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Real World Emissions of In-Use Off-Road Vehicles in Mexico

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Abstract: Off-road vehicles used in construction and agricultural activities can contribute substantially to emissions of gaseous pollutants and can be a major source of submicron carbonaceous particles in many parts of the world. However, there have been relatively few efforts in quantifying the emission factors (EFs) as well as for estimating the potential emission reduction benefits using emission control technologies for these vehicles. This study characterized the black carbon (BC) component of particulate matter and NOx, CO, and CO2 EFs of selected diesel-powered off-road mobile sources in Mexico under real-world operating conditions using on-board portable emissions measurements systems (PEMS). The vehicles sampled included two backhoes, one tractor, a crane, an excavator, two front loaders, two bulldozers, an air compressor, and a power generator used in the construction and agricultural activities. For a selected number of these vehicles the emissions were further characterized with wall-flow diesel particle filters (DPFs) and partial-flow DPFs (p-DPFs) installed. Fuel-based EFs presented less variability than time-based emission rates, particularly for the BC. Average baseline EFs in working conditions for BC, NOx and CO ranged from 0.04-5.7, 12.6-81.8, and 7.9-285.7 g/kg-fuel, respectively, and a high dependency by operation mode and by vehicle type was observed. Measurement-base frequency distributions of EFs by operation mode are proposed as an alternative method for characterizing the variability of off-road vehicles emissions under real-world conditions. Mass-based reductions for black carbon EFs were substantially large (above 99%) when DPFs were installed and the vehicles were idling, and the reductions were moderate (in the 20-60% range) when p-DPFs in working operating conditions. The observed high variability in measured EFs also indicates the need for detailed vehicle operation data for accurately estimating emissions from off-road vehicles in emissions inventories.

Implications: Measurements of off-road vehicles used in construction and agricultural activities in Mexico using on-board portable emissions measurements systems (PEMS) showed that these vehicles can be major sources of black carbon and NO_X. Emission factors varied significantly under real-world operating conditions, suggesting the need for detailed vehicle operation data for accurately estimating emissions inventories. Tests conducted in a selected number of sampled vehicles indicated that diesel particle filters (DPFs) is an effective technology for control of diesel particulate emissions and can provide potentially large emissions reduction in Mexico if widely implemented.

Introduction

Off-road vehicles (e.g., forklifts, specialty vehicles, portable generators, and a wide array of other agricultural, construction, and industrial 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. However, in contrast to on-road mobile sources, there have been relatively less efforts in quantifying the potential benefits for reducing emissions from off-road mobile sources. Currently there is no legislation available on emissions levels for in-use off-road vehicles in Mexico, and there are no incentives to install emissions controls technologies. Due to their durability, off-road vehicles are often kept in service for several decades and thus their relative emissions contributions increase over time as emissions from on-road vehicles continue to be reduced by technological improvements. These factors highlight the importance of designing emissions control strategies for off-road vehicles to protect human health and reduce impacts on climate and ecosystems.

Estimating emissions from in-use off-road sources is challenging because the extent of emission factors datasets available is considerably more limited compared to on-road vehicles, which have been traditionally studied extensively. Steady-state engine dynamometer tests with one or more settings of constant load and engine speed are typically used for emissions characterizations; however, these laboratory tests are not representative of the in-use off-road vehicle operation conditions (e.g., Gautam et al., 2002). In addition, there is very limited data available on the operating activities for-off-road vehicles to fully characterize their emission patterns. There is a need to obtain emissions measurements and activity data under real-world operating conditions.

Depending on location, current estimates suggest that off-road diesel vehicles are a major source of black carbon (BC) and other submicron carbonaceous particles in many parts of the world (Bond et al., 2013). In Mexico, the most recent BC emissions estimates are for the 2013 greenhouse gases and black carbon emission inventory (2013 GHG-BC MNEI) and suggest that off-road vehicles contribute about 13% of the total 125 Gg annual BC emissions (SEMARNAT, 2015). In comparison, on-road mobile sources are the second largest contributor with about 25% of the total BC emissions. However, the off-road emission estimates for Mexico have not been obtained using local emissions factors data; instead they have been based on the default databases in the NONROAD EPA emissions model (EPA, 2010a) and by adapting activity data such as vehicle population, hours of operation, and load factors using several assumptions (SEMARNAT, 2015). The development of accurate emission factors and activity data for off-road vehicles is a critical step that needs to be addressed in order to reduce uncertainties in the emissions inventories.

Several studies have been carried out to characterize the emissions of in-use off-road vehicles using on-board Portable Emissions Measurement Systems (PEMS). Abolhassani et al. (2008) estimate the activity data, fuel use, and emissions from three excavators and demonstrated the importance of accounting for inter-cycle variability in real-world emissions to develop more accurate emissions inventories. Frey et al. (2008a) measure emissions from four front-end loaders, five backhoes and six motor graders under real-world operating conditions using diesel versus B20 biodiesel and further characterized the activity, fuel use, and emissions of selected motor graders (Frey at el., 2008b). Lewis et al. (2009) use the data collected by Frey et al. (2008b) to demonstrate the use of real-world emissions data obtained by PEMS for developing annual-based emission inventories. The emissions impacts of retrofitting with diesel particulate filter technologies and the use of ultra-low sulfur fuel in two excavators, a crane and a loader were investigated as part of an emissions reductions program from off-road construction equipment at the World trade Center in New York (Vojtisek-Lom, 2003). EPA has developed the Simple Portable On-Board Test (SPOT) instrument to measure the emissions of 50 vehicles in the construction sector for comparison with the dynamometer-based emissions data in the NONROAD model (EPA, 2002). In a recent study the California Air Resources Board (CARB) measure the emissions of 6 wheel loaders, 4 backhoes, 4 excavators, 2 scrappers, 6 bulldozers and 4 graders using the AVL Micro-Soot Sensor (AVL-MSS) PEMS and developed NO_X-PM relationships with fuels use and engine brake horse power (Durbin et al., 2013).

