranes in this study.

In the idling mode, the equipment was not moving or working, and the engine was operating at a low number of revolutions per minute (after the warming up period). $PM_{2.5}$ emitted by each piece of equipment in the idling mode was sampled for 20–30 min. In the moving mode, the engine was operating, and the equipment was moving forward or backward without performing work. For example, the equipment may have been moving from one location to another without performing a work task. $PM_{2.5}$ emitted by each piece of equipment in the moving mode was sampled for 10–20 min. In the working mode, a loader or crane was working under normal conditions. $PM_{2.5}$ emitted by each piece of equipment in the working mode was sampled for 10–20 min.

2.2. Real-World Emission Measurements

At least two hours were required to install and commission the PEMS on the tested equipment before measurements were made. The personnel performing the experiment needed to arrive at an agreed time to install the instrument before the equipment to be tested was used under normal operating conditions. The PEMS was generally placed flat on top of the equipment being tested. A rubber pad was placed underneath the PEMS to prevent vibrations in the equipment from affecting data collection.

The RPM sensor used in this study was determined using an infrared pulse system, which identified each time a reflective strip stuck to the engine spindle passed the sensor. The RPM sensor was installed in a position that allowed the infrared ray emitted by the sensor to hit the reflective strip without any obstruction. The MAP and IAT sensors were installed between the intercooler and the engine cylinder. The ET sensor and gas and PM_{2.5}



sampling pipes were inserted into the exhaust pipe of the equipment and anchored using iron wire. Examples of the PEMS installed on the equipment are shown in Figure 2.

Figure 2. Installation of the PEMS to the selected equipment for emission measurements.

Blank and used filters were equilibrated in a temperature- and humidity-controlled chamber for 24 h and then weighed using an electronic balance. The instrument specifications are shown in Table 2.

Table 2. Specification and precision of filter treatment instrument.

Instrument	Model	Specification	Precision
Temperature- and humidity-controlled chamber	YiHeng LHS-80HC-I, China	−5−80 °C; 40−85%RH	High temperature: ±0.5 °C; Low temperature: ±1 °C; Humidity: ±3%RH
Electronic balance	Sartorius Quintix 35–1CN, Germany	0–30 g	0.01 mg

Each $PM_{2.5}$ measurement was made by performing one test, so a fresh filter was installed after a test was completed. Measurements were made more than three times for each duty mode, and each measurement process lasted at least three hours.

2.3. Data Quality Control and Analysis

Data quality control checks were performed to ensure that the collected data were correct and suitable for further analysis. The main steps involved in processing the emission and engine parameter data collected using the PEMS were (1) data synchronization, (2) processing missing and stagnant data, and (3) eliminating abnormal data. The processes have been described in detail in previous publications [22,23]. After the quality control processes had been performed, the data were analyzed further.

2.3.1. Instantaneous Emissions Analysis

Instantaneous emissions mean second-by-second emissions of gaseous pollutants (e.g., NO, HC, CO, and CO₂). Instantaneous emission rates for gaseous pollutants and fuel consumption were determined for 100 s in the idling, moving, and working modes.

2.3.2. Modal Emissions Analysis

The effects of the equipment duty mode on emissions were assessed. The duty modes (idling, moving, and working) were defined above. The mean pollutant emission values and 95% confidence intervals for the different duty modes were used in the analyses.

Furthermore, in order to determine the influence of power on emissions under different duty modes, the engine power was divided into two ranges (75 kW \leq P < 130 kW and 130 kW \leq P < 225 kW).

2.3.3. Composite Emissions Estimation

Composite emission factors for each piece of equipment were calculated using emissions data acquired using the equipment in the idling, moving, and working modes and time-weighted ratios for operation of the equipment determined from video recordings of the equipment during use. The composite emission factors were calculated using Equation (1):

$$CEF_i = \sum_j (EF_{i,j} \times T_j) \tag{1}$$

where CEF_i is the composite emission factor (g/(kg-fuel)) for pollutant *i* (CO, HC, NO, or PM_{2.5}), *j* is the duty mode (idling, moving, or working), $EF_{i,j}$ is the mean emission factor for pollutant *i* in mode *j*, and T_j is the proportion of the time the equipment was operated in mode *j* (determined in a preliminary survey).

