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Tailpipe emission characterizations of diesel-fueled forklifts under real-world operations using a portable emission measurement system

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ARTICLE INFO

Article history:
Received 29 March 2020
Revised 8 July 2020
Accepted 9 July 2020
Available online 23 July 2020

Keywords:
Non-road equipment
Forklifts
Portable emission measurement system (pems)
Emission factors
Emission inventory

ABSTRACT

Non-road equipment is one of the key contributing sources to air pollution. Thus, an accurate development of emission inventory from non-road equipment is imperative for air quality management, especially for equipment with a large population such as diesel-fueled forklifts. The objective of this paper is to characterize duty-cycle based emissions from diesel-fueled forklifts using a portable emission measurement system (PEMS). Three duty-cycles were defined in this study, including idling, moving, and working (active duty operation) and used to characterize in-use emissions for diesel-fueled forklifts. A total of twelve diesel-fueled forklifts were selected for real-world emission measurements. Results showed that fuel-based emission factors appear to have smaller variability compared to time-based ones. For example, the time-based emission factors for CO, HC, NO, and $PM_{2.5}$ for forklifts were estimated to be 16.6–43.9, 5.3–15.1, 26.2–49.9, 5.5–11.1 g/hr with the fuel-based emission factors being 12.1–20.3, 4.1–8.3, 19.1–32.4, 3.5–6.5 g/kg-fuel, respectively. NO emissions appear to be the biggest concern for emissions control. Furthermore, most of the emissions factors estimated from this study are significantly different from those in both National Guideline for Emission Inventory Development for Non-Road Equipment in China and well-developed emission factor models such as NONROAD by US EPA. This implies that localized, preferably fuel-based emission factors should be adjusted based on real-world emission measurements in order to develop a representative emission inventory for non-road equipment.

Introduction

Non-road equipment (e.g., forklifts, excavators, backhoes, and a variety of other agricultural and construction equipment) can substantially contribute to emissions of hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x), carbon dioxide (CO_2), particulate matter (PM), and other harmful air pollutants. For example, HC, CO, NO_x and PM emissions from non-road equipment can account for 18–29% of global mobile source emissions (Yan et al., 2014), and are expected to increase due to relatively long useful life and emissions from other sources such as on-road vehicles being significantly reduced.

Forklifts are one of the key non-road equipment for materials handling and have been widely used world-wide. Compared to other non-road equipment, forklifts have a relatively larger population and will continue to increase as economy grows (CCMA, 2018). For example, in 2017, there are nearly

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https://doi.org/10.1016/j.jes.2020.07.011

2.6 million forklifts in China, which is approximately 55.9% and 52.8% more than that of excavators and loaders, respectively (CCMA, 2018). Thus, emissions from forklifts, especially for those powered by diesel fuel, are discernable and should be paid attention. For example, HC, NO_x and PM emissions from forklifts in China in 2017 were estimated to be 6.5×10^4, 3.77×10^5, and 3.1×10^4 tons, accounting for 21.2%, 19.1% and 23.8% of the total emissions of construction equipment, respectively (MEE PCR, 2018). However, due to the existence of large variability in emissions from limited study on real-world emission measurements on non-road equipment, the current emission inventory for non-road equipment is expected to have a large uncertainty. For example, emission factors used for non-road equipment emission inventory development are usually from laboratory engine dynamometer test (Fan et al., 2018; Gautam et al., 2002; Lindgren et al., 2010; MEE PCR, 2014 and 2018), which the testing duty-cycle may not be representative of the real-world situation. Several studies have showed that there may be an order of magnitude difference in emission rates between real-world measurements and laboratory tests (Heidari and Marr, 2015; Pirjola et al., 2017). Thus, an accurate emission inventory will have significant impact on policy making for air quality improvement.

In order to improve the accuracy of emission inventory, emissions of non-road equipment have to be well characterized based on real-world in-use measurements. In recent years, portable emission measurement systems (PEMS) have been proved to be a practical approach in characterizing real-world emissions for non-road equipment (Cao et al., 2016; Frey et al., 2010; Heidari et al., 2015). A variety of PEMS have been used for real-world emission measurements for non-road equipment, including OEM-2100 Montana System (Clean Air Technology International Inc., aka. CATI), SEMTECH-DS/ECOSTAR (Sensors Inc.), AVL 483/MSS plus Micro-Soot Sensor (Anstalt für Verbrennungskraftmaschinen List Inc., aka. AVL), and OBS-2000/ONE-GS12 (Horiba Inc.) and many others. Studies in the literature have shown even under real-world situations, there existed a large variability in emissions for non-road equipment (Abolhasani et al., 2008; Cao et al., 2016; Durbin et al., 2013; Frey et al., 2008, 2010; Fu et al., 2012; Giannelli et al., 2010; Lewis et al., 2011; ***Liu et al., 2018***; Pang et al., 2009; Rasdorf et al., 2010; Zavala et al., 2017). Emissions vary by equipment type, operation conditions, PEMS used, fuel type, and many other factors. For example, NO_x emission rate for excavators varied largely under real-world situations with different ranges being reported in different studies, e.g., from 189.0 to 319.0 g/hr by Frey et al. (2010), from 117.0 to 913.0 g/hr by Sandanayake et al. (2015), and from 6.9 to 664.9 g/hr by Ma et al. (2019), respectively; A wide range of PM emission rate were also found the in different studies, e.g., from 2.4 to 15.0 g/hr by Fu et al. (2012), from 0.2 to 63.4 g/hr by Cao et al. (2016), and from 1.3 to 99.1 g/hr by Ma et al. (2019). It was reported that the fuel type can impact the soot composition in the tailpipe emissions (Ge et al., 2019). Furthermore, similar large ranges of variation were also reported in the literatures for many other non-road equipment, such as loaders (Cao et al., 2016; Frey et al., 2010; Zavala et al., 2017) and bulldozers (Cao et al., 2016; Frey et al., 2010).These studies showed that intra-equipment variability in emissions are mainly due to duty-cycle changes under real-world operation conditions.