In general, the PEMS studies have revealed that the off-road emissions are highly transient, with rapid and repeated changes in engine speed and load depending on the vehicle's operating conditions, indicating the need to characterize the off-road emissions by operational cycles. In this study the BC, CO, CO_2, and NO_X emissions of selected diesel-powered off-road mobile sources in Mexico were characterized under real-world operating conditions using PEMS. The emissions factors were obtained by operational cycles on a time and fuel basis and emissions control devices were further installed in some of the test vehicles to investigate the initial reduction benefits of filter technologies. To our knowledge, this is the first pilot study of emissions characteristics for off-road vehicles in Mexico and the results have contributed to the understanding of the emissions from off-road vehicles under real-world operating conditions. The results can also be useful in improving the emissions inventories, supporting the development of legislation, and promoting emission control technology implementation for off-road vehicles in Mexico.

Methodology

Instrumentation

Three complementary PEMS were used for the emissions characterization of the tested vehicles. A schematic of the sampling setup for the tested vehicles is presented in Figure SM1 of the Supplemental Material document. Carbonaceous soot was measured by the AVL-MSS (AVL, 2008) and CO, CO_2, NO and NO_2 were measured by the SEMTECH ECOSTAR (Sensors, 2014) in all sampled vehicles. In this paper we refer to the carbonaceous soot measured by the AVL-MSS as a surrogate for black carbon. In addition, total HC, CO, CO_2, NO_X, and PM10 were measured in some of the tested vehicles by the AXION (Karim, 2013) PEMS system. Although this paper uses the engine data obtained with AXION, we focus on the emissions measurements obtained with the AVL-MSS for BC and with the ECOSTAR for CO_2, CO and NOx data. A companion paper focused on the inter-comparison of the selected co-measurements obtained with the ECOSTAR and AXION instruments is under preparation (Huertas et al., 2017).

The AVL-MSS obtained 1-sec resolution BC measurements using a photo-acoustic micro-soot filter gravimetric sensor module with a detection limit of 1 $\mu g/m^3$ and a 10 $\mu g/m^3$ resolution defined as 3 times the standard deviation of the measurement variation of the zero signal (clean, filtered air) with 1 sec data smoothing (Schindler et al., 2004). In the photo-acoustic technique, an intensity-modulated light beam produces periodic heating of absorbing particles, which subsequently dissipate their heat and the resulting pressure fluctuations are detected by a microphone. The microphone signal is linearly related to the BC concentration in the measuring volume. Therefore, the AVL-MSS operating principle is not based on the opacity of the sample and has no cross-sensitivity to other compounds, such as hydrocarbons or sulfates. The instrument has a flow and data signals calibration protocol established by the manufacturer on the basis of artificial soot generator CAST (Combustion Aerosol Standard), which produces very stable concentrations of soot, together with a rotating disc diluter (Schindler et al., 2004). The instrument was calibrated by the manufacturer prior to launching the field measurements and the corresponding calibrations recommended by the manufacturer at the beginning of each period of measurements for all test vehicles were performed accordingly.

The ECOSTAR system measured CO and CO_2 by a non-dispersive infrared system (NDIR) both with accuracies of ±2%, whereas O_2 is measured with an electrochemical sensor with an accuracy of ±0.3%. Nitrogen monoxide (NO) and nitrogen dioxide (NO_2) are measured separately and simultaneously by a non-dispersive ultraviolet system (NDUV) with accuracies of ± 0.3%, using the EPA´s recommended methods for measuring these pollutant concentrations (Sensors, 2014). Measurements were obtained using a heated sampling tube flow measuring system to determine the mass of pollutants emitted. Thus, data concentrations and exhaust flow can be measured in real time, along with exhaust pressure and temperature. Manufacture-recommended calibrations of the equipment were performed using high quality trace gases before and after each test.

The AXION measured HCs, CO and CO_2 via NDIR, while NO_X was measured as NO by an electromagnetic cell (Karim, 2013). The PM was measured using a photo detector of the intensity of the light scattered by the particles. This light scattering method is similar to an opacity measurement and is intended for inter-comparisons of the results from the sampled vehicles rather than for quantification of PM (Abolhassani et al., 2008). In this experiment, neither the mass concentration of PM nor their size distributions were measured independently to calibrate the AXION PM measurements. Data from several laboratories using various vehicles and fuels have indicated that the AXION accuracy is typically less than 10% for aggregate mass of NO_X and CO_2 (Yazdani and Frey, 2012) while the accuracy of HC and CO measurements depends on the fuel used and on the emission levels. Two global positioning systems (GPS) were used for tracking the location and movements of the sampled vehicles. In addition to pollutant concentrations, the measurement system also recorded vehicle speed, engine rpm, torque, pressure, exhaust flow, the air-fuel ratio, and fuel mass flow rates. This system has a calibration protocol directly designed by the manufacturer that includes “zero” calibration performed using ambient air at frequent intervals, and “span” calibration using a gas mixture of known composition. Calibrations for the gaseous species were performed before the tests as needed following the manufacturer's recommendations.