3. Results

This section contains (1) a brief description of the emission data; (2) instantaneous emissions for the loaders and cranes; (3) modal emissions for the loaders and cranes; (4) composite emission factors for the loaders and cranes; (5) a comparison of emission data acquired in different studies.

3.1. Brief Description of Collected Emission Data

Second-by-second gaseous pollutant emission and engine parameter data were acquired for 2–3 h for each loader and crane. As shown in Table 3, the quality control processes indicated that 73.2–91.6% and 86.6–94.1% of the loader and crane emission data, respectively, were valid. Between 5 and 11 PM_{2.5} filter samples were obtained for each piece of equipment.

Test Count	Equipment Type	Equipment Model	Date Amount (s)	Data Validity (%)	PM _{2.5} Samples Number
1		CG ZL50E-3	6349	73.2	6
2	T 1	CG ZL30B-2	8249	88.3	7
3	Loader	CG ZL30B	12,032	91.6	11
4		CG ZL30B	9150	88.4	8
5		XG XZJ5160JQZ12	10,993	94.1	11
6		XG XAJ5164JQZ12	7660	86.6	8
7	Crane	XG XZJ5164JQZ12	9085	93.9	6
8		XG XZJ5164JQZ12	9957	89.8	5
9		CJ QZC5102JQZQY8F	9295	90.9	7

Table 3. Data collection and quality control results of emissions.

3.2. Instantaneous Emissions from the Loaders and Cranes

The instantaneous emissions for a typical diesel-fueled loader are shown in Figure 3. The real-time emission and fuel consumption rates for the loader in the idling, moving, and working modes were different. The real-time emission and fuel consumption rates were relatively stable in the idling mode but varied in the moving and working modes. The real-time CO, HC, and NO emission rates in the idling mode were 9.5–18.9, 0.3–0.8, and 3.2–7.0 mg/s, respectively. The CO, HC, and NO emission rates in the moving mode were 12.4–39.5, 0.8–2.1, and 13.1–37.5 mg/s, respectively. The CO, HC, and NO emission rates in the working mode were 10.8–102.4, 0.3–1.7, and 18.4–56.0 mg/s, respectively. The emission rates would have been stable in the idling mode because the engine revolution and fuel consumption rates would have been stable as the engine would not have been under a load. The loader was within the construction area traveling on a very bumpy

road during the moving mode test. The driver needed to apply and release the accelerator passing through the construction area. The fuel consumption rate would therefore have varied, causing the gaseous pollutant emission rates to vary. The loader was used to dig, move, and dump during the working mode test. This would have meant that the engine load and fuel consumption rate kept changing dramatically, meaning pollutant emissions would have varied widely. The HC emission rate was higher in the moving mode than in the other modes. This may have been because the loader was traveling over an uneven road during the moving mode test. Combustion would have been unstable because of frequent changes in road conditions, causing incomplete fuel combustion and increased HC emissions.



Figure 3. Typical emission time series for a diesel-fueled loader in the three duty modes (* FC = fuel consumption).

Instantaneous emissions from a typical crane are shown in Figure 4. Like for the loader, the instantaneous gaseous pollutant emission rates for the crane in the idling, moving, and working modes were different. The real-time CO, HC, and NO emission rates and fuel consumption rates were more stable in the idling mode than in the moving and working modes. The real-time CO, HC, and NO emission rates were 7.2–9.9, 0.4–0.9, and 14.4–19.4 mg/s, respectively, in the idling mode, 7.4–29.3, 2.1–12.6, and 13.4–265.7 mg/s, respectively, in the moving mode, and 9.1–16.4, 2.4–5.0, and 29.7–107.2 mg/s, respectively, in the working mode. The gaseous pollutant emission rates varied more in the moving mode than the other modes. This would have been because there were many traffic lights on the road the crane traveled along from the parking area to the construction area during the test. The driver needed to apply and release the accelerator to speed up and slow down during the journey. The variations in fuel consumption rate caused by this would have caused gaseous pollutant emissions to vary.