Due to the relatively large population with a majority being powered with diesel fuel for forklifts, tailpipe emissions from forklifts are expected to increase with economy development and will have a significant impact on air quality. Therefore, an accurate estimation of emissions for diesel-fueled forklifts are imperative for emissions control measures selection such as electrification. However, current emission factors used for emission inventory development for forklifts are mainly from laboratory engine dyno testing (Dallmann and Harley, 2010; Huang et al., 2018; MEE PCR, 2018; Wang et al., 2016) and may not represent the real-world operation conditions. Although there have been many emission studies on non-road equipment in the literature, few of them have been focused on diesel-fueled forklifts or have covered a wide range of emission standards compliance. For example, Ye et al. (2018) selected seven diesel-fueled forklifts for real-world emissions measurements. However, only forklifts with compliance of Stage I or II emission standards of China were included in that study. Furthermore, there were not any actual duties performed by the forklifts during the measurements, which may underestimate the real-world emissions. Therefore, the data gap for emissions from non-road diesel-fueled forklifts under real-world operation conditions is still huge. Thus, the objective of this study is to characterize real-world tailpipe emissions of diesel-fueled forklifts using a PEMS. Emission measurements from this study will fill in the data cap for forklifts with respect to emissions and can also be used for emission inventory development and policy-making.

1. Materials and methods

The methodologies used in this study include an experimental design for real-world emission measurements for diesel-fueled forklifts and emissions data analysis. The details are given in the following:

1.1. *Experimental design*

The experimental design for real-world emission measurements for diesel-fueled forklifts in this study includes: (1) selection of instrumentation; (2) selection of forklifts; (3) predefinition of duty-cycle; and (4) procedure development for real-world measurement.

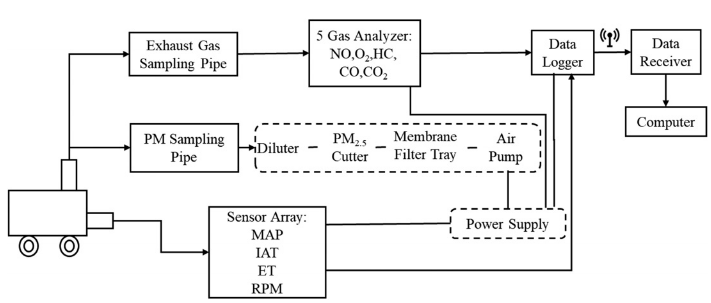

Fig. 1 – The schematics of the portable emission measurement system (PEMS) used in the study.

Table 1 – Selected diesel-fueled forklifts for emission measurements in this study.

No.	Manufacturer	Engine model*	Model Year	ESC[1] (Stage)	EP[2] (kW)	ED[3] (L)	DT[4] (ton)	AT[5]	Activity[#] (hr/year)	Materials weight (ton)	Raw data (sec)	Valid data (%)
1	Maximal[a]	C490BPG	2013	II	40	2.7	3.5	EGR	3000	3–4	7386	78.3
2	Maximal[a]	C480BPG	2014	II	40	2.7	3.5	EGR	1008	1–1.5	6890	93.1
3	Lonking[b]	C490BPG	2009	II	40	2.7	3.5	/	1440	3–4	8929	84.0
4	Heli[c]	C490	2004	Pre-I	40	2.7	3	/	2000	3–3.5	9784	86.2
5	Maximal[a]	C490BPG-221	2011	II	40	2.7	3.5	EGR	2880	3–4	6488	86.7
6	Maximal[a]	C490BPG-221	2011	II	40	2.7	3.5	EGR	2800	2–3	8495	88.3
7	Heli[c]	A498BPG	2014	II	45	3.2	4	EGR+SCR	1013	2–3	8703	86.7
8	Lonking[b]	4C2–50V32	2016	III	36	2.2	3.5	EGR+SCR	2960	3–4	8377	89.9
9	Maximal[a]	CY6102BG	2010	I	81	5.8	6	/	1440	4–5	7207	92.7
10	Lonking[b]	6BG1-NAABD	2008	I	82	6.5	10	/	547	8–9	7606	95.3
11	Heli[c]	YC6B125-T10	2007	I	92	6.9	3	/	1900	2–3	6696	88.8
12	Tisiam[d]	CA498	2009	II	45	3.2	3	/	900	1–2	7611	86.8

Notes:.

* Engines deployed in most forklifts are from major brands in the market. Forklifts from different manufacturers may have the same engine type;.

[1] ESC – Emission Standards Compliance. Currently there are four stages of emission standards for non-road equipment in China, i.e., pre-I, I, II, and III (GB 20,891–2007 and GB 20,891–2014);.

[2] EP - Engine Power;.

[3] ED - Engine Displacement;.

[4] DT - Deadweight Tonnage;.

