Title

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Permalink
https://escholarship.org/uc/item/0mk524b7

Journal
Atmospheric Environment, 147

ISSN
13522310

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Publication Date
2016-12-01

DOI
10.1016/j.atmosenv.2016.09.042

Peer reviewed

Atmospheric Environment 147 (2016) 234–245

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Evaluations of in-use emission factors from off-road construction equipment

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HIGHLIGHTS

- In-use emission measurements were made from twenty-seven pieces of construction equipment, which included four backhoes, six wheel loaders, four excavators, two scrapers (one with two engines), six bulldozers, and four graders.
- This is the largest study of off-road equipment emissions using 40 CFR part 1065 compliant PEMS equipment for all regulated gaseous and particulate emissions.
- The large variability in emissions, especially for NO_x and PM, could have important implications for developing accurate emissions inventories and models. This variability is primarily due to differences in engine load factors for different types of work and combinations of work and idle time and the displacement of the engines.

ARTICLE INFO

Article history:
Received 22 December 2015
Received in revised form
17 September 2016
Accepted 19 September 2016
Available online 20 September 2016

Keywords:
PEMS
Off-road emissions
Non-road emissions
Real world emissions
40CFR1065
Emissions inventory

ABSTRACT

Gaseous and particle emissions from construction engines contribute an important fraction of the total air pollutants released into the atmosphere and are gaining increasing regulatory attention. Robust quantification of nitrogen oxides (NO_x) and particulate matter (PM) emissions are necessary to inventory the contribution of construction equipment to atmospheric loadings. Theses emission inventories require emissions factors from construction equipment as a function of equipment type and modes of operation. While the development of portable emissions measurement systems (PEMS) has led to increased studies of construction equipment emissions, emissions data are still much more limited than for on-road vehicles. The goal of this research program was to obtain accurate in-use emissions data from a test fleet of newer construction equipment (model year 2002 or later) using a Code of Federal Requirements (CFR) compliant PEMS system. In-use emission measurements were made from twenty-seven pieces of construction equipment, which included four backhoes, six wheel loaders, four excavators, two scrapers (one with two engines), six bulldozers, and four graders. The engines ranged in model year from 2003 to 2012, in rated horsepower (hp) from 92 to 540 hp, and in hours of operation from 24 to 17,149 h. This is the largest study of off-road equipment emissions using 40 CFR part 1065 compliant PEMS equipment for all regulated gaseous and particulate emissions.

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1. Introduction

Off-road equipment is one of the most significant sources of nitrogen oxides (NO_x) and particulate matter (PM). According to U.S. Environmental Protection Agency (EPA) emissions inventory, off-road diesel equipment is estimated to be the 3rd largest source for NO_x emissions and 2nd largest source for PM emissions among all of the mobile sources, representing 14.5% and 24.3% of total mobile NO_x and PM emissions, respectively (EPA, 2011). Although increasingly more stringent emission standards are being implemented for off-road engines, there is still a time lag between the implementation of these standards and the implementation of

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http://dx.doi.org/10.1016/j.atmosenv.2016.09.042
1352-2310/Published by Elsevier Ltd.

similar standards for on-road (Federal Register 2004; 2005). Off-road engines also have relatively long lifespans, due to their inherent durability. It is anticipated that the relative contribution of these sources will continue to increase as on-road emissions continue to be reduced. These factors make the control of emissions from off-road equipment one of the more critical areas in terms of reducing emissions inventories and protecting public health.

Developing emissions factors and emissions inventories for off-road equipment has inherently been more challenging than for on-road vehicles. Off-road engines are typically certified on engine dynamometer tests that are not necessarily representative of the engine's diverse in-use operation. Although a number of studies have measured in-use emissions from off-road equipment (e.g., Abolhasani et al., 2008; Abolhasani and Frey, 2013), the available data for off-road equipment is still considerably more limited compared to on-road mobiles sources, which have been studied extensively for decades. Additionally, data on in-use activity patterns is scarce for off-road equipment to identify typical equipment operating modes that's needed to identify the greatest contributors to emissions.

The development of accurate emissions factors for off-road equipment under in-use conditions remains an important factor in improving emissions inventories. The continuing development of Portable Emissions Measurement Systems (PEMS) has allowed the characterization of in-use emissions from off-road equipment. Over the past few years, there has been a considerable effort to standardize PEMS measurement to meet regulatory requirements for in-use compliance measurements for on-road vehicles and off-road equipment (e.g., Durbin et al., 2007, 2009a). Much of this work was performed as part of the Measurement Allowance program, which included extensive laboratory testing at Southwest Research Institute (SwRI) and in-use testing using the University of California Riverside (UCR), College of Engineering, Center for Environmental Research and Technology (CE-CERT)'s Mobile Emission Laboratory (MEL) (Fiest et al., 2008; Johnson et al., 2008, 2009, 2010, 2011a, 2011b; Khalek et al., 2010; Khan et al., 2012; Miller et al., 2006). The MEL has been demonstrated to conform to Code of Federal Regulations (CFR) requirements for laboratory grade emission measurements (Durbin et al., 2009b).

Studies of construction equipment have been carried out over the years using different generations of PEMS technology. Gautam et al. (2002) measured in-use emissions using non-CFR compliant prototype portable analyzer on a street sweeper, a rubber-tired front-end loader, an excavator, and a track-type tractor in the field in an effort to develop test cycles for subsequent engines dynamometer testing. Scora et al. (2007) and Barth et al. (2008, 2012) also measured gas phase (NO_x, CO, CO_2) and PM emissions from heavy-duty construction equipment using a non-CFR compliant portable gas analyzer and gravimetric based PM from a self-designed mini-dilution tunnel, respectively. The EPA and its collaborators have also conducted an extensive study of construction emissions in EPA region 7 using CFR compliant PEMS from Sensors Inc. (Kishan et al., 2011; Giannelli et al., 2010; Warila et al., 2013). Frey and coworkers conducted emission and activity studies of construction equipment and studies of how to model their emissions impact using non-CFR compliant PEMS system (Abolhasani et al., 2008, Abolhasani and Frey, 2013; Frey and Bammi, 2003, 2008a, 2008b, 2008c, 2010a, 2010b; Lewis et al., 2009a, 2009b, 2011, 2012; Pang et al., 2009; Rasdorf et al., 2010). Huai et al. (2005) also measured the activity for different fleets of off-road diesel construction equipment.

The primary purpose of this research is to obtain gaseous and PM emissions from high-use and newer off-road construction equipment using a 40 CFR part 1065 compliant PEMS to provide accurate estimates of emissions from off-road construction equipment under real-world scenarios. The gaseous and PM exhaust emissions and the engine work were measured using CFR compliant PEMS on a second-by-second basis for twenty-seven pieces of construction equipment. Videotaping and on-site observations were also used to determine the type of construction activity (e.g. digging, pushing, idling, moving, etc.) that the equipment was performing. This study represents the most robust dataset available for off-road construction equipment in terms of the number of pieces of equipment tested and the use of state-of-the-art 1065-compliant PEMS system.