Vehicles sampled

The vehicles sampled were provided at no cost by government agencies and private vehicle owners. For the selection of the tested vehicles several visits were arranged to government and private institutions that own and operate a wide variety of off-road vehicles as part of their routine operational activities. The visits included the collection of the engine and vehicle technical specifications, measurement of opacity, performing oil tests, installation of temperature data loggers, and inspection of the general conditions of the vehicles. Of a total of 24 vehicles originally inspected, 11 vehicles were selected for the emissions sampling on the basis of mechanical conditions and vehicle accessibility (see Table 1). The selected vehicles have engines ranging from 32 to 531 hp and include two backhoes (BH), two bulldozers (BD), two large wheel loaders (WL), one excavator (EX), one crane (CR), and a tractor (TR). All the sampled vehicles have been used continuously throughout the year and receive only corrective maintenance. Although not strictly considered as off-road vehicles, an air compressor (AC) and an electricity generator (EG), typically used in construction activities, were also included in this study. It should be noted that it is difficult to know how representative the selected vehicles or their engine conditions are since currently there is very limited information on the characteristics of the off-road vehicles in Mexico. Emissions inventories estimates in Mexico for these sources rely on assumptions on fuel consumption and activity data, whereas fleet characteristics are mostly assumed to be similar to those in the US. As described above our project team interviewed and discussed with key stakeholders to ensure that the selected off-road vehicles are typically used in Mexico. Nevertheless, there is additional associated uncertainty whenever vehicle sampling includes voluntary participation in the vehicle selection process. Due to limited information available on the fleet characteristics, this uncertainty could not be quantified in this pilot project

Data were collected at the regular on-site working locations of the selected vehicles. The backhoes, bulldozers, wheel loaders and excavator were tested directly at the working yards of the excavation and processing asphalt plants by performing controlled operations related to earthwork activities, such as moving material, clearing, material stocking and excavating. The crane was tested at a building construction site performing material pulling and moving activities. The tractor was operated during soil preparation activities for planting corn at the private field of the tractor's owner. The generator and air compressor were used to provide temporary source of electricity and compressed air respectively at the mechanical shop of the asphalt excavation plant. The vehicles and equipment were operated by qualified personnel provided by the participating institutions and all the activities were time controlled by the measurement team in order to regularly check the instruments and data collection status. All measurements were performed within the Mexico City Metropolitan Area (MCMA), which has an average altitude of 2250 m.a.s.l. with an average temperature of 16 ^{o}C and relative humidity of 64% during the sampling period (September to December 2014). Ultra-low sulfur diesel (ULSD, < 15 ppm in S) in Mexico is currently available only in the MCMA and the metropolitan areas of Monterrey and Guadalajara as well as in the main US-Mexico border cities; however, according to the recent Energy Reform, it will be available in all Mexican territory soon. All the sampled vehicles use ULSD fuel.

Sampling protocol

Given their different geometries and operation characteristics, a sampling protocol for each tested vehicle was established on the basis of accessibility and safety conditions. Details of the protocol are included in the Supplemental Material. The protocol was intended to be continuously updated as needed by the project team before and during tests to adjust for whatever unexpected special requirements in the field. Samples were collected by directly coupling the engine emissions exhaust to the PEMS sampling lines with a flow exhaust SEMTECH-FEM meter containing a heated sample probe (to avoid condensation), a heated filter, a water/fuel trap, and a Nafion dryer. Dilution air was provided by an air pump connected to a water trap and a HEPA filter and directed to an exhaust conditioning unit also to prevent the formation of condensate. Engine speed, manifold absolute pressure (MAP), and intake air temperature were measured using a sensor array temporarily installed on an engine's compartment without modifying it. Additional details on the sampling setup are included in the Supplemental Material.

The working operations performed by the vehicles were discussed and reviewed with the vehicle operators before each test and were carefully recorded in the logbook. Sampling periods for each operation typically lasted about 10 minutes and were repeated at least three times for each vehicle. In between each of these tests, the off-road vehicles were stopped (without turning them off) and the data acquisition was confirmed and equipment safety conditions were reviewed. If any error conditions were detected, they were corrected before initiating the repetition of the next test. Due to the coincidence of the measurements program with the end of the raining season in Mexico, weather conditions were a constant concern during the planning and execution of the measurements; some of the scheduled measurements had to be interrupted and re-scheduled because of rain.

Once the vehicles were sampled without any after-treatment control technologies, some of them were selected for later installation of either a diesel particulate filter (DPF) or a partial-flow DPF (p-DPF) by a CARB-certified installation company and re-sampling. The WH, BD, and EX vehicles were installed with a wall-flow DPF with passive regeneration coated and vacuum brazed stainless steel, whereas the BH, TR, and EG had tinfoil substrate and ceramic wall-flow p-DPF. Particulate filters for off-road vehicles are currently not manufactured in Mexico; therefore, DPFs were imported from a professional manufacturer who recommended the selection of the DPFs and p-DPFs based on the vehicle technical specifications, engine data and temperature data loggers analyses obtained during the vehicle selection process. The installation of the emissions control devices typically lasted several hours and the vehicles were scheduled for re-sampling at a later day.

Due to time and budget constraints, however, for some of the vehicles it was not possible to fully replicate the sampling operating conditions used in the baseline (i.e., without control device) tests. As a result, measurements with emission control devices were obtained under the same operating conditions for the baseline tests only for the BH-1, EX, EG, and TR vehicles. For the BH-2, BD-1, BD-2, WL-1, and WL-2 vehicles, the measurements with emissions control device installed were obtained only during idling and ramping sampling conditions. During the sampling periods for BH-2 with emission control devices, the vehicle was stationary because of a flat tire. Furthermore, installing DPFs in the bulldozers and wheel loaders would require permanently modifying the vehicle, a request that was not granted by the owners. Consequently, for these vehicles the DPFs were only temporarily installed but not fit-secured (to avoid modifications to the exhaust system) and thus these vehicles could not be safely moved. Sampling ramping conditions thus consisted of asking the operator to push the pedal to maintain a specific engine speed for about 20-30 seconds in stationary conditions multiple times.