Figure 4. Typical emission time series for a diesel-fueled crane in the three duty modes (* FC = fuel consumption).

3.3. Modal Emissions for Loaders and Cranes

The time-based and fuel-based emission factors for the loaders and cranes in the idling, moving, and working modes are shown in Figure 5. The time-based CO, HC, NO, and PM_{2.5} emission rates for the loaders were 5.6, 2.1, 3.4, and 6.2 times higher, respectively, in the moving mode than in the idling mode and 8.5, 2.3, 3.7, and 9.5 times higher, respectively, in the working mode than in the idling mode. The time-based CO, HC, NO, and PM_{2.5} emission rates for the cranes were 2.1, 2.2, 3.8, and 7.0 times higher, respectively, in the moving mode than in the idling mode and 1.3, 2.3, 2.6, and 3.0 times higher, respectively, in the working mode than in the idling mode. The emission rates were, on average, higher in the moving and working modes than in the idling mode.



Figure 5. Emission rates for (a) loaders and (b) cranes in the three duty modes.

The time-based emission factors for the different modes were more variable than the fuel-consumption-based emission factors. For example, the maximum to minimum time-based NO emission rate ratios for the loaders in the idling, moving, and working modes were 8.7, 3.7, and 4.7, respectively, and the maximum to minimum fuel-based NO emission rate ratios in the idling, moving, and working modes were 3.2, 2.5, and 2.8, respectively. The maximum to minimum time-based NO emission rate ratios for the cranes in the idling, moving, and working modes were 2.5, 2.6, and 2.3, respectively, and the maximum to minimum fuel-based NO emission rate ratios in the idling, moving, and working modes were 1.6, 1.5, and 1.5, respectively. Similar results have been found in previous studies [17,24]. Furthermore, there were no significant differences between fuel-based emissions in the idling and working modes. For example, the estimated fuelbased CO emission factors for loaders were 10.9–33.8 g/(kg-fuel) in the idling mode and 10.9–30.6 g/(kg-fuel) in the working mode. This indicated that more accurate emission inventories may be constructed using fuel-consumption-based data than time-based data.

The time-based emission rates were higher when the loaders were used in the working mode than in the moving mode. The time-based emission rates were higher when the cranes were used in the moving mode than in the working mode, which would have been caused by the cranes moving relatively quickly from one job to another during the tests. These results indicated that equipment such as cranes and forklifts that can move quickly along a road may give higher emission rates in the moving mode than when loading and unloading.

The time-based and fuel-based emissions for the tested equipment were analyzed using the unified power division method to assess differences in the emission rates of loader and crane engines at different powers. The CO, HC, NO, and PM_{2.5} emissions for the loaders and cranes with different engine powers in the different duty modes are shown in Table 4. It can be seen that the time-based CO, HC, NO, and PM_{2.5} emissions for the loaders in the three duty modes increased as the engine power increased.

Duty	Engine		Time-Based E	Emissions (g/h)	Fuel-Based Emissions (g/kg-fuel)				
Mode	Power	СО	HC	NO	PM _{2.5}	СО	HC	NO	PM _{2.5}
Idling	$75 \le P < 130$	19.1 ± 11.3	3.4 ± 1.8	38.2 ± 30.3	0.8 ± 1.1	13.9 ± 9.3	2.6 ± 1.9	25.0 ± 12.3	0.6 ± 0.9
	$130 \le P < 225$	33.4 ± 7.7	5.3 ± 4.5	50.3 ± 23.9	2.6 ± 3.2	17.9 ± 12.6	2.4 ± 1.6	19.9 ± 8.8	2.0 ± 3.3
Moving	$75 \le P < 130$	53.9 ± 26.1	7.9 ± 2.8	110.3 ± 14.6	8.2 ± 8.8	13.4 ± 7.1	2.9 ± 1.6	27.8 ± 3.0	2.5 ± 2.8
	$130 \le P < 225$	164.2 ± 211.9	12.9 ± 6.9	253.4 ± 96.5	14.9 ± 21.0	17.4 ± 8.1	3.2 ± 2.6	26.5 ± 10.0	1.9 ± 1.5
Working	$75 \le P < 130$	82.0 ± 55.9	10.7 ± 9.4	108.1 ± 61.1	14.3 ± 12.9	16.8 ± 9.2	3.5 ± 2.3	25.8 ± 12.2	4.0 ± 2.9
	$130 \le P \le 225$	212.7 ± 340.3	12.9 ± 7.3	200.0 ± 88.1	16.2 ± 27.0	10.5 ± 6.2	2.2 ± 1.7	23.7 ± 9.2	0.7 ± 0.6