2. Methodology

2.1. Test matrix

Emission measurements were made for the following equipment: four backhoes, six wheel loaders, four excavators, three scrapers (one with two engines tested), six bulldozers, and four road graders. The six different types of equipment tested in this study make up about 80% of the equipment population in the State of California (CARB, 2014). The basic information for the off-road equipment tested is summarized in Table 1. (Table S1 in Supplementary Material contains more detailed information about the equipment and engines tested). The twenty-seven pieces of equipment included seven pieces of Tier 2 equipment with model years ranging from 2003 to 2007, with horsepower ratings ranging from 92 to 540 hp, and engine hours ranging from 946 to 17,149 h. The other twenty pieces of equipment were Tier 3 and Tier 4i equipment with model years ranging from 2006 to 2012, horsepower ratings ranging from 99 to 520 hp and engine hours ranging from 242 to 5233 h. All diesel fuel used in this study is ultra-low sulfur diesel (ULSD) with sulfur content less than 15 ppm.

Backhoe operation included digging with the backhoe and/or the front end shovel, filling in holes with the front end shovel, idling, and general equipment movement. The primary activity for three of the wheel loaders was gravel loading into a truck bed, while two other wheel loaders were primarily digging (one also did some filling), and one wheel loader was primarily cleaning and smoothing the shoulder of a road (similar to a road grader). One excavator was measured during digging, movement, and idling; one excavator had only limited emission data for loading and idling; the last two excavators were part of a designed study that included moving from place to place, trenching with various arm swings, backfilling, dressing, and idling. Three scrapers were tested for this program. One scraper worked near a landfill scraping up dirt to cover the trash. This scraper had a front engine that is used to move the machine and a back engine to operate the machinery that scrapes the dirt up into the hopper. The second scraper had a single engine and a hopper that is lowered so that the front edge cuts into the soil and forces the soil into the hopper. The six bulldozers tested were working in either a landfill or a riverbed; their operations included idling and pushing trash and/or dirt. The four graders were used for grading (scraping) dirt roads; and their operations included idling, moving, and grading.

2.2. PEMS description

Two different gaseous PEMS systems were utilized over the course of the test campaign for the measurement of gaseous emissions. For the first ten pieces of equipment, the gaseous emissions were measured with a SEMTECH DS PEMS, and the last seventeen pieces of equipment were measured with an AVL 493 PEMS. Both systems measure NO_x using a non-dispersive ultra-violent (NDUV) analyzer, total hydrocarbons (THC) using a heated flame ionization detector (HFID), carbon monoxide (CO), and

Table 1
Detailed information of the off-road equipment tested during in-use operation.

Date tested	Plot ID	Equipment type	Engine Mfg	Model	Year	EPA Tier	Dis. (L)	Rated power (bhp)	Engine hours	Work performed
12/3/2010	1_BH	1_Backhoe	Deere	410J	2007	2	4.5	99	1182	Digging and backfilling
12/7/2010	2_BH	2_Backhoe	Deere	310SJ	2010	3	6.8	99	242	Digging and backfilling
12/8/2010	3_WL	3_Wheel loader	Deere	644J	2007	3	6.8	225	1735	Digging and backfilling
12/9/2010	4_BH	4_Backhoe	Deere	310SG	2006	2	4.5	92	2599	Digging and backfilling
12/10/2010	5_BH	5_Backhoe	Deere	410G	2006	2	4.5	99	946	Digging and backfilling
2/9/2011	6_WL	6_Wheel loader	Komatsu	WA470-6	2009	3	11.04	273	900	Loading trucks
2/10/2011	7_WL	7_Wheel loader	Caterpillar	928G	2004	2	6.6	156	2294	Loading and smoothing asphalt
3/17/2011	8_EX	8_Excavator	Caterpillar	345D	2008	3	12.5	520	n/a	Loading trucks
4/20/2011	9_SC	9_Scraper	Caterpillar	637E	2006 (Rebuild)	2	8.8	280	>10000	Scraping dirt
4/21/2011	10_SC	10_Scraper	Caterpillar	637E	2006 (Rebuild)	2	15.2	540	>10000	Scraping dirt
5/4/2012	11_EX	11_Excavator	Volvo	EC360B	2006	3	12.1	269	5233	Loading trucks
5/14/2012	12_BD	12_Bulldozer	Caterpillar	D8R	2003	2	14.8	338	17149	Pushing trash
10/16/2012	13_GR	13_Grader	Perkins	120M	2008	3	6.6	163	3815	Grading shoulder
10/17/2012	14_WL	14_Wheel loader	Caterpillar	928Hz	2011	3	6.6	171	289	Cleaning ditch
10/18/2012	15_GR	15_Grader	Caterpillar	120M	2010	3	6.6	163	1308	Grading dirt road
10/22/2012	16_GR	16_Grader	Perkins	120M	2008	3	6.6	163	2706	Grading dirt road
10/23/2012	17_GR-DPF	17_Grader	Caterpillar	120M_DPF	2010	3	6.6	168	952	Grading dirt road
10/29/2012	18_WL	18_Wheel loader	Caterpillar	928Hz	2011	3	6.6	171	345	Digging dirt
10/30/2012	19_SC	19_Scraper	Caterpillar	613G	2010	3	6.6	193	439	Scraping dirt
10/31/2012	20_WL	20_Wheel loader	Caterpillar	928Hz	2011	3	6.6	171	242	Grading road shoulder
11/13/2012	21_BD	21_Bulldozer	Caterpillar	D6T	2012	4i	9.3	223	24	Pushing Rock
12/4/2012	22_HB-BD	22_HB bulldozer	Caterpillar	D7E (hybrid)	2011	4i	9.3	296	2528	Pushing trash
12/6/2012	23_BD	23_Bulldozer	Caterpillar	D8T	2012	4i	15	316	32	Pushing Rock
12/11/2012	24_BD	24_Bulldozer	Caterpillar	D6T	2012	4i	9.3	223	44	Building slope, pushing dirt
12/12/2012	25_HB-BD	25_HB bulldozer	Caterpillar	D7E (hybrid)	2011	4i	9.3	296	589	Building slope, pushing dirt
3/1/2013	26_EX	26_Excavator	Komatsu	PC200	2007	3	4.5	155	2097	Digging Trench
2/28/2013	27_HB-EX	27_HB excavator	Komatsu	HB215 (hybrid)	2012	3	6.7	148	245	Digging Trench

carbon dioxide (CO_2) using a non-dispersive infrared (NDIR) analyzer. Both systems collected raw exhaust through a sample line heated to 190 °C, consistent with the conditions for regulatory measurements for THC. Therefore, the two systems were similar, notwithstanding minor differences in design and packaging. The reason for the analyzer switch was solely based on PEMS availability at the time of testing. Additionally, both PEMS were evaluated by UCR during previous studies and found to be accurate for gaseous measurement levels expected during this research (Johnson et al., 2008, 2009; Fiest et al., 2008).

The PM analyzer used for all twenty-seven units was an AVL Micro Soot Sensor (MSS) 483 with a constant filter flow heated gravimetric filter attachment. The MSS measures soot concentration on a second–by-second basis using the photo-acoustic principle (Schindler et al., 2004). The gravimetric filter attachment measurement is used to calibrate the time resolved MSS soot measurements by comparing the accumulated soot signal from the MSS with the total mass from the filter. The range of calibration factors observed varied from 1.15 to 1.25 for this testing project. This very same PM unit participated in the 2010 EPA PM measurement allowance study and showed excellent correlation to the reference PM 2.5 method (Johnson et al., 2011a).