Data processing

Due to the high-time resolution (1 sec) of the measurements and the multiple parameters obtained by each of the PEMS systems, abundant databases of the emission characteristics of the sampled vehicles were obtained for each of the tested vehicles. Data quality assurance procedures suggested by Abolhasani et al. (2008) were followed for identification of errors and data flagging and removal. This included removing data from zero and span calibration periods and "freezing" data corresponding to periods of miscommunication between the analyzer and the engine data. During the sampling of the BD-2, a leakage in the sampling line system was detected and the data was removed for that period.

The sampling time amounted to more than 44,330 s (~10.7 hrs.) of raw data of which about 13% were deemed invalid during quality assurance (see Table 1). This is a relatively large percentage of data removed from the database but it is mainly the result of frequent data monitoring between tests for inspecting and correcting any safety conditions. Valid sampling size varied from about

33 minutes for the AC to about 107 minutes for the BH-1. Synchronization of multiple parameters is probably the most important challenge during the processing of high-time resolution real-world data obtained with PEMS (Sandhu and Frey, 2013). For synchronization of parameters between the PEMS, temporal trends of the targeted signal and ECOSTAR CO_2 concentrations were compared for periods of drastic change of emissions conditions (e.g., acceleration from idle conditions and calibration periods). A synchronization time was obtained as the shift needed to be applied to the PEMS data to match the initial rise (or decrease) in CO_2 during these changing conditions. The synchronization time was applied to all data corresponding to the sampling test, but varied between vehicles. Dry dilution air was controlled by the measuring team with the exhaust conditioning unit to establish the dilution ratio values (from 2 to 20) for each vehicle depending on the initial concentration levels displayed.

The calculation procedure of mass per time and fuel based emission factors using PEMS has been described in detail elsewhere (e.g., Frey et al., 2008c). Briefly, PEMS measure the dry basis exhaust pollutant mole fractions (y_i) (for ECOSTAR and AXION) and the BC mass concentration (C_{BC}) (for the AVL-MSS); pollutant mass per time emission rates for gases (m_i) are estimated as shown in eq 1 using the dry basis molar exhaust flow rate ($\dot{N}_e$), y_i, and the pollutant molecular weight (M_i):

$$\dot{m}_i = y_i \, M_i \, \dot{N}_e \qquad (1)$$

The BC mass per time emission rate shown in eq 2 is estimated using C_{BC}, $\dot{N}_e$, the molecular weight of the exhaust gas (M_e), and the density of the exhaust gas (ρ_e) under standard conditions:

$$\dot{m}_{BC} = C_{BC}\, M_e\, \dot{N}_e / \rho_e \qquad (2)$$

The AXION instrument uses a proprietary algorithm to estimate exhaust flow using engine operating data (engine speed, intake air temperature, and MAP), known engine and fuel properties, and exhaust gas concentrations following the method described by Vojtisek-Lom, M. and J.T. Cobb (1997). It was not possible to obtain data from the electronic control unit (ECU) of each vehicle because the interfaces are not standardized and the software needed to decode the data is proprietary. Thus, instead of using ECU data of mass air flow (MAF) and the air-to-fuel ratio (AFR) for estimating exhaust air flow, $\dot{N}_e$ was directly measured using the flow exhaust SEMTECH-FEM meter. Fuel-based emission factors for gaseous species (f_i) and BC (f_{BC}) are correspondingly estimated by eq 3:

$$f_{i,BC} = \dot{m}_{i,BC} / \dot{N}_e \left(y_{CO_2} + y_{CO}\right) M_f \qquad (3)$$

where M_f is the molecular weight of fuel (diesel) and y_{CO2} and y_{CO} are the mole fractions of CO_2 and CO, respectively. All emission factors are reported at standard conditions.

Results

Real-world emissions of off-road vehicles largely depend on the operating activities that often involve handling of materials with rapid maneuvers associated with rapid changes in engine loads. To illustrate this, Figure 1 shows an example of the type of emissions variability encountered during a typical working task for BH-2. The asphalt processing plant receives the raw material via off-road trucks that continuously dump it into a large flat area. The bulldozer task is to create a massive stockpile from which the material is fed into the plant's processing machinery by other equipment. Thus, the bulldozer's operating activities consisted of piling up the material by pushing it upwards (not carrying it) starting from the edge of the flat area to the top of the stockpile and then returning backwards to a place close to the starting point to repeat the cycle.

The corresponding emissions characteristics during the bulldozer's working task is shown in Figure 1 initiating with a forward acceleration that is associated with the largest peaks of CO, CO_2, NO_X and BC emissions. During the initial acceleration the engine speed is ramped from about 1,100 to 2,000 RPM in only 4 to 5 seconds but with limited load since there is not a lot of material being pushed; the vehicle then keeps moving forward at high engine speed for about 10 seconds and the material being pushed gradually accumulates in the bulldozer's bucket, therefore increasing the engine fuel consumption as reflected by the increase of CO_2 and NO_X emissions; as the slope moving upward starts to increase along with the material load, the operator progressively reduces the engine speed until it reaches the top of the stockpile; at this point all the emissions are in a downward trend until the operator starts moving backwards with a fast acceleration. Starting the second acceleration to return to the original position there is a second large peak observed in the CO and BC emissions but it is almost nonexistent in CO_2 and NO_X emissions. Mass contribution can be calculated by integrating the curve of time-based emission rates by operating condition. In this example, about 59 % and 86% of the BC and CO mass emissions for a given working cycle occur in the two short acceleration periods, respectively.

