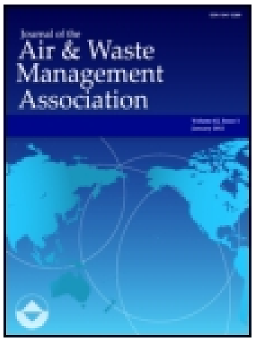

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TECHNICAL PAPER

Real-time emissions from construction equipment compared with model predictions

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The construction industry is a large source of greenhouse gases and other air pollutants. Measuring and monitoring real-time emissions will provide practitioners with information to assess environmental impacts and improve the sustainability of construction. We employed a portable emission measurement system (PEMS) for real-time measurement of carbon dioxide (CO_2), nitrogen oxides (NO_x), hydrocarbon, and carbon monoxide (CO) emissions from construction equipment to derive emission rates (mass of pollutant emitted per unit time) and emission factors (mass of pollutant emitted per unit volume of fuel consumed) under real-world operating conditions. Measurements were compared with emissions predicted by methodologies used in three models: NONROAD2008, OFFROAD2011, and a modal statistical model. Measured emission rates agreed with model predictions for some pieces of equipment but were up to 100 times lower for others. Much of the difference was driven by lower fuel consumption rates than predicted. Emission factors during idling and hauling were significantly different from each other and from those of other moving activities, such as digging and dumping. It appears that operating conditions introduce considerable variability in emission factors. Results of this research will aid researchers and practitioners in improving current emission estimation techniques, frameworks, and databases.

Implications: Construction equipment is an important source of air pollutant emissions. There are large uncertainties in estimates of emissions from construction equipment, partly due to the small number of published measurements. The authors have expanded the database by measuring emissions of CO_2, NO_x, hydrocarbons, and CO from construction equipment under actual operating conditions on-site. There were large discrepancies between measured emissions and those predicted by models, including NONROAD and OFFROAD. Emission factors associated with idling and hauling were significantly different from each other and from those of other activities. These results can be used to improve the next generation of emission estimation models.

Introduction

There are over two million pieces of construction and mining equipment in the United States, which consume over 6 billion gallons of diesel fuel per year (U.S. Environmental Protection Agency [EPA], 2005). The main environmental concern surrounding the use of construction and mining equipment is emissions of air pollutants that impact climate change and air quality. There are large uncertainties in emission inventories for construction equipment, up to a factor of 4.5 difference depending on the method used for estimation (Millstein and Harley, 2009). Therefore, there is a need for improved methods and data to assess, monitor, and estimate emissions from heavy-duty construction equipment accurately.

Several studies have been conducted in order to quantify and predict emissions from heavy-duty equipment (Gautan et al., 2002; May, 2003; Lewis, 2009). Some of these rely on a steady-state engine dynamometer test that may not be representative of real-world emissions during actual operation of the equipment (Hare and Springer, 1973; Wang et al., 2000). Others lack quality assurance of data or are not available to the public (Gautan et al., 2002; May, 2003). One widely used model to estimate emissions from nonroad engines is the U.S. Environmental Protection Agency's (EPA) NONROAD model (EPA, 2004, 2009). This model is based on measurements from tests on a limited number of engines at steady-state conditions (EPA, 1991, 2004).

The EPA has backed the development and use of portable emission measurement systems (PEMS), which are mounted on individual vehicles and measure concentrations of gases and particles in the exhaust (Fulper, 2002). Researchers have proved that this method can be practical and efficient in assessing real-time emissions from both light- and heavy-duty vehicles (Frey et al., 2003; Armos et al., 2009). Furthermore, Durbin et al. (2007), using PEMS, have shown that carbon dioxide (CO_2) and nitrogen oxides (NO_x) emissions measured from backup generators agreed relatively well with values determined by the Federal Reference Method (FRM). The

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EPA implemented this system to measure engine data and emissions from three pieces of construction equipment in 2002 (Hart et al., 2002). However, those data are neither comprehensive nor quality assured. Therefore, there is a need for more efforts in this area in order to augment existing databases and improve models by which emissions can be estimated accurately (EPA, 2002).

Almost all published data on real-time emissions from construction equipment originate from a group at North Carolina State University that uses PEMS among other methods (Abolhasani et al., 2008; Frey et al., 2010; Lewis et al., 2012b). Based on their results, the researchers developed a modal-based model (i.e., modal linear regression [MLR]) to predict real-time emission rates (Lewis, 2009). They also assessed the dependency of emission rates on the type of fuel used for each piece of equipment (Frey et al., 2008). This approach has the advantages of better representing real-world conditions compared to an engine dynamometer test (Lewis et al., 2009a) and providing information to support fleet management decision-making (Lewis et al., 2009b). Along the same lines, Fu et al. (2012) have applied PEMS to measure real-time emissions from construction equipment in China and found that emissions were higher compared with those reported in another study (Frey et al., 2010). Some studies have focused on idle emissions (Khan et al., 2006; Lewis et al., 2012a), which differ considerably from nonidle emissions.

Several different models for predicting emission rates from heavy-duty construction equipment have been proposed, and a few have been put into regulatory use. The NONROAD model (EPA, 2004, 2009) has been implemented in many environmental assessment models (Li and Lei, 2010; Rasdorf et al., 2012; Hajji and Lewis, 2013). The California Air Resources Board's (CARB) OFFROAD model is used to estimate emissions from construction equipment as well (CARB, 2010). Melanta et al. (2013) have summarized tools by which emissions can be estimated from the scale of a single equipment type to nationwide.