Three different sizes of SEMTECH's exhaust flow meters (EFM) were used to measure real-time exhaust flow in this study depending on the test engine displacement. Other important test parameters collected include location (via GPS), ambient temperature, pressure, and humidity. The majority of the vehicles tested had ECM data available; when necessary, special or manufacturer supplied logging tools were used to log the desired ECM channels. For two vehicles, where no ECM was available, the engine speed and engine percent load were estimated using real-time exhaust flow and brake-specific fuel consumption (BSFC). Videotaping and on-site observations were used to determine the type of construction activity (e.g., digging, pushing, idling, moving, etc.) that the equipment was performing.

2.3. PEMS installation

The complex design of off-road equipment required a unique installation approach for each equipment type. A custom steel frame instrument package with gaseous PEMS, PM PEMS, EFM, data logging equipment, batteries, battery charger, and other necessary operating auxiliary items was built as a single unit complete package. This PEMS package was warmed up and calibrated prior to installing it onto the off-road equipment. A calibration procedure was performed on-site daily, which includes a leak check and zero-span calibration procedure. Additional calibration procedures include monthly linearity and other checks needed for 1065 compliance. Once the PEMS package was secured with heavy duty ratcheting straps, only the routing of the exhaust pipes to the EFM, logging of the ECM signals, and installing the auxiliary generator for power was required.

Depending on the equipment type, the CE-CERT PEMS package generally fit best on the roof or large section of the hood due to its relatively large footprint. This study avoided testing small sized equipment where the weight of the PEMS package could impact the emissions. Vibration isolation mounts installed onto the steel frame along with six-inch-thick high-density foam pad between the frame and the vehicle provided vibrational dampening. Weather shielding protected the PEMS package from direct sunlight.

3. Results

Results from emissions testing of off-road equipment are usually expressed in units of grams of pollutant per horsepower-hour (or per kilowatt-hour) of work done by the engine as its the reporting units for engine certification purposes. However, emissions can also be expressed in units of grams of pollutant per hour (g/hour) or in units of grams of pollutant per kilogram of fuel consumed (g/kg-fuel). In terms of precision, emissions in g/hr are the most precise as they are a direct measurement from the PEMS, emissions in g/kg-fuel are the next most precise as off-road equipment fleet usually track accurate fuel usage, and emissions in g/hp-h are the least precise of the three measurement units as the true brake horsepower and torque versus engine speed for the particular engine is seldom known for off-road engines. Emissions results are reported using all three metrics in Table S2 of Supplementary Material. In this paper emissions comparisons are presented in g/hp-h in Table 2. Valid work values were not obtained for unit 8_excavator so no brake specific emission values are available for that unit; emissions for this excavator was limited to 30 min due to failure of the exhaust boot connecting the stack to the EFM, Nevertheless, observation of the unit throughout the work day indicated that this unit was repeating the same operation throughout the full work day, therefore the data on a g/hr and g/kg of fuel basis represent valid measurements can still be found on Table S2 in Supplementary Material.

The results presented in units of g/hp-h provide a 'high level' comparison against the engine certification standards. It should be noted that the certification test cycle for Tier 2 and Tier 3 diesel off-road engines is an 8-mode steady-state engine dynamometer certification test cycle, while Tier 4 diesel off-road engines are required to meet emissions standards for both a steady state cycle and the non-road transient cycle. As actual in-use engine/equipment operation is highly transient, with rapid and repeated changes in engine speed and load, the comparison of the in-use emissions with the certification levels is probably more directly applicable for the Tier 4 engines that are evaluated for transient operation as part of the certification process. In addition, the average engine “load factors” (a measure of how hard the engine is working) can be different than the certification test cycle load factors since the in-use testing was not designed to exactly mimic the certification cycle. Thus, results are not expected to be directly comparable to the certification test results, but nevertheless provide an indication of how emissions from actual, in-use diesel engines compare against their engine certification standards.

3.1. Idle emissions

Idle emissions represent a large fraction of all equipment usage (by time). Idle emissions for each pollutant are summarized in Table S4 in Supplementary Material in g/hr and g/hr-L, where L is the engine displacement in liters. Overall, the idle emissions for CO_2 correlate with engine displacement, as large engines require more fuel during engine idle. Load-specific idle emissions are not presented because the load during idle is near zero, and the idle ECM load estimates are far less accurate.

Table 2
Overall brake specific non-idle averaged brake specific emissions summary for each of the 27 units tested.

MY 20xx	EPA Tier	Plot ID	Fuel [b] kg/hr	Power [c] bhp	eLoad %	Engine load factor (ELF)	Brake specific emissions (g/hp-h)				
							CO2	CO	NOx	THC	mg PM [e]
03	2	12_BD	29.6	214.5	72.8	0.63	435	0.68	3.72	0.10	133
04	2	7_WL	8.3	42.4	29.8	0.27	624	2.12	4.8	0.28	131
06	2	4_BH	5.9	33.7	40.4	0.37	557	1.51	5.19	0.32	126
06	2	5_ BH	7.3	38.8	44.2	0.39	596	1.97	4.99	0.64	126
06	2	9_ SC [a]	25.9	161.3	61.1	0.58	507	3.06	1.78	0.28	129
06	2	10_ SC [a]	38.3	274.6	54.5	0.51	441	1.88	1.95	0.10	139
07	2	1_ BH	5.0	25.8	32.6	0.26	615	2.51	5.33	0.68	154
06	3	11_EX	25.1	134.5	55.0	0.50	587	0.93	2.86	0.21	274
07	3	3_WL	14.6	81.2	41.0	0.36	572	2.91	4.50	0.08	128
07	3	26_ EX	12.0	69.0	49.2	0.45	547	1.00	2.65	0.17	109
08	3	8_EX	28.4	n/a	n/a[d]	n/a	n/a	n/a	n/a	n/a	n/a
08	3	13_GR	10.6	51.8	34.1	0.32	641	2.08	4.24	0.29	365
08	3	16_GR	8.4	45.0	32.2	0.28	581	3.04	3.59	0.26	491
09	3	6_WL	15.5	87.1	n/a[d]	0.32	567	3.39	5.16	0.11	84.2
10	3	2_ BH	8.6	45.3	52.3	0.46	606	1.37	3.35	0.24	97.0
10	3	15_GR	7.4	38.6	28.2	0.24	601	2.49	3.78	0.30	478
10	3	17_GR-DPF	12.1	68.4	42.8	0.41	555	1.91	2.89	0.16	29.1
10	3	19_SC	19.9	100.7	58.4	0.52	622	1.36	3.13	0.05	142
11	3	14_WL	5.8	31.9	26.0	0.19	573	2.67	5.71	0.30	324
11	3	18_WL	16.0	89.9	56.1	0.53	558	1.45	3.14	0.15	175
11	3	20_WL	11.3	56.1	36.0	0.33	634	1.74	3.39	0.25	333
11	3	27_HB-EX	9.3	55.6	43.9	0.38	527	0.93	3.07	0.07	152
11	4i	22_ HB-BD	19.9	106.7	35.3	0.36	590	0.43	1.89	0.09	0.36
11	4i	25_HB-BD	14.4	82.2	27.6	0.28	555	−0.09	1.70	0.04	0.18
12	4i	21_ BD	19.1	90.7	40.6	0.41	665	−0.08	1.60	0.04	0.33
12	4i	23_ BD	23.4	104.0	39.4	0.33	712	−0.15	2.14	0.06	7.03 [f]
12	4i	24_ BD	14.2	74.5	34.5	0.33	605	−0.14	1.62	0.04	0.26

[a] Rebuilt engine.
[b] Averaged fuel rate calculated based on emissions measurements.
[c] Power estimated from manufacture supplied lug curves.
[d] No ECM data.
[e] Total PM using AVL's gravimetric span method.
[f] DPF regen occurred.