Thus, CO and BC seem to be more sensitive to rapid changes in engine speed even with small engine loads.

The large variability observed suggest that emission rates should be better characterized by their frequency distributions by operating activity, rather than by a single statistic. Figure 2 shows the time-based emission rates and fuel based emission factors frequency distributions of CO_2, CO, NO_X and BC for BD-2 during the pushing and earth-moving tasks. CO_2 time-based emission rates are bimodal corresponding to the backwards (with no load) and pushing forward (with load) movements. However, since most of the carbon from the combustion is converted to CO_2, the CO_2 fuel-based distribution is essentially centered on a constant value of about 3,130 g/kg fuel. Figure 2 shows that CO and BC distributions are mostly skewed towards lower values but with the presence of very large values that correspond to the short forward and backward acceleration periods. NO_X emission rates show wider spread but the distribution is less skewed than CO and BC's, being less sensitive to acceleration modes.

The example provided for BD-2 illustrates the complex emissions variability by operating mode and the need to use multiple statistics to better characterize the emission factors for off-road vehicles under real-world operating conditions. The frequency distributions of emission factors for the rest of the sampled vehicles and operating activities are shown in the Supplemental Material and are discussed in the next section. Tables 2 and 3 summarize the average, 25 and 75 percentiles of the time-based emission rates and fuel-based emission factors for the sampled vehicles without and with emission control devices installed, respectively.

Discussions

Variability among operating conditions

The measurement of emissions under real-world conditions captures the influence of multiple factors such as the working site's characteristics, materials handled, operations performed, fuel characteristics and even the operator's driving style; it is not surprising that substantial variability is observed in the results by operational cycle. The emission factors measured were highly dependent on the operation activities for each vehicle. Table 2 and the frequency distributions shown in Figures SM2, SM3 and SM4 in the Supplemental Material document indicate that although there are large differences in emission factors among vehicles, idling conditions present significantly lower values than the rest of the operating conditions for CO and BC but not for NO_X, for which the distributions were more similar among all conditions. The shape of the frequency distributions of emission factors varied for all vehicles; however, regardless of the vehicle type or engine size, CO and BC presented more skewed distributions during working conditions compared to idling conditions as a result of the rapid maneuvers and changes in engine loads. The presence of these short-term high emissions during working activities suggest that in most cases the representation of the emission conditions cannot be adequately obtained by a single statistic (e.g., average) of the emission factors. Thus the use of frequency distributions can be a more adequate method for representing the characteristics of emission factors in real-world operating conditions.

The results suggest that the rapidly-changing operating conditions for off-road vehicles can be characterized by obtaining the frequency distributions of emission factors. However, since the shape of the frequency distributions could be influenced by the sampling time considered in the analysis, it is important to normalize the sampling periods by operating condition. In this study, we pre-defined a set of operations (e.g., pushing, dragging, hammering, etc.) as working conditions for each tested vehicle in consultation with the vehicle operators to ensure that the defined operations are typical working activities for each type of vehicle. Sampling periods for each operation typically lasted about 10 minutes and were repeated at least three times for each vehicle to provide similar sampling size for each set of working activities. Figure 1 shows an example of the repeatability of the samplings during a defined working operating condition. As can be observed, the repeatability of the working operations creates a cycle in each sampling period representing the emission factors during an entire cycle of operation activities. The larger the number of cycles considered for each set of sampled operations, the more robust the frequency distribution represents the working conditions.

In general, the frequency distributions show that larger engines such as the wheel loaders and bulldozers presented higher values of emission factors than the vehicles with smaller engines. Nevertheless, the results show that even for the paired test vehicles with similar or identical engines (the backhoes, wheel loaders and bulldozers), there may be significant differences in emission factors that are at least partially related to operating conditions. This is also illustrated in the results from the two backhoes, of which BH-1 had higher emissions than BH-2 while performing similar earth dragging and piling operations with their large bucket, each vehicle being maneuvered by a different operator. However, the backhoes' emissions factors were very similar among them during working operations with the small bucket which required only lifting and dumping material while the vehicle is stationary and thus were less dependent on the operator's maneuvering skills.

In some occasions, it was possible to obtain measurements of the vehicle's emission factors while moving towards the test sampling site and then, after finishing the test, while returning to the mechanic shop to uninstall the sampling system. Thus, these represent conditions of moving the vehicles without performing a working activity other than transporting the sampling system and operator. This condition is listed as "Moving" in Table 2. It should be noted that in Mexico it is common that agriculture vehicles are transported relatively long distances from the towns to the working areas using them as transportation vehicles of field workers. However, the results in Table 2 indicate that these represent medium-to-high emission periods, particularly for NO_X, on occasions almost as high as during the working periods. This suggests that minimizing the use of off-road vehicles for transportation purposes would provide emission reduction benefits.

Frey et al. (2008b) found that fuel-based measurements of NO_X emission factors were more similar among different vehicles as compared to time-based emission rates. In our results, the coefficients of variation (CV) of the time-based emission rates for all sampled vehicles in working operating conditions are 2.1, 1.7, and 1.5 times higher than the corresponding CV for the fuel-based emission factors of CO, NO_X, and BC, respectively. This result confirms that there is substantially less variability of fuel-based emission factors when compared to time-based emission rates for gaseous and particulate pollutants. Thus, when normalized by fuel consumption (a surrogate parameter for the amount of work performed by the equipment/vehicle's engine) the emission of these combustion by-products is less sensitive to changes in engine load compared to the time-based emission rates. Therefore, fuel-based emission factors take into account changes in engine work. This suggests that emission inventories for off-road vehicles can be better estimated using fuel-based emission factors rather than time-based emission rates. The higher observed variability of time-based emission rates implies that their use for emissions inventory estimates would be considerably limited by the need of highly accurate time-based activity data on the vehicle operating conditions. Consequently, efforts for compiling activity data for emissions development purposes should focus on fuel consumption rates by operating conditions.