Although several studies have focused on quantifying and estimating emissions from construction equipment, there is still a need to expand and update the database of emissions as new emission standards are implemented, to validate current models used to predict emissions, and to assess the variability of emission factors with the equipment's action (e.g., digging, dumping, hauling, idling) in order to improve environmental assessment models. The reason for focusing on actions is that vision-based monitoring technology can identify different actions (Heydarian et al., 2012; Shiftefar et al., 2010), and there is interest in extending this technology to estimate emissions. In this study, we measured real-time emissions from 18 pieces of construction equipment and compared them with values estimated by methodologies used in NONROAD2008, OFFROAD2011, and Lewis's MLR model. We also investigated differences in emission factors by action and engine size. Results will enable more accurate estimation of emissions through environmental monitoring and assessment frameworks.

Methodology

Using a PEMS (AxionGO; GlobalMRV, Buffalo, NY), we measured concentrations of carbon dioxide (CO_2), nitrogen oxides (NO_x), hydrocarbons (HC), and carbon monoxide (CO) in the tailpipe exhaust of excavators, backhoes, and loaders during actual operation at various construction sites. We tested 18 different pieces of diesel-powered equipment involved in earthmoving activities on Virginia Tech's campus and at other sites in Montgomery County, Virginia. Table 1 lists their engine specifications, and Table S2 in Supplemental Material describes the conditions during each test.

Table 1. Engine specifications of each piece of equipment tested, all diesel-powered

Type	Make	Rated Power (kW)	Tier	Engine Displacement (L)	Model Year[a]	Assumed Engine Speed (RPM)
Bulldozer	Komatsu D31E	52	I	3.9	1993	2350
Loader	Komatsu WA180	82	I	5.9	1998	2200
Excavator	John Deere 120C	66	II	4.5	2004	2200
Excavator	Kobelco 135SR	70	II	4.3	2002	2200
Backhoe	John Deere 410G	73	II	4.52	2004	2200
Excavator	Komatsu PC228	82	II	6.69	2003	2000
Excavator	Caterpillar 320CL	103	II	6.37	2001	2000
Excavator	Hitachi EX270LC	125	II	6.7	1997	2050
Excavator	Kobelco SK250LC	131	II	5.9	2004	2100
Loader	John Deere 755C	132	II	10.0	2004	1800
Excavator	Volvo EC240	134	II	7.1	2005	2000
Excavator	Kobelco SK330LC	177	II	7.5	2008	2200
Excavator	Komatsu PC300LC	180	II	8.3	2005	1900
Excavator	Komatsu PC160-6	84	III	3.9	2009	2100
Excavator	Sany SY215CLC	116	III	5.86	2012	2000
Excavator	Komatsu PC200-8	116	III	6.7	2009	2000
Excavator	Caterpillar 308D	42	IV	2.83	2009	2000
Excavator	Volvo EC250D	151	IV	7.8	2012	1800

Notes: [a]Model years refer to the engine. None of the engines were rebuilt.

The PEMS uses nondispersive infrared (NDIR) absorption to measure CO_2, HC, and CO and an electrochemical cell to measure NO_x. Our PEMS was not capable of measuring particulate matter. We mounted the suitcase-sized device securely on the construction equipment and installed a probe inside the tailpipe to sample the exhaust. The PEMS recorded gaseous concentrations second by second and sent them remotely to a tablet, which recorded and saved the data.

Engine data, such as speed in revolutions per minute (RPM) and intake air temperature, can be measured via sensor arrays installed around the engine or via the on-board diagnostic (OBD) system. Unfortunately, neither option was available in this study, nor was it possible to measure the fuel consumed during a test. Therefore, we estimated engine speed based on information from manufacturers. Emission factors (mass of pollutant emitted per mass of fuel consumed) could be calculated directly from exhaust gas concentrations, but emission rates (mass of pollutant emitted per unit time) required an estimate of engine speed or the rate of fuel consumption. We recorded a video of construction activities during each test to enable the assignment of emissions at any given time to a specific type of action.

Quality assurance and quality control

We calibrated the PEMS against Bureau of Automotive Repair (BAR) 97 calibration standards, including propane for HC, and zero air according to the manufacturer's instructions within 2 days of each test. For each calibration event, we isolated gas cylinders and the PEMS in a fume hood, ran the gas through the PEMS for 2 min, and adjusted the reported concentrations to match those of the calibration standards. Before the actual construction activity began, we mounted the PEMS securely on a foam pad over the hood in order to minimize vibration and warmed it up for 15–30 min. We covered it with plastic to protect it from water and dust. Each test lasted between 15 and 120 min. After each test, we cleaned the probe.

We applied quality assurance and control measures to the data. After removal of data points when there were connection, power, or overheating problems or poor-quality video, 16 hr of data remained for analysis. We also removed periods showing discontinuous jumps in concentration induced by electrical noise (<10 sec per event in 4 out of 18 tests) or otherwise unrealistic concentrations (e.g., CO_2 above ~10% or near zero) and shifted the concentrations in time to synchronize the measurements with the video recordings.