Table 4. Emissions of different loader and crane engines in the different duty modes.

The time-based CO, HC, NO, and PM_{2.5} emission rates for loaders in the power range 130 kW \leq P < 225 kW in the idling mode were 1.7, 1.6, 1.3, and 3.3 times higher, respectively, than the emission rates for loaders in the power range 75 kW \leq P < 130 kW. The time-based CO, HC, NO, and PM_{2.5} emission rates for loaders in the power range 130 kW \leq P < 225 kW in the moving mode were 3.0, 1.6, 2.3, and 1.8 times higher, respectively, than the emission rates for loaders in the power range 75 kW \leq P < 130 kW. The CO, HC, NO, and PM_{2.5} rates for loaders in the power range 130 kW \leq P < 225 kW in the moving mode were 3.0, 1.6, 2.3, and 1.8 times higher, respectively, than the emission rates for loaders in the power range 75 kW \leq P < 130 kW. The CO, HC, NO, and PM_{2.5} rates for loaders in the power range 130 kW \leq P < 225 kW in the working mode were 2.6, 1,2, 1.9, and 1.1 times higher, respectively, than the emission rates for loaders in the power range 75 kW \leq P < 130 kW. An engine needs more air and fuel for combustion, and therefore the time-based emission rate increases as the engine power increases and the load increases.

For all pollutants, fuel-based emissions do not exhibit a clear trend among different engine powers and different duty modes. This may be because emissions based on fuel consumption depend on both emission rate and fuel consumption rate. Both emissions and fuel consumption will increase with the increase of engine power and load.

3.4. Composite Emission Factors for Loaders and Cranes

Activity information was estimated from video footage of eight loaders and seven cranes. The idling, moving, and working modes contributed 34.8%, 35.1%, and 30.1%, respectively, of total time for the loaders and 35.6%, 5.0%, and 59.4%, respectively, of total time for the cranes. A crane is not moved to the parking area from the working area until the required work is complete, so, in normal working practice, a crane will have only two duty modes, idling and working.

Composite emission factors based on fuel consumption were calculated for the four loaders and five cranes that were used in this study using Equation (1), and the 95% confidence intervals were also calculated. As shown in Table 5, the emission factors for each pollutant were different for the different types of equipment. The NO emission factor was higher than the emissions factors for the other pollutants; thus, NO emissions from material handling equipment should be the primary target for control. The maximum to minimum fuel consumption ratio for the loaders was 8.1, and the maximum to minimum fuel-based CO, HC, NO, and $PM_{2.5}$ emission factor ratios were 3.1, 5.7, 14.3, and 2.6, respectively. The maximum to minimum fuel-based CO, HC, NO, and $PM_{2.5}$ emission factor ratios for the cranes was 2.2, and the maximum to minimum fuel-based CO, HC, NO, and 5.2, respectively. The differences may have been caused by the different operating modes and working conditions for the different equipment.