[5] AT-After-treatment, EGR-Exhaust Gas Recirculation, SCR-Selective Catalytic Reduction;.

[#] Survey data in the real-world measurement process;.

[a] Maximal forklift Corporation of Zhejiang;.

[b] Lonking forklift Corporation of Shanghai;.

[c] Heli forklift Corporation of Zhejiang;.

[d] Tisiam forklift Corporation of Anhui.

1.1.1. *Selection of instrumentation for emission measurements*

A PEMS was developed for this study and has been used in real-world emission measurements of construction equipment (Li et al., 2016; Ma et al., 2019). As shown in Fig. 1, this PEMS consists of three key components, including a five-gas analyzer to measure NO, HC, CO, CO_2, and O_2; a sensor array to measure engine operation parameters such as engine revolutions per minute (RPM), manifold absolute pressure (MAP), intake air temperature (IAT), and exhaust temperature (ET); and a gravimetric PM sampling unit for $PM_{2.5}$ mass measurements. Measurements from these components are combined and used to estimate second-by-second emission and fuel consumption rates based on mass balance of fuel combustion and ideal-gas law which have been well developed and used in the literature (Abolhasani et al., 2008; Vojtisek-Lom and Allsop, 2001; Zhang, 2006). Both time-based and fuel-based emission rates are reported by this system.

The gas analyzer and sensors used in this study were all commercially available. The analyzer uses non-dispersive infrared (NDIR) to measure HC, CO, and CO_2, and electrochemical cells to measure NO and O_2, with a precision of 3 ppm for NO, 0.01% for CO and CO_2, and 1 ppm for HC, respectively. This system was compared to a HORIBA OBS-2000 on an engine dyno to verify its accuracy and precision. The R^2 of the scatter plot of the measured time-based emission rates of these two PEMS is above 0.98 for all pollutants. Other sensors to measure engine operation parameters were calibrated and certified in the Metrology and Testing Institute of Chengdu. The measurement ranges of MAP, IAT and RPM sensor are 0–400 kPa, −50–100 °C, 10–10000r/min, respectively, with a precision of 0.5% full scale (FS).

The gravimetric PM sampling unit consists of a sampling pump, a diluter, a $PM_{2.5}$ cutter and a filter tray. The exhaust gas is diluted (with a dilution coefficient of approximately 15–20) and then flows into the $PM_{2.5}$ cutter at a flow rate of 10 L/min. The particles are intercepted by the Teflon filter. The filters were balanced in a controlled temperature and humidity chamber (LHS-80HC-1, YiHeng, China) for 24 h before and after sampling (temperature:25 °C, humidity: 50%). An electronic balance (Quintix 35–1CN, Sartorius, Germany) with a precision of 0.001 mg was used for this study. Since the measurement of $PM_{2.5}$ for this PEMS is on a filter basis, $PM_{2.5}$ emissions are not reported instantaneously but on a test basis. Depending on the duration of the test, different time-resolution of $PM_{2.5}$ emissions can be obtained.

In order to reduce the interference of the installed PEMS on the operation of the measuring equipment, a data logger was used on-board to collect data from the gas analyzer and the sensor array and transmit the data wirelessly to a data receiver which can be stationed up to 200 ft away from the equipment for further analysis. This PEMS can also be powered on and off wirelessly as well. Furthermore, the PEMS was calibrated before and after each measurement. Calibration gasses of low and high concentrations were both used to calibrate the instrument in this study, with high concentrations being 8.02% for CO, 20.06% for CO_2, 1603 ppm for C_3H_8, and 2950 ppm for NO; and low concentrations being 0.50% for CO, 5.87% for CO_2, 200.8 ppm for C_3H_8, and 312.5 ppm for NO, respectively. The ambient air was used as clean air for zeroing the gas analyzer. A blower was also used to clean off the dust deposited to the PEMS after each measurement.

1.1.2. *Selection of diesel-fueled forklifts*

Unlike light duty gasoline-fueled on-road vehicles, non-road equipment usually is difficult to acquire for real-world emissions measurement. A total of 12 diesel-fueled forklifts were acquired and used for real-world emissions measurements in

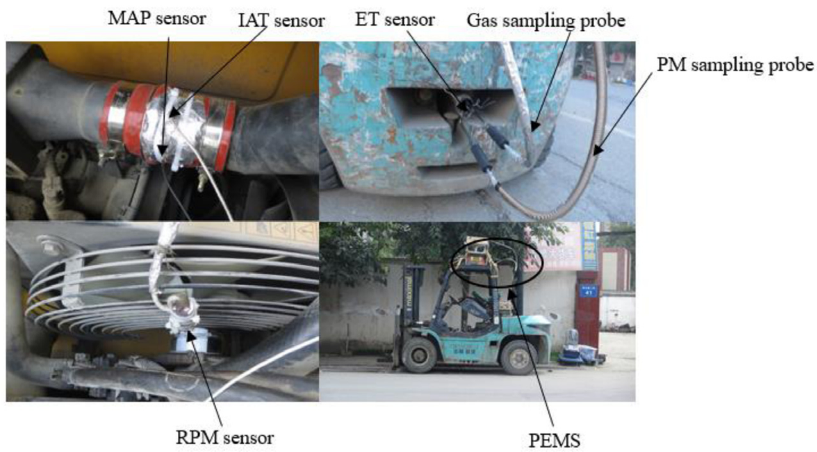

Fig. 2 – Installation of the PEMS used in this study to a forklift for emissions measurements.

this study mainly based on availability in the area as shown in Table 1 (amount of emission data collected for these forklifts were also included in this table, which will be discussed later). These forklifts comply with all stages of emission standards for non-road equipment in China, cover a wide range of model year, engine power, and engine displacement, and are deemed to be representative of the forklift fleet.