3.2. In-use load factor

The overall in-use brake power was typically light (Table 2): 8 units with rated hp's between 92 and 171 had average in-use hp's < 50 with average engine loads between 26.0 and 52.3%; 11 units with rated hp's between 148 and 296 had average in-use hp's between 51.8 and 90.7 with average engine loads between 27.6 and 56.1%; 4 units with rated hp's between 193 and 316 had average in-use hp's between 100 and 150 with average engine loads between 35.3 and 58.4%, and 3 units with rated hp's between 280 and 540 had average in-use hp's between 161 and 275 with average engine loads between 54.5 and 72.8%.

The California Air Resources Board's 2011 Inventory Model for off-road diesel equipment provides reference load factors (LF) for each type of off-road equipment. The EPA Nonroad model also has load factors for many different pieces of equipment. Load factors are used to adjust the rated horsepower's of equipment to reflect actual operation conditions. The load factor is the ratio of the average horsepower during a working period to the maximum horsepower for the given engine. Since this information has not been typically available the inventory models have used surrogate methods to estimate load factors. Table 3 compares average measured LFs in this study to the current LFs used in the inventory models. With the exception of the scrapers, the measured load factors are closer to the ARB load factors than to the EPA load factors. However, at two times the standard deviation the measured load factors encompass both the ARB and EPA load factors.

The difficulty with LF being a good metric for emissions estimation is that there is no measurable work associated with the idling emissions and thus the total emissions per unit work and per unit fuel are higher. Fig. 1 shows how two Units can have the same LF but significantly different duty cycles. Unit 1 is operated at various load conditions with frequent idle modes simulating performing work that requires decision making through the operation and Unit 2 represents steady work with a simple break between tasks. In both cases the LF is 35, but the percentage of idle time and loaded conditions varies significantly between the two Units, thus affecting the overall emissions as a function of the load. The emissions impact of the load factor will be discussed more in the subsequent section, but future emission models should consider evaluations of LF for idle and work conditions separately to truly characterize the emissions from a fleet.

3.3. NO_x emissions

Plots of the overall brake specific NO_x ($bsNO_x$) emissions for each of the units tested are presented in Figs. 2 and 3. In Fig. 2 the results are sorted by Tier and engine hours from left to right. The equipment type is indicated by BH for Backhoe/Loader, WL for Wheel Loader, SC for Scraper, BD for Bulldozer, HB-BD for Hybrid Bulldozer, EX for Excavator, HB-EX for Hybrid Excavator, GR for Grader, and GR-DPF for the grader with an aftermarket DPF. The red bars are the CARB zero-hour emission standards as given in the CARB Executive Order for the equipment Engine Family Name. For Tier 2 and Tier 3 the CARB standards are for NMHC + NO_x so the measured bars are for NO_x+0.98*THC. CH_4 is typically not measured with a PEMS, therefore NMHC is calculated as 0.98* THC, as per 40 CFR Part 1065. For Tier 4 the CARB standards are for NO_x so the measured bars are for NO_x. Seven of the twenty-seven units tested are Tier 2, fifteen are Tier 3, and five are Tier 4i. For Tier 2, all of the NMHC + NO_x are essentially equal to or lower than the standards. For Tier 3, 7 of the 15 have NMHC + NO_x emissions significantly higher than the standards. For Tier 4 all of the NO_x emissions are slightly above the standards. It should be emphasized that the NMHC + NO_x and NO_x standards are based on engine dynamometer measurements over specific test cycles, so any comparisons with emissions from the real-world operation are not meant to imply that an individual piece of equipment may or may not be operating within standard limits. There is no indication that NMHC + NO_x or NO_x emissions increase relative to the CARB standards as the engine hours increase with this data set.

The NO_x emissions show generally lower trends for engines certified to more stringent emissions standards. However, the highest brake specific NO_x ($bsNO_x$) emissions are from a 2011 wheel loader (#14, Tier 3). This is attributed to the differences in the type of work being done by each test unit; this wheel loader has the lowest engine load of any engine tested. Further, the other two wheel loaders (#18 and #20) have the same model engine, similar engine hours, MYs, and engine displacements, but shows almost 50% less $bsNO_x$ emissions. The average engine percent load over the time of operation was 56% and 36%, respectively, for these two units with lower NO_x emissions compared to the average percent load of 26% for unit #14. For on-road engines the percent engine load threshold for Not-to-Exceed (NTE) in-use compliance testing is 30%, thus, operation below 30% is excluded from compliance testing. While NTE is not currently applied to off-road engines, operation below 30% occurs during in-service operation and can even represent the overall average for some in-service operations, as shown by unit #14.

Fig. 3 presents the same emissions as Fig. 2 but the data is now sorted by engine Tier level and engine load factor (ELF). The ELF varies from 0.26 to 0.63 for Tier 2, 0.19 to 0.58 for Tier 3 (doesn't exceed 0.36 until after 3_WL), and from 0.28 to 0.41 for Tier 4. For a given emission standard there is a general trend for the measured emissions to decrease as the ELF increases. Higher ELF's appear to have a more significant effect on the emission factors on a work basis than engine hours or MY. The ELF for wheel loader 6_WL and grader 13_GR is 0.32 and for wheel loader 20_WL and excavator 26_EX_the ELF is 0.33. The NMHC + NO_x emissions for 6_WL are higher than for 13_GR and the NMHC + NO_x emissions for 20_WL

Table 3
Comparisons of modeled and measured engine load factors.