Test Count	_			Composite Emissions (g/kg-fuel)							
	Equipment Type	Fuel Con	sumption (g/s)		СО		HC		NO	I	PM _{2.5}
	~ 7 F	Ave	95%CI *	Ave	95%CI *	Ave	95%CI *	Ave	95%CI *	Ave	95%CI *
1		7.2	(2.5, 11.9)	33.4	(11.0, 62.7)	2.0	(0.5, 4.0)	6.6	(2.8, 11.5)	4.1	(0.8, 9.1)
2		2.4	(1.5, 3.3)	18.4	(6.0, 36.9)	3.4	(1.1, 6.7)	94.5	(39.6, 164.9)	4.0	(1.3, 7.9)
3	loader	0.9	(0.6, 1.2)	11.0	(4.6, 18.7)	4.2	(1.7, 7.3)	25.4	(12.6, 38.7)	1.8	(0.7, 3.4)
4		1.1	(0.7, 1.5)	24.1	(9.3, 42.7)	1.2	(0.5, 2.2)	26.1	(11.8, 45.5)	4.5	(2.2, 7.0)
5		1.0	(0.8, 1.2)	9.1	(7.0, 11.4)	3.1	(1.8, 4.7)	22.8	(17.8, 28.1)	0.4	(0.3, 0.5)
6		2.2	(1.4, 2.9)	9.0	(6.9, 11.1)	0.3	(0.2, 0.3)	31.4	(25.6, 37.3)	0.7	(0.5, 0.9)
7	Crane	1.9	(1.1, 2.7)	8.8	(6.8, 10.8)	4.6	(3.6, 5.7)	24.2	(19.0, 29.8)	0.2	(0.1, 0.2)
8		1.9	(1.1, 2.8)	8.9	(6.4, 11.6)	1.8	(1.4, 2.1)	26.7	(21.4, 32.1)	0.1	(0.1, 0.2)
9		1.4	(0.8, 1.9)	7.8	(6.1, 9.6)	2.2	(1.3, 3.3)	36.3	(27.7, 45.5)	0.2	(0.1, 0.2)

Table 5. Fuel-based emission factors of the tested equipment in this study.

* 95% confidence interval.

Differences between emissions from loaders and crane engines that comply with different emission standards were quantified, and the results are shown in Figure 6. Moving from stage I to stage II decreased NO and $PM_{2.5}$ emissions by 51.4% and 24.1%, respectively. CO and HC emissions were not significantly affected by moving from stage I to stage II. Therefore, under real-world conditions, compliance with emission standards will be closely related to the equipment used, the operating conditions, and the job characteristics. This implies that current Chinese NO regulations are stringent enough, but CO and HC regulations need to be stricter.



Figure 6. Emissions from loaders and crane engines that comply with different emission standards.

3.5. Comparison of Emission Factors Found in Different Studies

Exhaust gases emitted by loaders and cranes are affected by various factors, such as the engine design, duty mode, and operating conditions. Different emission results have been found in different studies, as shown in Table 6. Fuel-based emissions for the same type or similar types of equipment can vary by factors of between 1.1 and 14.3 for different pollutants. For loaders, CO and $PM_{2.5}$ emissions were high and HC and NO emissions were moderate in this study relative to previous studies. For cranes, CO, HC, and $PM_{2.5}$ emissions were lower and NO emissions were moderate in this study compared with previous studies. Few studies of pollutant emissions from non-road equipment in China have been performed, so well-established emission factor models such as NONROAD (developed by the US Environmental Protection Agency) and the Chinese National Guideline Emission Inventory Development for Non-Road Equipment have been used to construct emission inventories for non-road equipment. CO, HC, NO, and $PM_{2.5}$ emission factors estimated in this study were different from those used in

the NONROAD model and the Chinese National Guideline. A more accurate emission inventory for non-road equipment requires local real-world emissions measurements to be made.

Emission Factors (g/kg-Fuel)				Equipment Type	Sources		
СО	HC	NO	PM _{2.5}	-1			
21.73	2.70	38.18	3.59	Loader	This study		
14.28	2.37	24.42	2.01	Loader	NONROAD [8]		
17.47	7.61	83.38	1.48	Loader	Fu et al. [20]		
11.03	5.99	42.56	0.25	Loader	Frey et al. [17]		
8.70	2.39	28.29	0.30	Crane	This study		
9.91	2.43	25.48	1.70	Crane	NONROAD [8]		
10.72	3.39	32.79	2.09	Construction equipment	National Guideline [22]		

Table 6. Comparisons of emissions factors by different studies.