1.1.3. *Predefinition of duty-cycle*

Real-world emissions from industrial equipment vary by different work duties (Cao et al., 2016; Fu et al., 2012; Zhu et al., 2011). In order to obtain a relatively representative emission factor for emission inventory development, a composite emission factor, taking into account different work duties during a normal usage, is preferred.

Three duty-cycles were predefined, i.e., idling, moving, and working. The idling cycle refers to when the forklift is not doing anything while the engine is on; the moving cycle refers to activities when the equipment is moving from one location to another during the work transfer without completing a work task; and the working cycle refers to lifting, carrying, and other activities rather than idling and moving.

1.1.4. *Real-world emission measurements*

PEMS should be installed securely onto a flat surface of the testing forklift. The installation should not interfere with the operation of the equipment and also be convenient for researchers to replace the PM filter. Usually, the engine RPM sensor should be installed near the main shaft of the engine. Both MAP and IAT sensors were mounted between the turbocharger and the engine cylinder. The ET sensor along with two sampling probes (one for gaseous emissions and one for PM sampling) were inserted into the exhaust pipe. The sampling tubing is made of polytetrafluoroethylene (PTFE) with high temperature resistance for gaseous pollutants and stainless steel wrapped around with heating pad for PM. All components installed onto the testing forklift should be securely fastened before a measurement can start. An example of the PEMS installation on a forklift is shown in Fig. 2.

During the real-world measurements, the driver was instructed to follow a typical job sequence, i.e., idling, moving, and working to represent the three real-world duty-cycles of the forklift. Since the PEMS used for this study can only report $PM_{2.5}$ emission on a test basis, each test was designated to measure emissions for a specific duty-cycle. When a duty-cycle was finished, measurements were stopped to replace a new PM filter and then restart another new test. Usually, each test lasts 10 to 20 min with at least two tests being repeated for each duty-cycle.

1.2. *Emissions data analysis*

Materials presented in this section include (1) data error checking and postprocessing; (2) modal emissions analysis.

1.2.1. *Data error checking and postprocessing*

The purpose of data error-checking and postprocessing is to assure collected data are free of errors and ready for further analysis. Typical errors that occur during real-emission measurements using PEMS include the gas analyzer freezing, data missing, erratic data, and many others (Li et al., 2016). The key components of data error-checking and postprocessing in this study are: (1) synchronization of collected data from different measuring units of PEMS based on time stamps; and (2) interpolating missing values when the duration of missing data was within three consecutive seconds; and (3) removing unusual values.

In order to synchronize collected data from multiple measuring units, mainly between gas analyzer and RPM, IAT, and MAP sensors, the throttle pedal was quickly snapped to create RPM and CO concentration peaks. The time difference of these two peaks was then used to synchronize the engine data and gas analyzer data. In general, the peak of CO was approximately 3 s later than that of RPM.

For missing data, if only one second of data was missing, the average of the adjacent data was used to fill the gap. If only two consecutive seconds of data were missing, the prior second of data was used to replace the first missing data, and the posterior second of data was used to replace the second missing data. If there were three seconds of data were missing, the first and third missing data were replaced by its most adjacent data, respectively, and the missing data in the middle was replaced with the average of its adjacent data. If more than three consecutive seconds of data were missing, these data were eliminated.

Unusual values refer to extremely high and low values of measurements. For example, when an engine is started, the O_2 concentration in the exhaust should be much lower than that in the ambient air. Thus, based on previous studies, if the O_2 concentration is greater than 10%, this might indicate a leak in the measuring system, thus the data should be further investigated before being used. In this study, unusual data were identified for each type of data taking into account both engine operation and gas analyzer.

1.2.2. Modal emissions analysis

The purpose of modal emissions analysis was to explore variability in emissions with respect to variability in different duty-cycles and engine operation conditions. Three duty-cycles have been discussed above, i.e., idling, moving and working. Different engine operation conditions were defined as different engine-based modes, including RPM-based modes and MAP-based modes.

In order to define engine-based modes, both second-by-second RPM and MAP data were normalized using Eq. (1):

$$EV_{i,p,\ norm} = \frac{EV_{i,p} - EV_{p,\min}}{EV_{p,\max} - EV_{p,\min}} \tag{1}$$

where, $EV_{i,p,\mathrm{norm}}$ is the normalized data of the i^{th} second for a given engine variable p (e.g. RPM and MAP); $EV_{i,p}$ is the measured data of the i^{th} second for a given engine variable p; $EV_{p,\min}$ is the minimum value of measured second-by-second data for a given engine variable p; $EV_{p,\max}$ is the maximum value of measured second-by-second data for a given engine variable p.

Normalized RPM and MAP values were classified into 10 bins with an equal interval of 0.1.