Emission factors with DPFs

As mentioned above, measurements of emission factors were further obtained for the sampled vehicles after an emission control device was installed by a CARB-certified installation company. In Table SM1 in the Supplemental Material document we have included a list of the type of emission control devices in each of the tested vehicles. As indicated above only for the BH-1, EX, EG, and TR vehicles the measurements with emission control devices were obtained with similar operating conditions used during baseline tests, whereas for the BH-2, BD-1, BD-2, WL-1, and WL-2 vehicles the measurements with emissions control installed were obtained only during idling and ramping engine conditions (see Table 3 and Figures SM5, SM6 and SM7 in the Supplemental Material). Therefore, for these vehicles the results represent emissions reductions soon after the installation of the control devices and not conditions of medium or full filter saturation cycles.

In general, the emission reduction benefits of control devices varied by pollutant and operating conditions. For the BH-1 vehicle the CO and BC average emission factors during working conditions were largely reduced (about 54% and 61%, respectively) with the p-DPF installed, whereas the average NO_X emission factor apparently increased about 20%. However, the frequency distributions show that the predominance of high values was reduced for CO and BC but not for NO_X. The p-DPF installed in the EG equipment produced very similar frequency distributions for CO and NO_X compared to the baseline (i.e., no reduction benefits) but with moderate (about 32%) reductions of the average BC emission factor, and with substantial reductions in the range of higher values in the BC distribution. Reductions of CO can be explained by the catalysis employed as the coating materials in the DPF enhancing the oxidation of the exhaust. The EX with the DPF vehicle presented a moderate reduction (about 18%) of the average NO_X emission factor and a very large reduction (about 99 %) of the BC emission factors and both distributions became more skewed towards lower values in comparison with the baseline.

The agricultural tractor presents an interesting case of the impacts of a p-DPF on emissions during working operating conditions. NO_X distributions are again similar between the emission control device-installed and the baseline tests, but the CO presented large reductions (about 85%) of the average emission factor and drastic reductions of high values in the distributions. However, whereas the average BC emission factor apparently showed an increase of about 14 %, the distributions showed that lower BC values are more predominant in the test with the device installed compared to the baseline test but that higher BC values are still present, largely skewing the distribution and thus increasing the average. This further illustrates the need for using frequency distributions rather than single statistics for characterizing the emission conditions of off-road vehicles. This suggests that the p-DPF device was only moderately effective in reducing the bulk of BC emissions but not in reducing the short-term high emission peaks that result from the rapid transients from the working operations of the tractor. A proper comparison of the predominance of BC high values would need to account for levels of engine load and speed but it is beyond the scope of this paper. In a companion study (Huertas et al., 2017) we present a detailed description of the impacts of installing the control devices on the emissions and its relation to fuel consumption, engine speed, and engine loads in the sampled vehicles.

Ramping conditions were tested for four vehicles with DPF installed (BD-1, BD-2, WL-1 and WL-2) and one with a p-DPF (BH-2). Unfortunately, since there were no ramping sampling conditions during the baseline measurements, it was not possible to quantify the emission reduction impacts for these vehicles, except for the idling conditions. Nevertheless, the distributions for the vehicles installed with DPF show that in all cases the BC emissions increased as the engine speed increased during ramping conditions but CO remained relatively low, whereas NO_X distributions show some trends towards reduced values during periods of increasing engine speed. In the case of the BH-2 with the p-DPF installed, both the CO and the BC emissions increased as the engine speed increased and NO_X emissions were also reduced. Reduction impacts on average BC emission factors for vehicles in idling conditions with p-DPF installed were of 36%, 21% and 38%, for the BH-1, BH-2, and TR, respectively; while the corresponding average BC reduction impacts for the vehicles with installed DPF (WL and BD) were closer to 99 % during idling conditions. We emphasize that the results with emissions control devices for ramped sampling conditions should not be considered as representative of actual operating conditions.

The results of lower BC emission reduction benefits of the p-DPF compared to the DPF devices agree with the results of studies dedicated to evaluate the efficiency of PM filtration efficiency (Johnson, 2010). Although the efficiency of active DPF has been reported to be above 90 % for removing PM, the filtration efficiency for p-DPF ranges from 30 to 75 % depending on the operating conditions (Mayer et al., 2009; Jacobs et al., 2006). On the other hand, despite the lower PM removal levels, p-DPF devices employ catalyzed metal wire mesh structures and do not require active regeneration or ash removal and its operation practically does not need maintenance. Similarly, the values presented by Durbin et al. (2013) in Table 4 for the five newer bulldozers are low for NO_X and very low for CO and PM emission factors. This is because these vehicles comply with EPA Tier 4i emission standards that are aiming to reduce PM, NO_X, and air toxics for off-road engines and have installed DPFs and selective catalytic reduction (SCR).