Emission rates

The PEMS reported exhaust concentrations as volumetric mixing ratios (e.g., percent or parts per million). Given the estimated engine speed, ambient temperature, and ambient pressure, we calculated emission rates, or the mass of pollutant emitted per unit time, according to eq 1.

$$ER = Y \times MW \times D \times \frac{RPM}{2} \times \frac{1}{60} \times \frac{P}{R \times T} \times 1000 \qquad (1)$$

where

ER = emission rate (g sec^{-1})
Y = volumetric concentration of the pollutant of interest in the exhaust (unitless)
MW = molecular weight of pollutant (g mol^{-1})
D = engine displacement (L)
RPM = engine speed in revolutions per minute (min^{-1})
P = ambient pressure (atm)
R = ideal gas constant (82.05 × 10^{-6} m^3 atm mol^{-1} K^{-1})
T = temperature inside tailpipe (K)
2 = accounting for the fact that exhaust emissions are vented during every other revolution in a 4-stroke engine
60 = conversion factor between minutes and seconds
1000 = conversion factor between cubic meters and liters

Because engine data were not available, we assumed an engine speed equal to that reported by the manufacturer for the rated power while the engine was in nonidle mode (Table 1) and an engine speed of 1000 RPM while the engine was in idle mode (Abolhasani et al., 2008). As the probe sampled just inside the exit of the tailpipe, we assumed pressure was equal to that of the ambient environment. We assumed an exhaust temperature of 402 or 213 °C at the exit of the tailpipe, independent of ambient conditions, depending on whether the equipment was outfitted with a diesel particulate filter or not, respectively (Gonzales, 2008). To quantify the impact of these assumptions on the results, we conducted a sensitivity analysis using extreme values that would maximize the emission rate. After calculation and aggregation of emission rates, we normalized them to the engine's rated power for each piece of equipment.

Emission factors

We calculated emission factors in terms of the grams of pollutant emitted per liter of diesel fuel consumed on the basis of carbon balance using eq 2 (Singer and Harley, 2000). The equation assumes that all carbon in the fuel is emitted as CO_2, CO, or HC.

$$EF = \frac{\left(\frac{Y}{Y_{CO_2}}\right)}{\left(1 + \left(\frac{Y_{CO}}{Y_{CO_2}}\right) + 3 \times \left(\frac{Y_{HC}}{Y_{CO_2}}\right)\right)} \times MW \times 840 \times \frac{0.87}{12} \qquad (2)$$

where

EF = emission factor (g L^{-1})
Y = volumetric concentration of the pollutant of interest in the exhaust (unitless)
Y_{CO2} = volumetric concentration of CO_2 in the exhaust (unitless)
MW = molecular weight of the pollutant of interest (g mol^{-1})
840 = density of diesel fuel (g L^{-1}) (Singer and Harley, 2000)
0.87 = carbon content of diesel fuel (g C g^{-1} diesel fuel) (Singer and Harley, 2000)
12 = atomic weight of carbon (g mol^{-1})
3 = adjustment for use of propane with three carbons as a calibration gas (unitless) (Singer and Harley, 2000)

Modeled emissions

We compared our estimates of emission rates with those predicted by methodologies used in NONROAD2008 (EPA, 2004), OFFROAD2011's in-use off-road equipment module (CARB, 2007), and Lewis' MLR model (Lewis, 2009). To clarify, we did not run the actual NONROAD and OFFROAD models, but instead we used the equations in NONROAD2008 and OFFROAD2011, described in Supplemental Material, to calculate emission rates for each type of equipment. The MLR model is a statistical model that predicts fuel consumption and emissions based on the normalized manifold absolute pressure (MAP) in the engine. As engine data such as MAP were not available in this study, we used the same fractions of time spent in each MAP mode as recommended in the original formulation of the model to calculate emission rates associated with the MLR model for moving materials, fine grading, and excavating soil (Lewis, 2009).

Action-based emission factors

We examined videos of each test manually to identify actions, such as idling, scooping, and dumping, second by second. In addition, we aggregated some of the specific actions into five more general categories. Table 2 shows the types of specific actions detected as well as the general category to which they were assigned. We calculated emission rates and factors second by second using eqs 1 and 2, respectively. After assigning emission factors and rates to their corresponding specific and general actions, we compared time-averaged emission factors within each general action with those of other actions in order to determine whether they were significantly different from each other by the Tukey test. If emission factors were not normally distributed, we transformed them (e.g., log, log-log, or inverse transformation depending on the data set) in order to satisfy the assumption of normality for the Tukey test. If the emission factors remained non-normally distributed, even after transformation, we excluded them from further analysis. We calculated a P value for each comparison and defined the level of significance at 0.05. If emission factors from two different sets of actions were not significantly different from each other, we merged them together into a single category of action. To investigate the relationship between emissions and engine parameters, we grouped results by engine tier and calculated the least squares linear regression line between emission factor and engine power or displacement.