Composite emissions for each type of equipment measured in this study were compared with relevant national emission standards. As shown in Figure 7, emissions from in-use cranes tested in this study met the relevant emission standards. For loaders, real-world CO, NO, and PM_{2.5} emissions (particularly CO and PM_{2.5} emissions) might be higher than the relevant national emission standards. Thus, it is particularly important to improve emission measurements for in-use non-road equipment to manage high emission equipment.



Figure 7. Comparison of emissions measured in this study with national emission standards. The fuelbased emission factors from the National Emission Standards were converted from $g/(kW\cdot h)$ using the mean BSFC for a given power range from the NONROAD model, i.e., when $P \ge 75 \text{ kW}$, BSFC = 263.19 g/(kW·h) for loaders or 223.07 g/(kW·h) for cranes.

Emissions of four pollutants (CO, HC, NO, and $PM_{2.5}$) from loaders and cranes were measured and estimated. It has previously been found that large fractions of particles (e.g., PM_{10}) are emitted by diesel-fueled engines [29]. Pollutant emissions from diesel-fueled engines should therefore be quantified using real-world PM_{10} emission measurements and component analysis of PM should be performed in future work.

4. Summary and Conclusions

Emissions from four loaders and five cranes were determined using a PEMS that was capable of making real-world measurements of emissions from non-road equipment (e.g., cranes, excavators, forklifts, loaders, and pavers). The PEMS allows real-world emission data for non-road equipment in China to be collected.

Large intra- and inter-equipment variabilities in pollutant emissions were found. Intra-equipment emission variability was mainly caused by changes in the duty mode pattern. Duty modes should therefore be taken into account when developing representative emission factors for non-road equipment. Inter-equipment emission variability was mainly caused by differences in engine power, model, age, emission standard compliance, and other factors. The CO, HC, NO, and PM_{2.5} emission rates increased markedly as the engine power increased. The power classification of the engine in a piece of equipment is therefore useful for determining the emission rate.

The fuel-based emission rates were less variable than the time-based emission rates. Fuel-based emission factors may therefore provide relatively stable and accurate estimates for developing emission inventories.

The real-world emissions from diesel-fueled loaders and cranes were markedly different from emissions found in previously published studies. Few studies of emissions from non-road equipment have been performed in China, so standardizing and unifying the instruments and methods used to perform real-world measurements and making more measurements of real-world emissions from non-road equipment are required to improve the accuracy of emission factors. Non-road equipment activities need to be studied further to provide detailed information for developing emission models and inventories, which are necessary to establish appropriate air pollution control policies for China.

NO and $PM_{2.5}$ emissions from diesel engines were significantly lower for stage II than stage I, but CO and HC emissions were not significantly different for stage II and stage I. This implies that current Chinese emission standards for NO and $PM_{2.5}$ are stringent enough but current emission standards for CO and HC need to be stricter. Furthermore, even if a non-road equipment engine meets the relevant emission standards when it leaves the factory, emissions during use may exceed the emission standards because of engine aging. Emission inspections for in-use non-road equipment will therefore help effectively control emissions from non-road equipment.

Author Contributions: Conceptualization, K.P. and X.M.; data curation, K.P., X.M., S.M. and Z.Y.; formal analysis, K.P. and S.M.; investigation, K.P. and S.M.; methodology, K.P. and X.M.; software, X.M.; supervision, X.M., and S.M.; validation, K.P.; writing—original draft preparation, K.P.; writing—review and editing, K.P., X.M., S.M., and Z.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Research Project of the Bureau of Science and Technology of Sichuan (No. 2019YFS0498). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsor and the university.

Data Availability Statement: Not applicable.

Acknowledgments: We are grateful for financial support from the Research Project of the Bureau of Science and Technology of Sichuan (No. 2019YFS0498). The authors thank all the members of the Atmospheric Modeling and Environmental Data Analysis research group at Sichuan University for their help in real-world emission measurements in this study. We would also like to show deep thankfulness to the reviewers and editors who have contributed valuable comments to improve the quality of the paper.

Conflicts of Interest: The authors declare no conflict of interest.

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