Comparison with other studies. The results from this study indicate that emission factors for off-road vehicles are better characterized by their frequency distributions as they give information on the range of predominant values by operating conditions, including the extremes. A proper comparison with other results would thus entail comparing their distributions. Since this information is not available, as a first comparison we focus on the results of the average emission factors reported in other studies by working operating conditions and by engine tier. Table 4 shows the comparison of our average fuel-based emission factors with those obtained by Frey et al. (2008a) and Durbin et al. (2013), which are the two major studies of off-road construction vehicles with similar characteristics and working operating conditions to those in this study. In general, the NO_X and CO average emission factors are of the same order of magnitude when accounting by tier group. However, the results indicate that the average black carbon emission factors from the sampled vehicles in this study were in general higher than the total PM emission factors estimated in the other two studies. As black carbon corresponds to a fraction of total particulate matter, the results suggest that both BC and PM estimated in the emissions inventories can be substantially higher during full operating cycles. However, more data on BC emission factors is needed to better estimate the extent of the contribution of the off-road vehicles fleet on overall BC emissions.

The PM values reported by Frey et al. (2008a) are in general smaller than the values in Table 4 reported by Durbin et al. (2013) even when accounting by tier group. However, the PM emission factors reported by Frey et al. (2008a) were obtained using a light-scattering (opacity) based instrument similar to AXION and, as reported by the authors, the values are not likely to be useful for estimating the magnitude of total PM but for assessing the relative emission differences among vehicles. Similarly, Abolhasani et al. (2008) measure three excavators of 1998, 2002, and 2001 model years and obtain average emission factors in working conditions of 34.3, 24.4, 34.9 g/kg-fuel for NO, 4.1, 9.8, 4.5 g/kg-fuel for CO, and 0.36, 0.23, 0.25 g/kg-fuel for opacity-based total particulate matter, respectively, which are of similar magnitude to those presented by Frey et al. (2008a) and the NO_X values in this study.

Comparison with EPA´s NONROAD emission factors. Currently, the EPA's NONROAD emission factors are the most widely used in the emission inventories from off-road vehicles. They are obtained following the ISO 8178 type C test, also referred as Non-Road Steady Cycle or NRSC, in which the engine is subjected to a sequence of steady-state operational modes on an engine test bench and emissions are measured and averaged using different weighting factors. NSCR emission factors are reported in EPA (2010a) as function of vehicle type, model year and engine nominal power. Aiming to improve the representation of the dynamic engine operation encountered in off-road vehicles, these emission factors are adjusted by a transient factor, a deterioration factor and an adjustment factor for variation in fuel's sulfur content (EPA, 2010b). The deterioration factors are estimated based on the vehicle accumulated working hours, the median life at full load and a load factor. The NSRC emission factors are expressed as mass rate emitted per brake engine power delivered (g/bhp-hr). However, they can be converted to fuel based emission factor using brake-specific fuel consumption (g/kg of fuel). The brake-specific fuel consumption data for the most common off-road vehicles are also reported in EPA (2010a).

We calculated the CO, NOx and PM NRCS adjusted emissions factors for the vehicles evaluated in this study (Table 5) and compared them to the PEMS's emission factors obtained for idling, moving and working operational modes (Figures SM8-10 in Supplemental Material). We found that NSRC and PEMS´s emission factors are different but of the same magnitude, regardless of the operational mode, pollutant considered, and vehicle type. However, correlation analysis among them showed that they are uncorrelated even after considering potential outlier data. The same observation was obtained when the correlation analysis was performed in terms of fuel-based emission factors. Abolhasani et al., (2008) report a similar comparison of the measurements of three excavators with the NONROAD calculated emission factors using the closest matching model years and engine size ranges. Their comparison also show reasonable agreement between the measured NO fuel-based emission factors and those obtained with the model, but more pronounced differences of up to 40% and 60% for HC and CO emission factors, respectively. The results for their light-scattering measurements of PM are much smaller (within an order of magnitude) to the NONROAD estimates. These results further highlight the need for additional experimental work to obtain real-world emission factors for comparing with certification test that may result in more accurate emission inventories.

Conclusions

We present the measurements of BC, CO, CO_2 and NO_X emission factors of selected in-use diesel-powered off-road mobile sources in Mexico under real-world operating conditions using PEMS. To our knowledge, this is the first time that the emissions from off-road vehicles have been measured in Mexico. The results showed that fuel-based emission factors have less variability than time-based emission factors, particularly for the BC, suggesting that fuel-based emissions factors would be more adequate for comparing different machinery and work duties than time-based emissions factors. The results indicated that the off-road vehicles in this study had significantly high PM emissions, but the sampling size is too small and thus it is not clear if this is a predominant feature of the Mexican fleet. Nevertheless, even with the limited number of sampled vehicles, the results showed the complexity of emission characteristics under real-world operating conditions and highlighted the need to account for the large variability observed in the emission factors during the estimation of emissions inventories. There is a need for more studies of the emission characteristics of off-road vehicles, particularly for the agricultural sector, in order to refine and increase the available datasets of emission factors for inventory purposes. Further studies are also needed for the comparison of field-based emissions factors and those derived from certification tests that are used as the basis for more comprehensive datasets in emissions models.

Our results indicated that, instead of using a single statistic, obtaining the frequency distributions of emission factors by operating conditions may be an adequate method for characterizing the emissions of off-road vehicles. Given the large variability often encountered in real-world operating conditions, the emission factors distributions may be useful for comparing emissions among vehicles and for evaluating the impacts of emission control reduction technologies. The observed variability in measured emissions factors also suggests the need for detailed vehicle operation data (fuel consumption data by operating condition) for accurately estimating emissions from off-road vehicles. In this regard, the use of frequency distributions of fuel-based emissions factors may be a viable approach for estimating emissions from off-road vehicles. Frequency distributions of both emission factors and activity data could be used in any of several available uncertainty propagation methods such as Monte Carlo and bootstrap simulation in bottom-up emissions inventory developments for the quantification of uncertainties. Further work could be done in principle to increase the sampling size of vehicles tested and eventually obtain probability density functions for establishing probability-based ranges of emissions inventories.