Equipment type	ARB LF, offroad inventory Model[39]	EPA LF, nonroad inventory Model[42]	LF measured in this study		
			Units tested	Load factor	
				Average	Std. Dev.
Bulldozers	0.43	0.59	4	0.43	0.14
Hybrid Bulldozers	NA	NA	2	0.32	0.06
Excavators	0.38	0.59	2	0.47	0.04
Hybrid Excavators	NA	NA	1	0.38	NA
Graders	0.41	0.59	4	0.31	0.07
Wheel Loaders	0.36	0.59	6	0.33	0.11
Scrapers	0.48	0.59	3	0.54	0.04
Backhoes	0.37	0.21	4	0.37	0.08

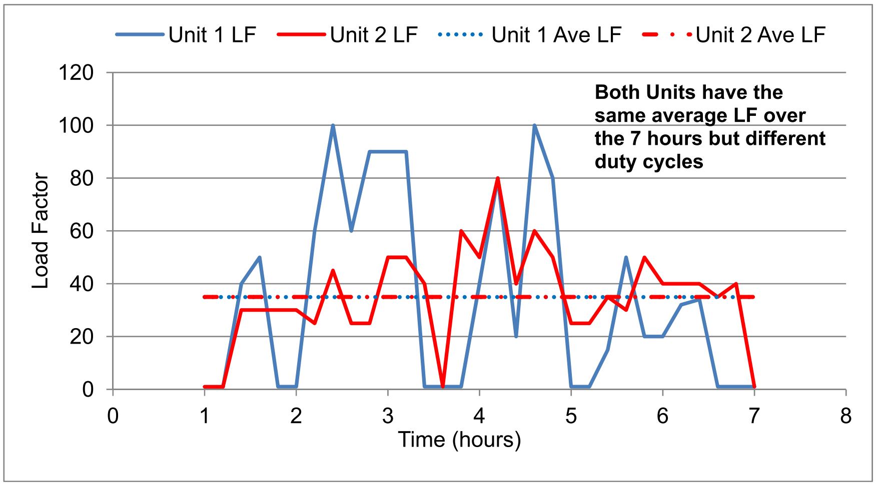

Fig. 1. Simulated duty cycles for two Units with the same load factor.

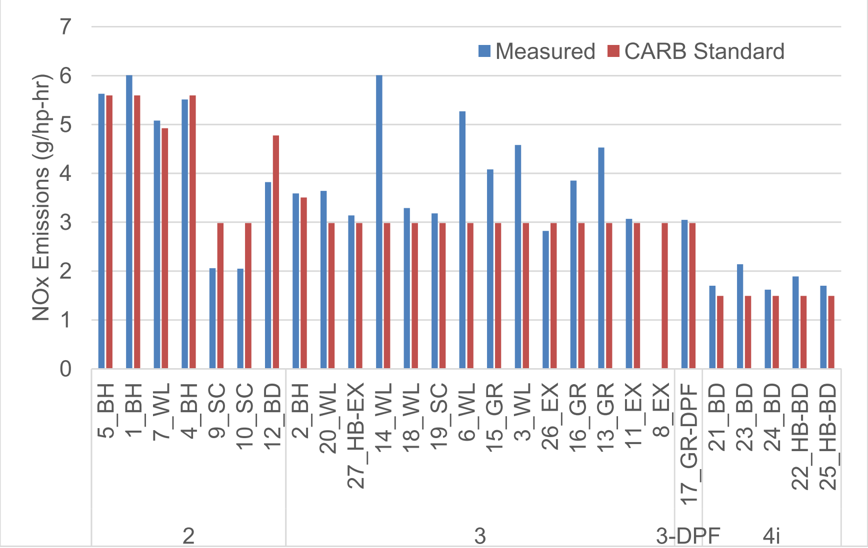

Fig. 2. Measured brake specific NO_x emissions by Tier and engine hours and CARB zero hour standards.

are higher than for 26_EX. Without considering other information one might conclude that this observation indicates that the type of work being performed influences the emissions. However, 6_WL has a Komatsu 273 hp, 11.0 L engine versus the Perkins 163 hp, 6.6 L engine for the 13_GR and the 20_WL has a Perkins 171 hp, 6.6 L engine versus a Komatsu 155 hp, 4.5 L engine for the 26_EX. Similarly, bulldozer 23_BD has higher NO_x emissions than bulldozer 24_BD even though they have the same ELF of 0.33. Bulldozer 23_BD has a Caterpillar 316 hp, 15.2 L engine versus a Caterpillar 223 hp, 9.3 L engine for 24_BD. We attribute the higher emissions in these comparisons to the higher engine displacement rather than the physical work being performed.

3.4. PM emissions

Plots of the overall PM emissions results for each of the units tested are presented in Figs. 4 and 5. The Tier 2 PM emissions are all below the standards. Six of the 15 Tier 3 PM emissions are significantly higher than the standards and 5 of them are for the same engines having significantly higher NMHC + NO_x emissions than the standards. Unit 11_EX has significantly higher PM than the standard whereas for NMHC + NO_x it had essentially the same emissions as the standard. This is the oldest Tier 3 equipment tested so the higher PM may indicate some engine deterioration. All units with diesel particulate filters (DPFs) show significant reductions (>90%) in PM in comparison with those units without aftertreatment. Note that for Tier 4i the measured PM emissions have been multiplied by 50 so that they will be visible in the figures. Equipment 23_BD has a ~50 min DPF regen included in the emission measurements and its PM is still well below the emission standard. If the DPF regen is not included then the PM emissions are 0.00121 g/bhp-h and the bar in Figs. 4 and 5 would be 0.0605 g/bhp-h. There is a slight trend of lower brake specific PM (bsPM) emissions for older MYs when comparing units without aftertreatment (Fig. 4) although any such trend is complicated by differences in the load factor between units. It is also possible that the engine calibration differences needed to achieve $bsNO_x$ emissions for the newer equipment could lead to increases in bsPM, although this is likely a secondary factor compared to the engine load differences. One of the units (#17, a 2010 grader) is equipped with an aftermarket DPF. The bsPM emissions from this unit averaged 29.1 mg/hp-h overall and ranged from 100.8 to 2.4 mg/hp-h depending

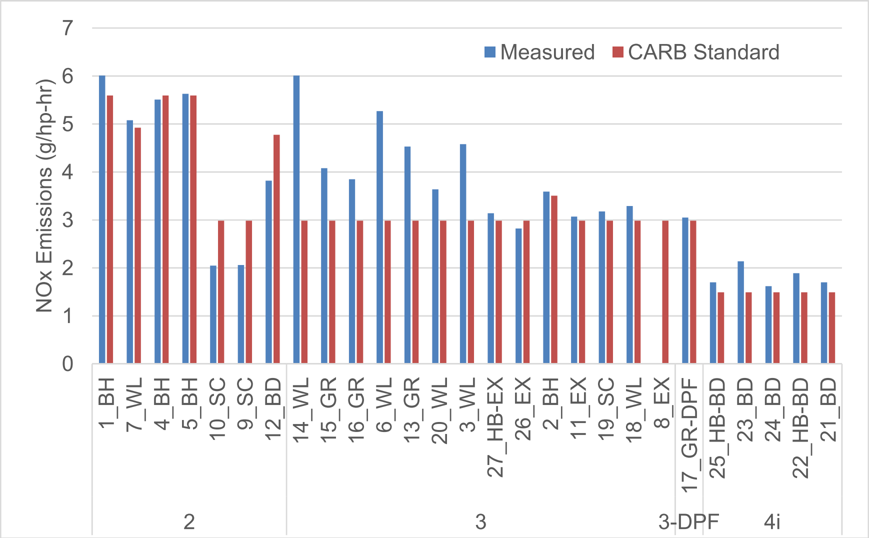

Fig. 3. Measured brake specific NO_x emissions by Tier and engine load factor and CARB zero hour standards.