Table 2. Types of actions detected

Specific Action	General Action
Idling	Idling
Scooping	Digging
Empty bucket in air	Idling
Empty bucket moving in air	Swinging
Full bucket in air	Idling
Full bucket moving in air	Swinging
Full bucket lifting	Swinging
Dumping	Dumping
Vehicle moving with empty bucket	Hauling
Vehicle moving with full bucket	Hauling

Results and Discussion

Emission rates

Tables 3 and 4 show emission rates and fuel-based emission factors, respectively, for each piece of equipment averaged over all valid data points. Because the duty cycle, including operational efficiency (ratio of nonidle time to total time), and environmental conditions differed between tests, we expected considerable variability in emission factors (Bishop et al., 2001; Clark et al., 2002; Ahn and Lee, 2013). Parameters such as site altitude, humidity, grade of terrain, and temperature can also affect emissions. Emission factors of CO_2 were much higher than for other pollutants, of course, as the majority of the fuel is oxidized to this product. Among the other three pollutants, NO_x was emitted in the largest amounts, and CO and HC emissions were low, as expected for diesel-powered engines. In some cases, the standard deviations of CO emission rates were larger than the mean value, implying that there were many instances in which the CO concentration was near zero.

Emissions did not exceed EPA's standards for nonroad engines. Prior to model year 2014, EPA regulated NO_x and HC emissions together, and none of the engines exceeded its respective standard for NO_x plus HC, 4–7.5 g kW^{-1} hr^{-1}, depending on engine size and model year. None of the equipment exceeded the CO emission standard of 5.0 g kW^{-1} hr^{-1} for engines smaller than 130 kW (174 hp) or 3.5 g kW^{-1} hr^{-1} for larger ones. EPA introduced a separate HC emission standard in model year 2014. Only two pieces of equipment, the Komatsu D31E bulldozer and John Deere 120C excavator exceeded the new standard of 0.19 g kW^{-1} hr^{-1}, although it does not apply to them because they were built prior to 2014.

In general, emissions of CO, HC, and NO_x decreased with higher tier number. For instance, emission rates of engines meeting stricter tiers (III and IV) were lower than those from equivalent-size engines of lower tiers. Emission rates were not proportional to engine power in this study. Substantial variability in duty cycle and/or engine load likely contributed to this observation (Abolhasani and Frey, 2013; McDonald et al., 2011).

Table 4 shows measured, fuel-based emission factors for the 18 pieces of equipment. Among all emission factors, CO_2 was the least variable. NO_x emission factors for tier III and IV engines were generally lower than those of tier I and II engines. Standard deviations of emission factors were generally smaller than those of emission rates, indicating larger variability in emission rates, as has been found in other studies (Frey et al., 2010). Generally, second-by-second emission factors, especially for CO_2, were not normally distributed.

Figure 1 shows the difference between CO_2 emission rates estimated from our measurements and those calculated according to methodologies used in NONROAD2008 and the MLR model. A

Table 3. Estimated emission rates[a]

Make	Rated Power (kW)	Engine Tier	Mean and Standard Deviation of Emission Rate (g kW^{-1} hr^{-1})			
			CO_2	NO_x	HC	CO
Komatsu D31E	52	I	199 ± 6	2.18 ± 0.09	0.290 ± 0.009	1.50 ± 0.05
Komatsu WA180	82	I	89 ± 8	1.92 ± 0.19	0.091 ± 0.005	0.57 ± 0.07
John Deere 120C	66	II	316 ± 6	2.83 ± 0.04	0.290 ± 0.026	0.02 ± 0.01
Kobelco 135SR	70	II	240 ± 11	1.82 ± 0.09	0.149 ± 0.012	0.15 ± 0.02
John Deere 410G	73	II	9 ± 5	0.11 ± 0.05	0.006 ± 0.002	0.05 ± 0.16
Komatsu PC228	82	II	89 ± 8	1.92 ± 0.19	0.091 ± 0.005	0.57 ± 0.07
Caterpillar 320CL	103	II	15 ± 8	0.07 ± 0.05	0.004 ± 0.002	0.02 ± 0.08
Hitachi EX270LC	125	II	183 ± 18	1.93 ± 0.20	0.079 ± 0.004	0.83 ± 0.32
Kobelco SK250LC	131	II	9 ± 7	0.05 ± 0.04	0.004 ± 0.005	0.02 ± 0.06
John Deere 755C	132	II	58 ± 7	0.64 ± 0.06	0.034 ± 0.002	0.27 ± 0.05
Volvo EC240	134	II	15 ± 5	0.11 ± 0.05	0.010 ± 0.010	0.01 ± 0.01
Kobelco SK330LC	177	II	48 ± 7	0.27 ± 0.03	0.026 ± 0.003	0.10 ± 0.03
Komatsu PC300LC	180	II	107 ± 6	0.54 ± 0.03	0.030 ± 0.002	0.18 ± 0.02
Komatsu PC160-6	84	III	60 ± 5	0.41 ± 0.06	0.037 ± 0.003	0.25 ± 0.02
Sany SY215CLC	116	III	35 ± 6	0.16 ± 0.02	0.020 ± 0.001	0.14 ± 0.01
Komatsu PC200-8	116	III	53 ± 4	0.16 ± 0.01	0.022 ± 0.002	0.08 ± 0.01
Caterpillar 308D	42	IV	138 ± 5	0.57 ± 0.03	0.028 ± 0.003	0.19 ± 0.04
Volvo EC250D	151	IV	31 ± 7	0.14 ± 0.02	0.011 ± 0.002	0.01 ± 0.01

Note: [a]Assumptions in engine speed, exhaust temperature, and pressure may have introduced uncertainties in these rates, such that they could be higher by up to a factor of 4.5 in the most extreme case (Table 5).