1.2.3. Comparisons of emissions rates by different studies

In order to obtain well representative emissions for diesel-fueled forklifts in China to account for variability in real-world duty-cycles and facilitate comparison with emission data from NONROAD model (US EPA, 2005) and National Guideline for Emission Inventory Development for Non-Road Equipment of China (MEE PCR, 2014), referred to as National Guideline herein, composite emission factors for both gaseous and $PM_{2.5}$ pollutants were estimated using the following Eq. (2):

$$CEF_k = \sum_j (EF_{k,j} \times T_j) \tag{2}$$

where, k is a given pollutant, e.g., CO, CO_2, HC, NO and $PM_{2.5}$; j is a given duty-cycle, e.g., idling, moving and working; CEF_k (g/kg-fuel) is the average emissions factor for a given pollutant k; $EF_{k,j}$ (g/kg-fuel) is the average emission factor of for a given pollutant k under duty-cycle j; T_j is the average time percentage for duty-cycle j. The time percentages of the three duty-cycles when forklifts are in operations are estimated based on-site video-surveillance of twenty-five forklifts performing normal duties. Typically, the idling, moving, and working cycle account for 7.4% ± 3.0%, 24.6% ± 3.1% and 68.0% ± 4.5% of the total operation time, respectively. These numbers were used for composite emission factors estimation.

2. Results and discussion

Emission data collected from preselected forklifts were error-checked and postprocessed before being used for further data analysis. Materials presented in this section include: (1) a brief description of collected emission data; (2) instantaneous emission rates of forklifts; (3) modal emissions analysis of forklifts; and (4) forklifts emission comparisons by different studies.

2.1. A brief description of collected emission data

In order to cover a wide range of variability in emissions, approximately 2–3 hr of second by second gaseous emission data were collected for each preselected forklift as shown in Table 1. After error-checking and post-processing of the data, approximately 78.3%–95.3% of the second-by-second gaseous data was used for further data analysis. In addition, more than 6 PM filter samples were collected for each forklift.

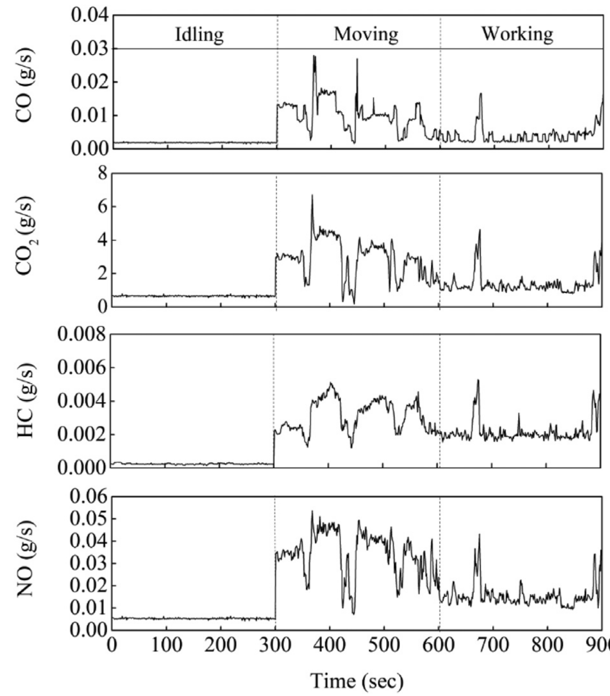

Fig. 3 – Typical time series of emissions of a diesel-fueled forklift on duty.

2.2. Instantaneous emission rates of forklifts

The instantaneous emission rates in this study mainly refer to the second-by-second emissions for gaseous pollutants such as NO, HC, CO and CO_2. Since $PM_{2.5}$ was determined using a filter-based gravimetric approach, $PM_{2.5}$ emission rate was the timely average for the duration when a filter sample was collected.

Depending on job duties, emission rates from forklifts varied largely. For example, as shown in Fig. 3, when a forklift is idling, emissions are relatively lower compared to those when the forklift is moving or working. Because forklifts usually move quickly between jobs, this led to higher emissions for moving than those for loading/unloading materials.

Furthermore, when a forklift is performing a normal duty, idling and moving together account for approximately 30% of the operation time. Thus, a reduction of idling and moving frequency will signficantly reduce the overall emissions, especially when emissions for the moving mode are comparable to those for the work mode.

2.3. Modal emissions analysis of forklifts

This section presents the results of modal emissions analysis based on real-world emission measurements for preselected forklifts, including both duty-cycle based and engine-based modal emissions.

2.3.1. Duty-cycle based modal emissions

Table 2 shows the hourly average emissions from forklifts for different job duties, referring to duty-cycles herein. Depending on the duty-cycles, time-based emission rates can range

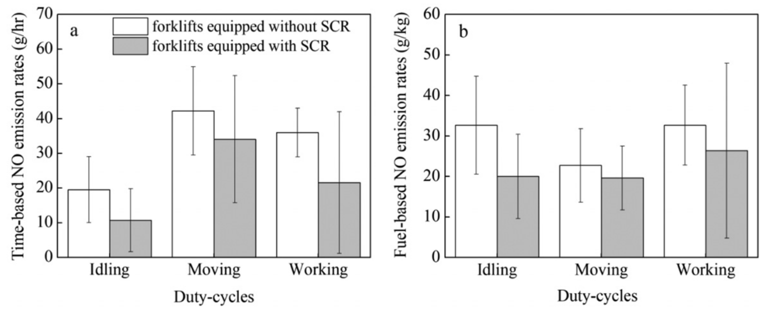

Fig. 4 – Average modal NO emission rates for forklifts with and without SCR (a) time-based, and (b) fuel-based. SCR - Selective Catalytic Reduction. In order to mitigate the confounding impact of engine power on emissions, the power range of forklifts selected for this analysis is all within 35<P ≤ 45 kW.