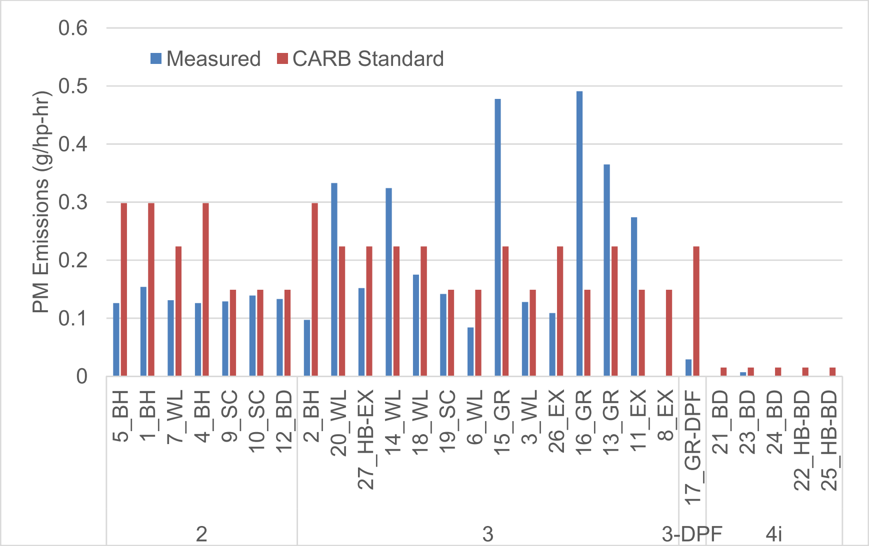

Fig. 4. Measured brake specific PM emissions by Tier and engine hours and CARB zero hour standards.

on the operating mode. The average bsPM for five Tier 4 interim units was 1.1 mg/hp-h, suggesting the particular aftermarket DPF is not as efficient as the ones on the factory equipped DPF Tier 4 interim machines.

The trend for lower emissions with increasing ELF (Fig. 5), for engines produced to the same emissions standards, is not as pronounced as it is for NO_x emissions. In Fig. 5 the comparison between units having exactly the same ELF only holds for 20_WL and 26_EX. The most likely reason that the comparison between 6_WL and 13_GR doesn't hold is that 6_WL has an engine produced to a lower PM standard than 13_GR. The DPF regeneration in the emissions from 23_BD rules out making a comparison between it and 24-BD.

3.5. Other criteria emissions

Plots of the overall THC emissions results for each of the units tested are presented in Figs. 6 and 7. Since there are no CARB standards for THC emissions only the measured emissions are shown in these figures. The general overall trend of THC emissions in Fig. 6 is similar to the general overall trend of NO_x emissions in Fig. 4 with some, but not all, of the same units that had NO_x emissions significantly higher than the standards having higher THC emissions than the rest in the Tier group. Two units (#1 and #5, both 410 Deere backhoes) showed relatively high THC emissions of greater than 0.63 g/hp-h, which is almost two times more than the other units tested. As can be seen in Fig. 7 equipment 1_BH has the lowest ELF but there are two units having lower ELF's than equipment 5_BH which suggests the high THC is not necessarily due to light load operation. A similar Deere backhoe model 310 (4_BH) used over a very similar duty cycle, for example, showed about half the emissions of the 410 backhoe. It is unclear what caused the higher THC emissions for the 410 backhoe compared to the 310 backhoe. The Tier 4i THC and CH_4 emissions were on average 71% and 84% lower than the Tier 3 and Tier 2 THC and CH_4 emissions on a g/hp-h basis, respectively.

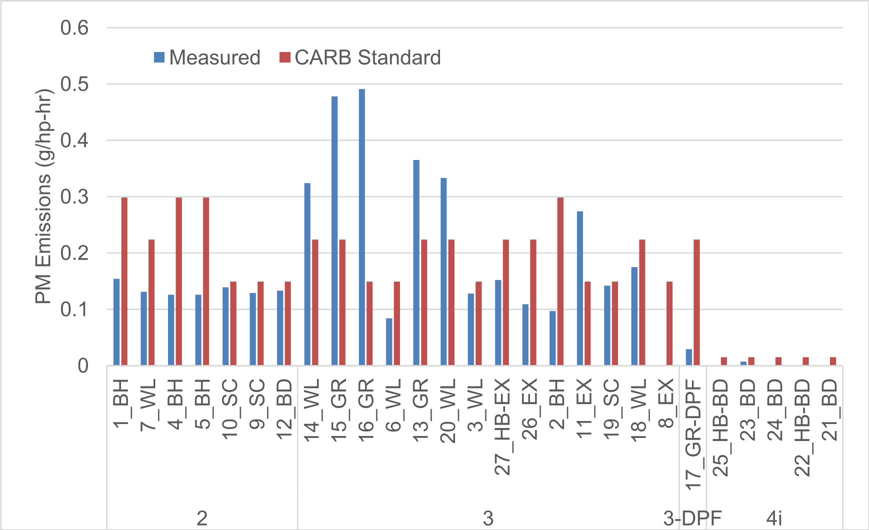

Fig. 5. Measured brake specific PM emissions by Tier and engine load factor and CARB zero hour standards.

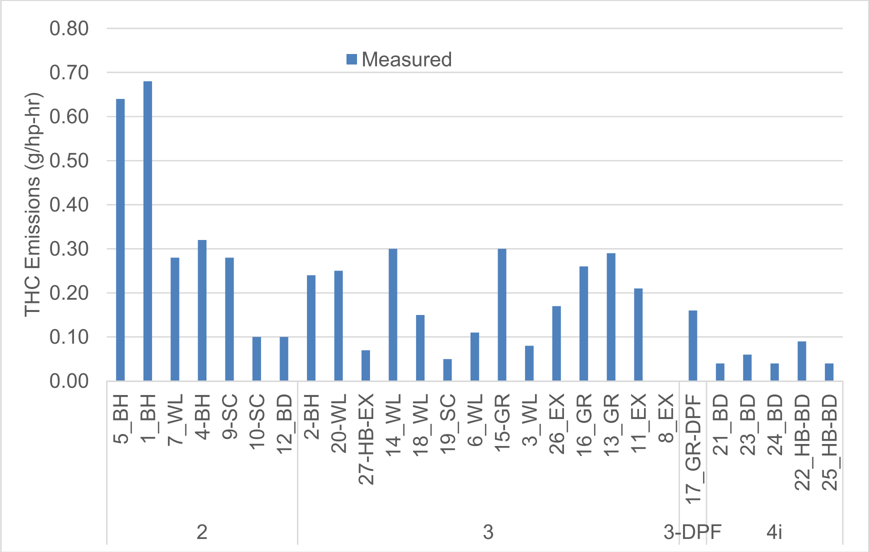

Fig. 6. Measured brake specific THC emissions by Tier and engine hours.