Table 4. Measured emission factors

Make	Rated Power (kW)	Engine Tier	Mean and Standard Deviation of Emission Factor (g L^{-1})			
			CO_2	NO_x	HC	CO
Komatsu D31E	52	I	2628 ± 74	30.1 ± 13.6	5.2 ± 12.3	23.0 ± 24.0
Komatsu WA180	82	I	2608 ± 159	63.1 ± 55.6	3.7 ± 8.5	54.3 ± 124
John Deere120C	66	II	2671 ± 6	24.1 ± 2.4	2.5 ± 1.8	0.4 ± 2.2
Kobelco 135SR	70	II	2668 ± 44	21.7 ± 26.9	2.4 ± 10.6	3.0 ± 8.4
John Deere 410G	73	II	2643 ± 85	41.9 ± 51.0	3.0 ± 9.8	17.7 ± 39.8
Komatsu PC228	82	II	2654 ± 16	36.4 ± 8.7	3.8 ± 2.9	9.5 ± 7.1
Caterpillar 320CL	103	II	2670 ± 16	14.9 ± 4.5	1.0 ± 1.0	4.0 ± 9.1
Hitachi EX270LC	125	II	2650 ± 43	23.7 ± 7.1	1.5 ± 1.0	15.9 ± 26.4
Kobelco SK250LC	131	II	2667 ± 36	16.7 ± 4.7	1.3 ± 1.3	5.8 ± 22.5
John Deere 755C	132	II	2647 ± 46	27.6 ± 8.1	16.3 ± 47.9	30.1 ± 4.6
Volvo EC240	134	II	2672 ± 5	19.2 ± 3.8	1.7 ± 0.9	4.6 ± 3.6
Kobelco SK330LC	177	II	2669 ± 22	19.7 ± 9.9	2.2 ± 1.6	4.2 ± 11.5
Komatsu PC300LC	180	II	2669 ± 11	14.1 ± 9.6	0.9 ± 1.0	5.2 ± 5.3
Komatsu PC160-6	84	III	2652 ± 20	12.3 ± 4.1	2.0 ± 1.0	13.7 ± 12.1
Sany SY215CLC	116	III	2649 ± 13	3.5 ± 1.4	2.4 ± 1.0	15.2 ± 7.1
Komatsu PC200-8	116	III	2667 ± 8	8.6 ± 2.6	1.3 ± 0.7	5.7 ± 4.5
Caterpillar 308D	42	IV	2672 ± 13	10.6 ± 3.2	0.5 ± 0.6	4.2 ± 7.7
Volvo EC250D	151	IV	2664 ± 23	17.5 ± 9.6	3.6 ± 4.4	2.9 ± 9.2

comparison with OFFROAD2011 is not shown because it does not predict CO_2 emissions. In subsequent usage, the models appear as NONROAD and OFFROAD without the version number. Values of 0%, 20%, or −20% mean that estimated emission rates are the same as, 20% higher than, or 20% lower, respectively, than those predicted according to the model. Estimated CO_2 emission rates were 60–90% lower than predicted by NONROAD, whereas they were more evenly distributed between being 70% lower to 70% higher than predicted by the MLR model. Obviously, different methods produced very different estimates of emission rates. For

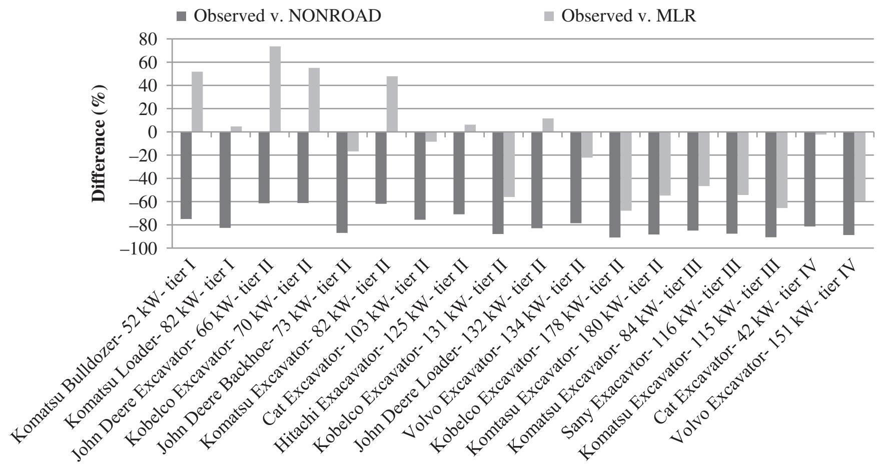

Figure 1. Differences between CO_2 emission rates and those calculated using other methods.

engines meeting stricter emission standards (higher tier), differences between the two models converged, except for the 42-kW Caterpillar excavator. Large negative differences imply that the actual fuel consumption rate was less than predicted. Differences between observed and predicted emission rates are likely partially due to the fact that the database used to construct both models does not contain newer engines (EPA, 1991; Lewis, 2009). Of course, the possibility that measurement errors or mischaracterization of operating conditions may have contributed to the discrepancies cannot be ruled out, despite efforts to minimize such errors.