Table 2 – Average time-based emission rates for different duty-cycles (g/hr).

Pollutant	Duty-cycles		
	Idling	Moving	Working
CO	15.8 ± 4.6	56.1 ± 21.9	26.3 ± 7.6
HC	5.0 ± 1.1	16.4 ± 4.2	8.6 ± 2.9
NO	15.8 ± 3.6	60.1 ± 12.2	35.3 ± 5.1
Test-based $PM_{2.5}$	1.4 ± 1.0	17.5 ± 11.6	4.8 ± 1.9
CO_2 (× 10^3)	2.1 ± 0.2	10.5 ± 1.8	4.7 ± 0.7

Table 3 – Average fuel-based emission rates on different duty-cycles (g/kg).

Pollutant	Duty-cycles		
	Idling	Moving	Working
CO	23.2 ± 6.0	16.2 ± 2.9	15.5 ± 2.6
HC	8.2 ± 1.9	6.3 ± 1.2	5.8 ± 1.4
NO	24.4 ± 5.1	21.8 ± 3.2	27.5 ± 4.3
Test-based $PM_{2.5}$	2.8 ± 1.0	7.7 ± 3.3	4.3 ± 1.6
CO_2(× 10^3)	3.1 ± 0.01	3.1 ± 0.01	3.1 ± 0.01

from 11.2–78.0 g/hr, 1.9–12.3 kg/hr, 3.9–20.6 g/hr, 12.2–72.3 g/hr, and 0.4–29.1 g/hr for CO, CO_2, HC, NO, and $PM_{2.5}$, respectively. On average, as expected, emission rates for moving and working cycles were higher than those for idling with the moving cycle being the highest for all pollutants. This is because the engine load is higher when the forklift is moving or working than when the engine is idling. Furthermore, for this study, as discussed before, since forklifts were moving at a relatively high speed when shifting from one job to the other, thus emission rates for the moving cycle are higher than those for the working cycle for all pollutants.

Fuel-based average emissions derived from this study are shown in Table 3. Since CO and HC emissions are directly related to incomplete combustion of fuel, emissions for these two pollutants exhibit similar patterns. On average, fuel-based CO and HC emissions vary by duty-cyles with idling cycle being the highest and working cycle being the smallest. This is because the fuel consumption generally is closely associated with engine load. A higher engine load usually leads to a higher fuel consumption (Frey et al., 2010). Thus, the fuel consumption of idling cycle is relatively small compared to other duty cycles. As a result, fuel-based emissions for idling cycle are usually higher than those of other duty cycles. Since CO_2 emisison is usually propoetional to fuel consumption, fuel-based CO_2 emission factor is expected be relatively constant.

For NO and $PM_{2.5}$, fuel-based emissions do not exhibit a clear trend among different duty-cyles. Compared to the idling cycle, NO emissions for the working cycle are higher while those for the moving cycle is smaller. This may be because the increase of NO emissions for forklifts from idling mode to working mode was much higher than the increase of fuel consumption due to modal changes. However, changing the duty cycle from idling to moving exhibited the opposite trend in this regard. $PM_{2.5}$ emissions for the moving and working cycles were higher than those for the idling cycle. Since these forklifts were not equipped with any after-treatment device for PM emissions, the increasing rates of $PM_{2.5}$ emissions are larger than that of fuel consumptions when engine load increases from idling.

Compared to time-based emission rates as shown in Table 2, fuel-based emissions appear to be less variant with the ratio of average highest to the lowest being much smaller. The ratios of average highest to lowest of time-based emissions for CO, CO_2, HC, NO and $PM_{2.5}$ were 7.0, 6.5, 5.3, 5.9 and 72.8, respectively, while the ratios for fuel-based emissions are 2.3, 1.0, 2.3, 1.7, and 6.1, respectively. Thus, in order to improve the accuracy of emission inventories for non-road equipment, fuel-based emission factors are preferred.

Furthermore, two of the selected forklifts in this study were equipped with Selective Catalytic Reduction (SCR), *one of the aftertreatment technologies which have been demonstrated for effective engine out emissions reductions* (Beatrice et al., 2016; Fleischman et al., 2018). As shown in Fig. 4, the average time-based NO emission rates for forklifts with SCR are 45.2%, 19.3%, and 40.1% lower than those without SCR for idling, moving, and working cycle, respectively (Fig. 4a), while the average fuel-based NO emissions are 38.7%, 13.6%, and 19.3% lower, respectively (Fig. 4b). This indicates that the installation of SCR can effectively reduce NO emissions, especially when forklifts are idling.