Plots of the overall CO emissions results for each of the units tested are presented in Figs. 8 and 9. The general overall trend of CO emissions in Fig. 8 is similar to the general overall trend of NO_x emissions in Fig. 4 with some, but not all, of the same units that had NO_x emissions significantly higher than the standards also have CO emissions higher than the standards. The general overall trend of CO emissions in Fig. 9 is similar to the general overall trend of NO_x emissions in Fig. 5 but the decrease in the CO emissions is generally greater than the decrease in NO_x emissions as the ELF increases. The CO emissions for the Tier 4i units are essentially at the limits of detection of the PEMS, as indicated by the negative CO emissions values for all but one of the units.

3.6. Comparison with prior studies

Frey and co-workers performed some of the most recent measurements of emissions from off-road construction equipment (Frey et al., 2010a, 2010b). With the PEMS equipment they were using they measured CO_2, CO, NO_x, THC and fuel rate in g/sec and reported emissions in g/hr and g/gal of fuel. They did not have measurements of the engine ECM and therefore could not calculate brake-specific emissions, and also did not measure PM emissions. The majority of their data is for Tier 0 and Tier 1 equipment. Their results in g/gal for Tier 2 and Tier 3 equipment are presented in Table S3 of Supplementary Material, along with our results for comparable Tier 2 and Tier 3 equipment. Fig. 10 shows a comparison of NOx emissions between Frey et al. and this study sorted by Tier level and equipment types. Tier 2 NOx emissions from Frey study ranged from 73 to 172 g/gal compared to 80–96 g/gal in the current study. For Tier 3, the comparison was 58–86 g/gal for Frey et al. and 50 to 101 for the current study. Overall, the emissions in g/gal of fuel in our study are similar to the results in the Frey and co-worker studies (Frey et al., 2010a; 2010b). In some cases, however, Frey et al. measured considerably higher emissions for specific pieces of equipment (i.e., MG2-04-0SH, BH3-04MS, BH5-04MS). This suggests the potential importance of high emitters in the

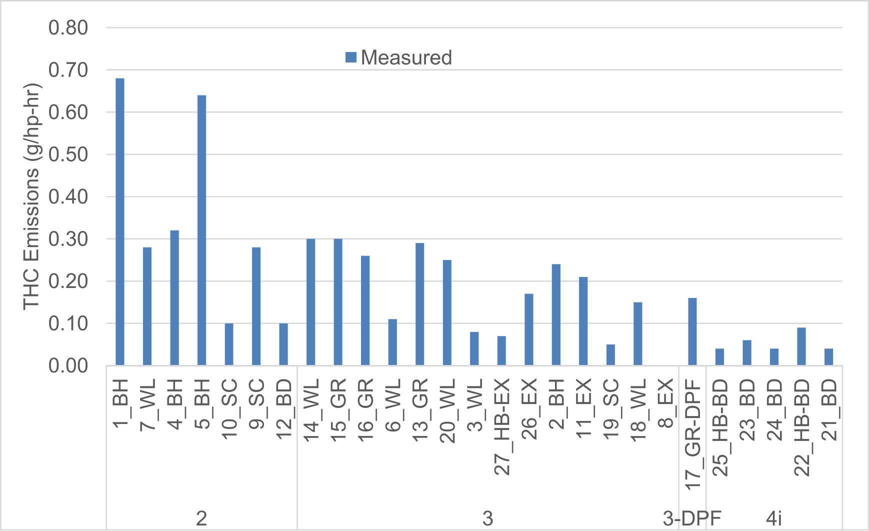

Fig. 7. Measured brake specific THC emissions by Tier and engine load factor.

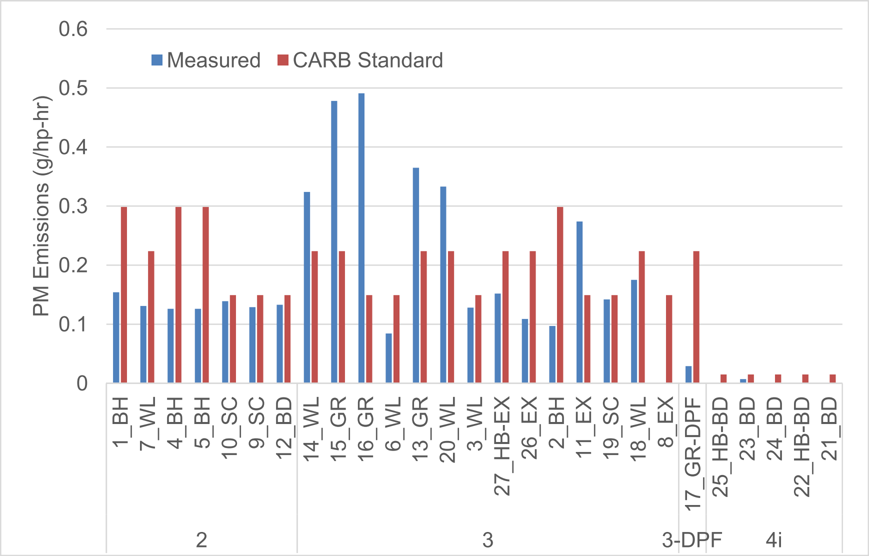

Fig. 8. Measured brake specific CO emissions by Tier and engine hours and CARB zero hour standards.

construction equipment population, and that further testing of a wide range of in-use equipment could provide a more comprehensive assessment of in-use construction emissions.

3.7. Discussion

The results of this study show that in-use emissions show emissions trends that are somewhat consistent with the different certification levels of specific engines. This is particularly true for the comparisons between the Tier 4 with earlier engine certification levels. Another key finding from this study is that in-use brake-specific emissions for off-road equipment can vary significantly within a given engine Tier, primarily depending on the engine load factor and the engine displacement.

For NOx emissions, the lowest NOx emissions were found from the Tier 4 engines, while the highest emissions were generally found for the Tier 2 engines with the higher certification standards and high number of engine hours. The NO_x emissions for the Tier 4i units are lower than all of the Tier 3 units and, with one exception, all of the Tier 2 units. The NO_x emissions for the Tier 2 and 3 units do not show strong trends as a function of model year for any of the units of comparison. Engine load factor appears to be an important factor for NO_x emissions, with equipment with low average engine loads factors showing generally higher NO_x emissions on a g/hp-h basis. All of the Tier 3 units with a CARB NO_x standard of 3.0 g/hp-h had higher NO_x emissions than the older Tier 2 units having the same CARB standard. The Tier 2 engines were on the scraper (09_SC and 10_SC) and had relatively high load factors of 0.58 and 0.51, respectively, while the Tier 3 engines had load factors from 0.19 to 0.58, with only 3 of the 13 Tier 3 engines having load factors above 0.38. This suggests that in some cases the type of engine operation can have a more significant impact on emissions that the age/Tier of the engine for pre-Tier 4 engines. The overall in-use brake power average load factors over all Tiers were between 0.19 and 0.41 for nearly all units, with only 7 units having average load factors >0.41, and only one unit having an average load factor of 0.63.