Figures 2, 3, and 4 show differences between emission rates estimated from our measurements and those calculated according to methodologies used in NONROAD, OFFROAD, and the MLR model for NO_x, HC, and CO. The discrepancies were similar in magnitude and sometimes larger than for CO_2. In most cases, observed emission rates were much lower than predicted values, especially for engines meeting tighter emission standards (tiers III and IV), and the discrepancies were generally smaller for the MLR model compared with NONROAD and OFFROAD. Much of the difference can be ascribed to lower fuel consumption rates than predicted. This is not the first study to show large discrepancies between measured versus modeled emissions from construction equipment. In measurements of three excavators using PEMS, emission factors of NO, HC, and CO were found to be 50% lower to 70% higher than those predicted by NONROAD (Abolhasani et al., 2008).

For equipment meeting lower tier standards, discrepancies were more similar between NONROAD and OFFROAD than between either of these and the MLR model. Generally for the same pieces of equipment, the largest and smallest discrepancies between different approaches were associated with CO and CO_2, respectively. As tier increased, discrepancies between the emission rates estimated in this study and those predicted by the models grew. It is possible that model inputs are not sufficient to predict emissions accurately under actual operating conditions. It is likely that further consideration of improved emission control technologies implemented in engines meeting tier III and IV standards—particulate filters, selective catalytic reduction, exhaust gas recirculation—is needed.

We conducted a sensitivity analysis in order to quantify the uncertainty associated with estimating engine speed and exhaust pressure and temperature, which were needed to

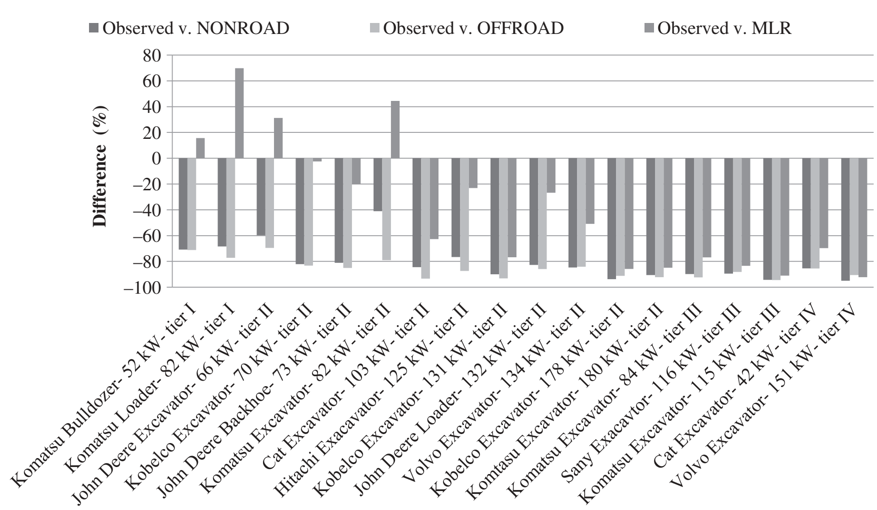

Figure 2. Differences between NO_x emission rates and those calculated using other methods.

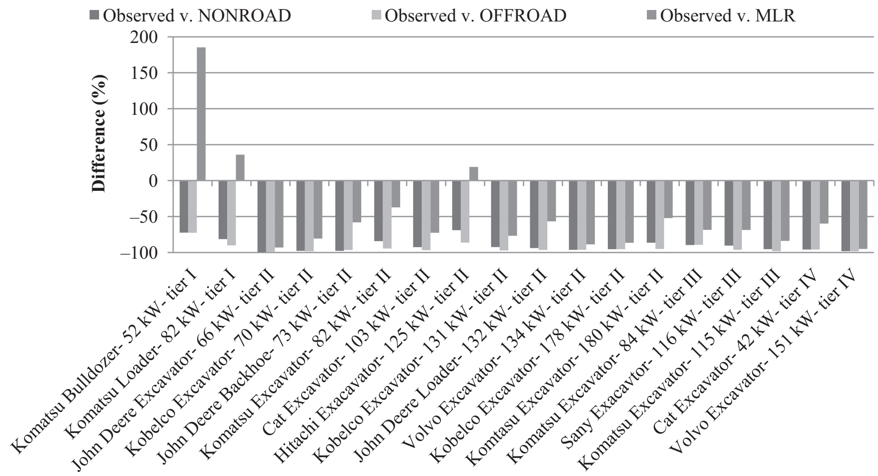

Figure 3. Differences between CO emission rates and those calculated using other methods.

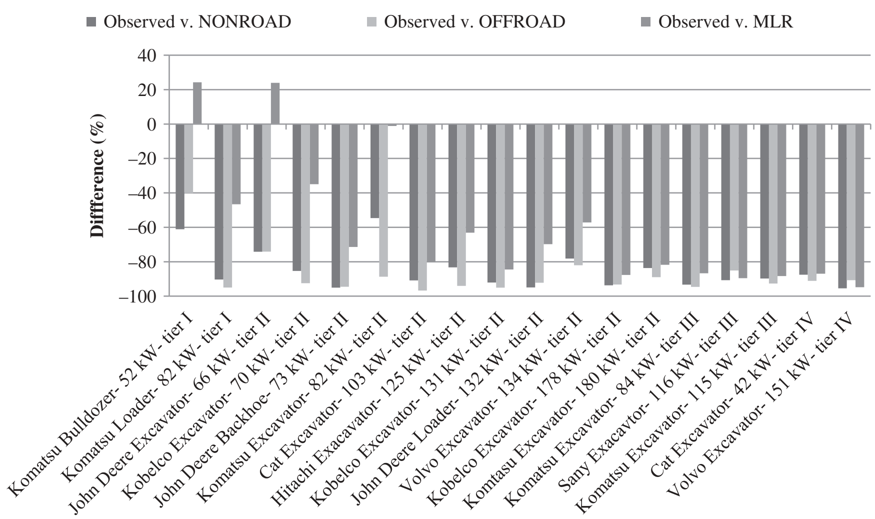

Figure 4. Differences between HC emission rates and those calculated using other methods.