2.3.2. *Engine-based modal emissions*

Fig. 5 presents RPM-based and MAP-based modal average emissions rates. In general, the time-based CO, CO_2, HC, NO average emission rates increase as both RPM and MAP increase. This is because a larger RPM or MAP indicates a larger power demand, leading to both higher emissions and fuel consumption. Thus, when the engine was idling (lowest RPM and MAP normalized values), the associated emissions and fuel

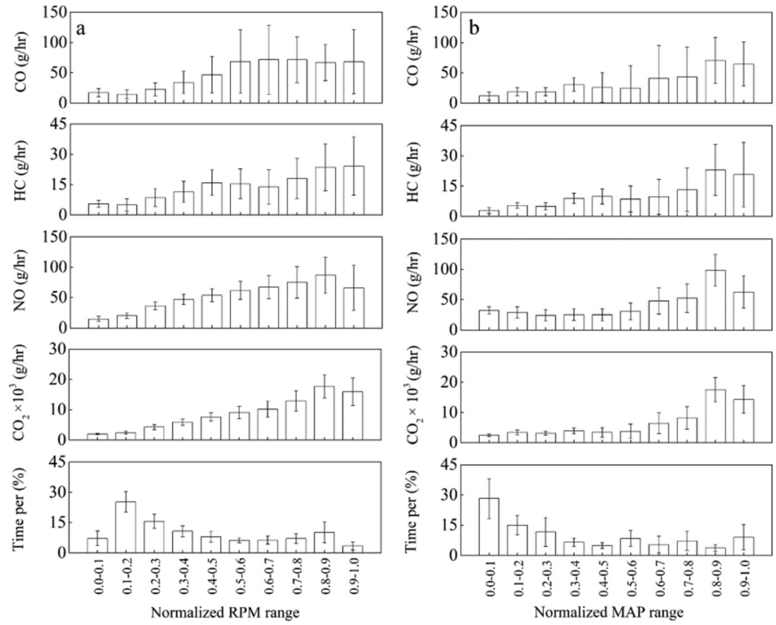

Fig. 5 – Average time-based emissions rates and time percentage for different engine modes (a) RPM-based and (b) MAP-based.

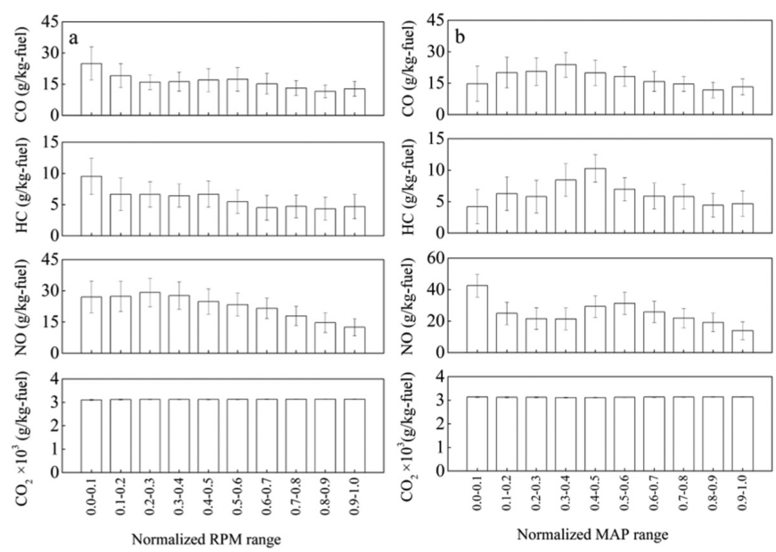

Fig. 6 – Average fuel-based emissions rates for different engine modes (a) RPM-based and (b) MAP-based.

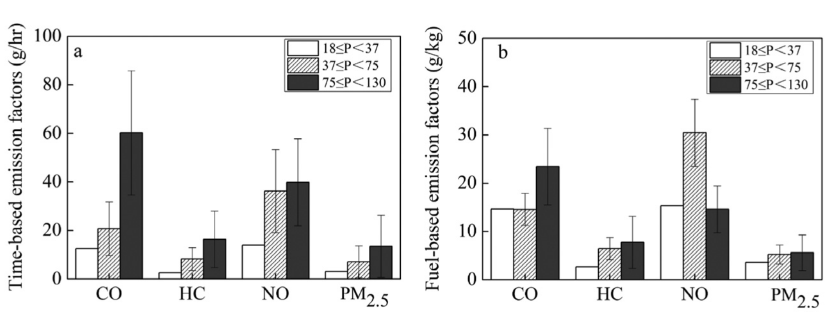

Fig. 7 – Average emission rates of CO, HC, NO and $PM_{2.5}$ of forklifts with different engine power capacity range (a) time-based, and (b) fuel-based. There is only one forklift within the power range of 18≤P<37 kW.