Engine displacement or manufacturer could be another

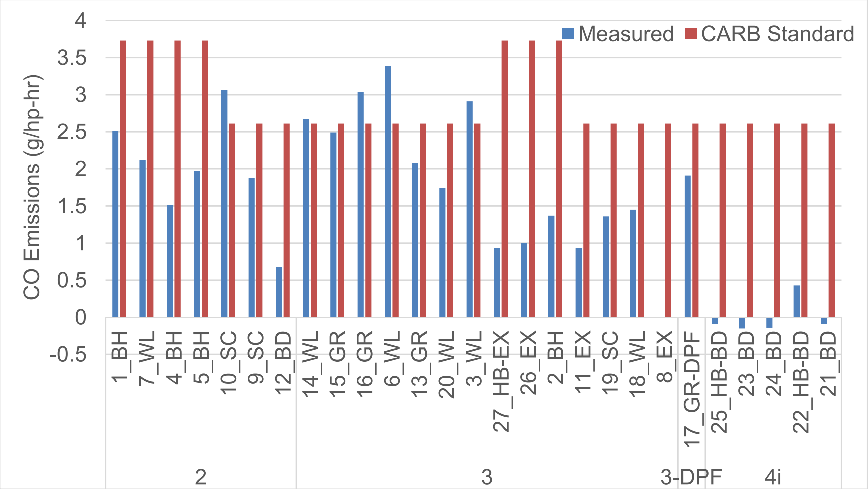

Fig. 9. Measured brake specific CO emissions by Tier and engine load factor and CARB zero hour standards.

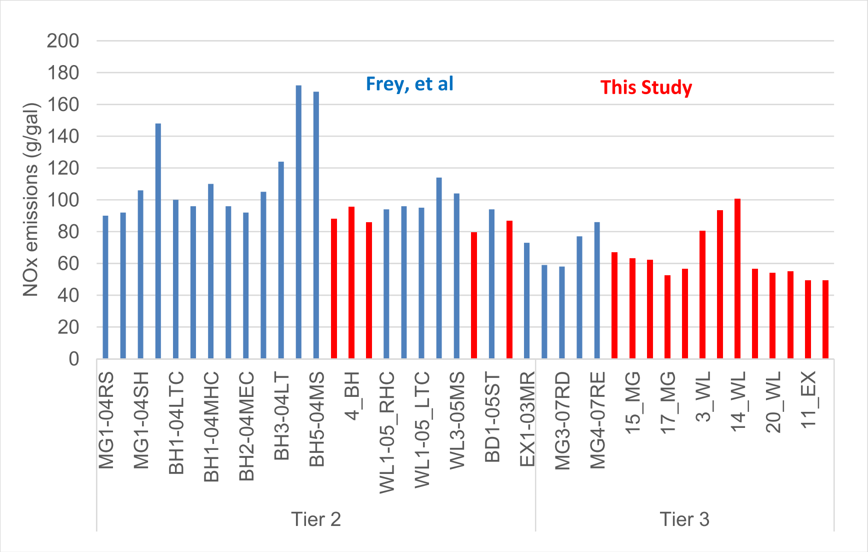

Fig. 10. Comparison of measured fuel specific NOx emissions by Tier and equipment type between Frey et al. and this study.

important consideration in comparing emissions from different equipment. The displacements differed for the Tier 2 and Tier 3 units, with the Tier 2 units having displacements of 8.8 and 15.2 L and Tier 3 engines having generally smaller displacements ranging from 4.5 to 11.0 L. The possible effect of displacement/manufacturer can be seen when comparing 6_WL with 20_WL, which have engines with 11.0 L and 6.6 L displacements, respectively. Although the load factors were similar at 0.32 for 6_WL and 0.33 for 20_WL, the NO_x emissions were 5.27 and 3.64 g/hp-h, respectively. The PM emissions showed opposite trends for 6_WL and 20 WL, with emissions of 0.0842 and 0.333 g/hp-h, respectively, suggesting there is some tradeoff between NOx and PM emissions for these engines.

While the data indicate that for a given engine Tier the emissions are primarily influenced by the engine load factor and secondarily by the engine displacement, there are some emissions which cannot be explained only by these factors. There is not enough information available in the present dataset to provide a plausible explanation of other factors influencing these emissions.

The Tier 4 units with DPFs all showed significant reductions in PM in comparison with those units without aftertreatment. For the Tier 2 and Tier 3 units, the majority of the units had PM emissions lower the CARB standard. Five of the six units that had higher bsPM emissions relative to the standard had load factors of $\leq$0.33, and engines with the same displacement of 6.6 L. These units have PM emissions from 0.10 to 0.34 g/hp-h. One of the units (#17 a 2010 grader) was equipped with an aftermarket DPF. The bsPM emissions from this unit averaged 0.029 g/hp-h overall, which is above the 0.0016 g/hp-h average of the four Tier 4i units that didn't have a DPF regeneration, and even above the 0.007 g/hp-h for the Tier 4 unit that had a regeneration. This aftermarket DPF may not be quite as efficient as DPF's on the Tier 4i units, but it still has average PM emission rates that are considerably lower than those for the non-DPF equipped Tier 2 and Tier 3 units. It is not known how many hours of use this aftermarket DPF has had, so it could be that the difference in comparison with the tier 4 DPF equipment is due to deterioration with age.

The THC emissions ranged from 0.04 to 0.68 g/hp-h. Two units (#1 and #5 both 410 Deere backhoes) showed relatively high THC emissions of greater than 0.63 g/hp-h, which is almost two times more than the other units tested. The Tier 4i THC emissions were considerably lower than the Tier 2 and Tier 3 THC and CH_4 emissions, averaging 84% and 72% lower on a g/hp-h basis, respectively. CO emissions did not show a trend of increases with hours of engine use. The CO emissions ranged from −0.15–3.39 g/hp-h. Three units in the 175–600 hp range have average emissions that are higher than the 2.6 g/hp-h standard. Two units in lower power categories (50 hp–175 hp) also had average CO emissions in the same range, but they were below the 3.7 g/hp-h standard for the smaller engine category. The CO emissions for the Tier 4i units were on average 99% lower than the Tier 3 and Tier 4i units, and were essentially at the limits of detection of the PEMS.

The large variability in emissions, especially for NO_x and PM, could have important implications for developing accurate emissions inventories and models. This variability is primarily due to differences in engine load factors for different types of work and combinations of work and idle time and the displacement of the engines. Load factors are significantly affected by idle percentage, as more engine idle operation over a given test interval will lower the average power. Thus, idle and loaded conditions should be modeled separately for Load factor and emission estimates. Additional activity studies will be important in understanding the overall emissions profiles of construction equipment and their real-world load factors. This could include data logging of the ECM, GPS data for positional information, as well as video to better differentiate between different modes of operation. As an alternative to activity measurements, it may be possible to investigate construction permits to identify work modes, tons-earth to be moved, and project durations to estimate idle and work based Load Factors and idle/work percent time fractions. In general, the development of emissions factors as a function of load factors will likely also be important in further emissions inventory development.

Acknowledgements

The authors would like to thank the California Air Resources Board (#08-315) and the California Department of Transportation (#65A0441) for their financial support, Don Pacocha, Edward O'Neal, and Joe Valdez for conducting the emission tests, B&B Equipment Rental, Kurt VanDusen and employees of Riverside Waste Management, Luke Trickett and employees of Waste Management Inc., Steve McFarland, Kevin Lough and employees of the County of Riverside who made equipment and testing locations available and provided equipment to place the emission measurement equipment on the construction equipment.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2016.09.042.

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