calculate the emission rates (eq 1). We consulted several practitioners who stated that the engine speed for this type of equipment typically ranges from 1750 to 2200 RPM. We considered a minimum temperature of 97 °C for the exhaust, the lowest of observed exhaust temperatures for hot conditions in diesel engines (Gonzales, 2008), and a maximum pressure of 250 kPa (2.47 atm), which is equal to the maximum MAP observed in other studies (Lewis, 2009). We recalculated emission rates using values of the three variables that would maximize the emission rate. Table 5 shows the resulting differences between the upper bound of the estimated emission rate and that predicted by NONROAD for each pollutant, the same metric shown in Figures 1–4 for individual pieces of equipment but averaged across all of them here. Since eq 1 is linear in engine speed, temperature, and pressure, a change in one assumed input value will result in a proportional change in the emission rate. For instance, increasing MAP by a factor of 2 will double emission rates. Even after recalculation of emission rates with these extreme input values, the mean differences remained negative. Thus, the finding was robust that our PEMS-based emission rates, which required a number of assumptions about engine speed and exhaust parameters, were lower than those predicted by widely used models.

Emission factors at idling were also of interest because they can have a large impact on average emission factors, which depend on the time spent in each mode. Table 6 shows the differences between measured idling emission factors and those recommended by the MLR model for all 18 pieces of equipment. The MLR model assigns a constant emission factor that is independent of engine size, power, and tier for mode 1, which represents idling. There was good agreement for CO_2, but for NO_x, HC, and CO, differences were mostly negative, averaging −46%, −33%, and −64%, respectively, meaning that measured idle emission factors were lower than those recommended by the model. There were large differences for bulldozers and loaders, even though the testing procedure in both studies was similar. Results suggest that using a single emission factor for idling for all construction equipment may not be ideal. Factors other than engine mode must also affect idling emissions.

Table 5. Differences between nonidle emission rates and those predicted by NONROAD2008 and OFFROAD2011 (%), with different assumptions for exhaust temperature, pressure, and engine speed

Case	Exhaust Temperature (°C)	Exhaust pressure (atm)	Engine Speed (RPM)	CO_2	NO_x	HC	CO
NONROAD baseline	402 or 213[a]	0.93[b]	Table 1	−80 ± 10	−81 ± 13	−85 ± 11	−90 ± 9
NONROAD extreme	97	2.47	2200	−16 ± 31	−24 ± 44	−40 ± 37	−60 ± 31
OFFROAD baseline	402 or 213[a]	0.93[b]	Table 1	NA	−86 ± 7	−88 ± 13	−94 ± 6
OFFROAD extreme	97	2.47	2200	NA	−41 ± 23	−50 ± 42	−75 ± 22

Notes: [a]402 °C is for equipment with a diesel particulate filter, and 213 °C is for equipment without. [b]All sites were ~600 m above sea level.

Table 6. Differences between idling emission factors and those predicted by the MLR model

Make and type	CO_2 (%)	NO_x (%)	HC (%)	CO (%)
Komatsu bulldozer 52 kW tier I	1	−19	6	113
Komatsu loader 82 kW tier I	2	−91	−53	−64
John Deere excavator 66 kW tier II	2	−31	−42	−99
Kobelco excavator 70 kW tier II	1	−38	−43	−92
John Deere backhoe 73 kW tier II	−8	14	−34	−57
Komatsu excavator 82 kW tier II	1	4	−11	−73
Caterpillar excavator 103 kW tier II	1	−58	−78	−89
Hitachi excavator 125 kW tier II	1	−32	−64	−55
Kobelco excavator 131 kW tier II	1	−50	−62	−84
John Deere loader 132 kW tier II	2	−21	255	−12
Volvo excavator 134 kW tier II	2	−45	−61	−87
Kobelco excavator 177 kW tier II	1	−44	−49	−76
Komtasu excavator 180 kW tier II	1	−60	−80	−85
Komatsu excavator 84 kW tier III	1	−65	−53	−62
Sany excavator 116 kW tier III	1	−90	−45	−59
Komatsu excavator 116 kW tier III	1	−75	−69	−84
Caterpillar excavator 42 kW tier IV	2	−70	−89	−88
Volvo excavator 151 kW tier IV	1	−50	−15	−92
Average	1	−46	−33	−64

Variability in emission factors with action

Based on the videos of each piece of construction equipment's actions, we assigned emission factors to one of the specific actions in Table 2 on a second-by-second basis. Table 7 shows the number of tests for which a significant difference was observed in emission factors between each combination of actions. For example, the value of 5/16 in Table 7 for CO means that in 5 out of 16 tests, there was a significant difference between digging and dumping in terms of their emission factors. Since emission rates were not directly measured (i.e., they required assumptions about engine speed and exhaust parameters), they were excluded from this analysis. Although there were 18 different pieces of equipment, not all of them performed all categories of actions defined in Table 2, nor were their emission factors normally distributed; thus, the total numbers of comparisons for a pair of actions was not the same for each combination.