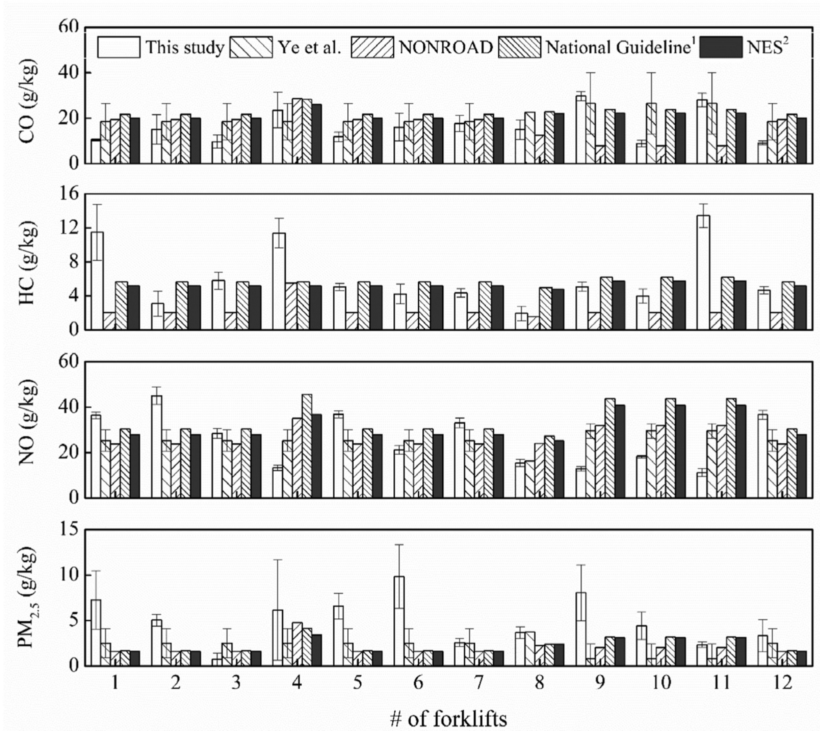

Fig. 8 – Forklifts emission comparisons by different studies. [1]National Guideline – National Guideline for Emission Inventory Development for Non-Road Equipment in China (MEE PCR, 2014); [2]NES – National Emission Standards (GB 20,891–2007 and GB 20,891–2014) for non-road equipment of China. Details for forklifts being tested are listed in Table 1; HC emissions were not measured in the study by Ye et al. (2018); The fuel-based emission factors for NONROAD and National Emission Standards were converted from g/hp-hr using the average BSFC for a given power range provided in NONROAD model, i.e., when P<100 hp, BSFC=186.88 g/hp-hr; When $P \geq 100$ hp, BSFC=168.29 g/hp-hr.

consumptions were usually lower compared to other engine modes with higher RPM and MAP values. Fig. 6 presents RPM-based and MAP-based modal average emissions rates on a fuel consumption basis. The fuel-based emission factor appears to have less variability than the time-based one as RPM or MAP changes. This is because a larger RPM or MAP also uses more fuel to meet the power demand when the associated emissions are higher.

In addition, since the time percentages for when the RPM and MAP are relatively low with normalized values less than 0.3 accounts for more than 50% of the total operation time, hence, reducing the duration of operation modes with low RPM and MAP can effectively reduce the overall emissions for forklifts.

Furthermore, as well known in the literature (Frey et al., 2010), emissions are impacted by a variety of factors. For example, although the sample size of the forklifts being tested in the study is relatively limited, the engine power capacity of the equipment did appear to have impacts on emissions. As shown in Fig. 7, for the time-based emission rates, engines with higher power capacities tend to have higher emission rates for all the pollutants, including CO, HC, NO and $PM_{2.5}$ (Fig. 7a). For the fuel-based emissions, similar trend was also found except for NO (Fig. 7b). This may be due to the limited sample size of forklifts being tested, which showed a large variation in duty-cycles and fuel consumptions, thus a higher power demand may result in different increments of NO emissions and fuel consumptions.

2.4. *Forklifts emission comparisons by different studies*

In order to compare emission factors among different studies, composite emission factors for preselected forklifts were estimated using Eq. (2) in this study. Tailpipe emissions from forklifts are influenced by a variety of factors such as engine technology, duty cycles, operation conditions and many others, leading to different findings for different studies as shown in Fig. 8.

In general, compared to the National Emission Standards for Non-Road equipment of China, emission factors used in NONROAD model are smaller while higher in the National Guideline. However, for CO, HC, and NO, approximately 75% of the real-world emission measurements are generally lower than both the corresponding national emission standards and NONROAD model. In contrast, real-world $PM_{2.5}$ emission measurements are generally higher than not only the corresponding emission standards and the NONROAD model, but also the National Guideline as well. Thus, emission inventory development using emission factors recommended by the National Guideline may overestimate the CO, HC, and NO emissions but underestimate the $PM_{2.5}$ emissions.

Furthermore, due to the difference in duty-cycle and limited number of forklifts being tested, real-world measurements of emissions from forklifts also exhibited a large variability. Depending on forklift and pollutant, the fuel-based average emissions can differ by a factor of seven. This implies that localized extensive real-world emissions measurements for forklifts are needed in order to develop an accurate local emission inventory.

3. Summary

This study used a PEMS to measure the real-world tailpipe emissions for 12 diesel-fueled forklifts. Experiments were designed to conduct the emissions measurements taking into account a variety of emissions influencing factors such as types of forklifts and different duty-cycles.

Real-world emission measurements showed that there exist a large inter-and intra-forklifts variability in emissions. The inter-forklift variability in emissions is mainly due to engine make, model, age, compliance emissions standards, and others. The intra-forklift variability in emissions is mainly due to duty-cycle changes. Comparing time-based emissions with fuel-based emissions, the latter exhibit less variability. Thus, for emission inventory development purpose, the use of fuel-based emission factors may provide a relatively stable and accurate estimates.

Real-world emissions measurements for diesel-fueled forklifts in this study have shown significant differences among limited studies in the literature. Thus, in order to obtain representative emission factors, extensive real-world measurements will be needed. Furthermore, activity studies on how forklifts operate under the real-world are also imperative for an accurate estimate of emission inventory, which will have significant impact on air pollution control policy-making.

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.

Acknowledgement

The authors thank all the members of Atmospheric Modeling and Environmental Data Analysis research group of Sichuan University for their helps in real-world emissions measurements in this study.

This work was supported by the Public Environmental Service Project of the Ministry of Environmental Protection of PRC (No. 201409012) and the Research Project of the Bureau of Science and Technology of Sichuan (No. 2019KJT0087–2019YFS0498). 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.

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