In general, there were significant differences between idling and other working modes. Differences in emission factors by action were not consistent by pollutant. The results suggests that using different emission factors for certain actions, as well as using fuel consumption specific to that action, can help practitioners to estimate actual emission rates more accurately. It is likely that that action-specific emission rates follow the same trend.

As expected, emission factors for engines within the same tier were not correlated with engine characteristics, namely, displacement and rated power. Regression analysis on measurements from 10 tier II engines indicated that for all pollutants, there was no significant relationship between displacement, rated power, and emission factors ($P > 0.05$). Under actual operating conditions, duty cycle, load factor, other engine parameters, and environmental conditions must have contributed to variability in emission factors. Thus, these

Table 7. Numbers of significant differences observed in emission factors between actions

	Idling	Digging	Swinging	Dumping	Hauling
CO_2					
Idling	—	2/4	4/4	3/4	4/4
Digging	—	—	3/4	2/4	2/4
Swinging	—	—	—	4/4	4/4
Dumping	—	—	—	—	4/4
Hauling	—	—	—	—	—
NO_x					
Idling	—	9/11	10/11	7/10	8/12
Digging	—	—	5/10	1/10	7/11
Swinging	—	—	—	5/10	7/11
Dumping	—	—	—	—	6/10
Hauling	—	—	—	—	—
HC					
Idling	—	15/17	14/17	12/16	15/18
Digging	—	—	11/16	4/16	11/17
Swinging	—	—	—	11/16	14/17
Dumping	—	—	—	—	7/16
Hauling	—	—	—	—	—
CO					
Idling	—	15/17	12/17	13/16	16/18
Digging	—	—	8/16	5/16	14/17
Swinging	—	—	—	8/16	12/17
Dumping	—	—	—	—	10/16
Hauling	—	—	—	—	—

variables must be taken into account when predicting emissions from construction equipment activity.

Recommendations and Future Work

The lack of real-time engine data was a limitation of this study, as we had to assume an engine speed in order to estimate emission rates from the measured exhaust gas concentrations. Development of a database on RPM, MAP, and temperature during equipment operation would be valuable. Doing so would require access to the engine control unit (ECU) via an OBD port, which currently is not available on most construction equipment. Therefore, we encourage equipment manufacturers to install such ports. Also, further investigation into the effect of engine load on emission rates and fuel-based emission factors under real operating conditions would promote better understanding of emission trends and discrepancies between monitored and modeled values.

The relationship between emissions and site and operational characteristics (e.g., type of soil hauled and traveled on, terrain grade, etc.) should be investigated further. This will help researchers to develop models to benchmark real-time construction emissions in the preconstruction phase and compare real-time performance with expected benchmarked values.

Although there have been recommendations to use PEMS for construction emission measurement, few studies have used this technique. Therefore, there is a need for more work in this domain to measure real-time emissions. Future research should focus on emissions of particulate matter (PM) because of its strong link to air quality and impact on climate change.

Finally, results of studies such as this one should be incorporated into the development and refinement of emissions models, including the successor to NONROAD, which will be MOVES (EPA, 2010b; Koupal et al., 2002).

Conclusion

Due to the substantial contribution of the construction industry to emissions of greenhouse gases and pollutants that degrade air quality, there has been an ongoing need to quantify and predict emissions at scales ranging from a single piece of equipment to nationwide. The goals of this study were to augment the limited database of emission rates and emission factors for construction equipment, evaluate the ability of widely used models (NONROAD, OFFROAD, and MLR) to predict emissions, and investigate effects of equipment action and engine characteristics on emission factors under actual operating conditions.

Real-time emission rates of CO_2, NO_x, HC, and CO varied more than did fuel-based emission factors, confirming previous findings. Therefore, real-time emissions are best predicted by collecting real-time fuel usage data and combining them with relatively constant emission factors. Emission rates determined in this study were significantly different from those predicted by models, nearly an order of magnitude lower than predicted by methodologies used by NONROAD and OFFROAD and −95% lower to 185% higher than predicted by the MLR model. In general, monitored emission rates agreed better with the MLR model compared with the others. Using a single emission factor for different engines, even for the same action within each engine duty cycle, does adequately reflect actual emissions. Thus, equipment specifications such as rated power and tier may not be sufficient for accurate prediction of emissions. Other factors may also influence emissions; MAP has been proposed to account for these, but it is not easily monitored. The type of emission control technology, engine load factor, and time spent in each duty cycle are variables that probably have a large influence on overall emission rate and factor.

Emission factors associated with idling and hauling were significantly different from those for digging, swinging, and dumping. Therefore, these two actions—idling and hauling—should be treated uniquely rather than lumped together under the umbrella of an overall emission factor. On the other hand, idling emission rates may vary between high-idle and low-idle modes. In the real-world conditions of this study, emission factors were not linearly proportional to rated power and size. This outcome calls for future studies on the duty cycle and fuel consumption of engines used in construction equipment. Since emission factors are less variable than emission rates, a thorough understanding of fuel usage by action and duty cycle can enable more accurate estimation of emissions.

There were significant differences between emissions measured under real-world conditions and those predicted by widely used models. Results from this study could be used to help improve the accuracy of the models. Differences were largest for engines meeting higher tier standards, indicating that emission databases and estimation models should be updated to account for advances in emission control and manufacturing technologies.

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