Emissions control devices were installed in some of the same sampled vehicles and their emissions were characterized again to test the efficiency of the control devices, but only in a few of the sampled vehicles the samplings were performed under similar operating conditions. Under these limitations, the results indicate that the reductions for black carbon emission factors were significantly large (above 99%) when DPFs were installed and the vehicles were idling, and the reductions were moderate (in the 20-60% range) when p-DPFs were installed and the vehicles were in working operating conditions. Given the potentially large emission reductions involved, there is a strong need to further study the emission benefits of control technology for retrofitting diesel-powered vehicles in Mexico.

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Disclaimer: The use of U.S. EPA NONROAD model in this paper is for illustrative purposes and should not be considered as an evaluation of the model's performance.

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Table 1. Summary of sampled vehicle characteristics.

Code	Equipment	Engine manufacturer	Tier	Model year	HP[1]	RPM[2]	Cyl.[3]	Disp. (L)	Hours of operation	Site[4]	Raw data (sec)	Valid data (%)
BH-1	Backhoe	Komatsu	2	2007	96	2200	4	4.5	1,397	APP	6,428	85.1
BH-2	Backhoe	Komatsu	2	2007	96	2200	4	4.5	2,306	AEP	4,806	83.2
BD-1	Bulldozer	Komatsu	3	2008	360	1900	6	15.24	7,504	APP	2,901	84.9
BD-2	Bulldozer	Caterpillar	3	2008	312	1850	6	15.2	1,482	AEP	3,507	89.4
WL-1	Wheel loader	Komatsu	3	2010	531	1800	6	23.15	9,851	APP	4,120	79.8

WL-2	Wheel loader	Komatsu	3	2010	531	1800	6	23.15	10,323	AEP	3,543	86.0
CR	Crane	Linkbelt Hitachi	3	2009	182	2000	6	7.5	5,974	BCS	2,206	88.6
EX	Excavator	Volvo	3	2010	198	1700	6	12.1	3,289	AEP	2,713	96.2
TR	Tractor	New Holland	3	2008	110	2200	4	4.5	NA	ASF	3,191	92.5
AC	Air compressor	Cummins	1	1999	216	1800	6	7	NA	AEP	1,973	79.9
EG	Generator	Cummins	3	2010	32	1500	4	3.9	NA	AEP	3,056	96.9

[1]Rated horsepower. [2]Engine speed at rated horse power. [3]Number of cylinders. [4]Sampling sites APP: Asphalt-processing plant; AEP: Asphalt-excavation plant; BCS: Building construction site; ASF: Agricultural soil field.

Table 2. Summary of emissions factors for the sampled vehicles without emissions control technology.[a]

Code	Operation	CO_2 [g/s]	CO [mg/s]	NO_X [mg/s]	BC [mg/s]	CO [g/kg]	NO_X [g/kg]	BC [g/kg]
BH-1	Idling	1.48 (1.4, 1.5)	2.6 (2, 3)	46.1 (44, 48)	0.038 (0.03,0.04)	5.7 (5, 7)	98.9 (97, 101)	0.081 (0.07, 0.08)
	Working with big bucket	8.22 (7.2, 8.9)	40.0 (17, 46)	82.7 (73, 92)	11.9 (3, 12)	16.4 (6, 19)	32.2 (28, 36)	4.83 (1.0, 4.4)
	Working with small bucket	7.17 (6.7, 7.7)	8.7 (6, 11)	74.3 (71, 78)	2.2 (2, 3)	3.9 (3, 5)	33.2 (31, 35)	0.99 (0.7, 1.1)
	Moving	3.62 (3.0, 4.2)	3.7 (2, 4)	62.0 (56, 69)	1.7 (0.6, 2.6)	2.9 (2, 3)	58.2 (50, 64)	1.22 (0.5, 1.7)
BH-2	Idling	1.72 (1.7, 1.7)	5.5 (4, 7)	47.8 (47, 49)	0.026 (0.02, 0.03)	10.0 (7, 12)	87.0 (84, 89)	0.047 (0.04, 0.05)

	Working with big bucket	5.09 (3.5, 5.7)	16.7 (6, 13)	85.3 (73, 95)	2.43 (0.3, 3.0)	9.4 (5, 10)	59.0 (46, 72)	1.75 (0.2, 2.1)
	Working with small bucket	5.14 (4.4, 5.8)	8.0 (6, 9)	84.3 (76, 94)	1.91 (0.6, 2.8)	5.1 (4, 6)	52.3 (48, 57)	1.20 (0.4, 1.8)
BD-1	Idling	2.27 (2.2, 2.3)	6.8 (5, 8)	32.5 (32, 33)	2.00 (1.9, 2.1)	9.3 (8, 11)	41.7 (41, 46)	2.79 (2.6, 2.9)
	Working	19.35 (10.9, 27.1)	261.9 (27, 108)	115.4 (77, 145)	19.6 (5, 18)	40.6 (4, 20)	22.4 (13, 27)	2.87 (1.3, 2.4)
	Moving	6.83 (6.5, 7.3)	24.3 (21, 26)	61.6 (60, 64)	1.69 (1.2, 1.9)	12.0 (11, 13)	32.0 (31, 33)	0.67 (0.5, 0.8)
BD-2	Idling	2.57 (2.4, 2.7)	5.3 (5, 6)	134.3 (129, 136)	0.082 (0.07, 0.09)	6.5 (6, 7)	165.9 (159, 178)	0.100 (0.09, 0.11)

	Backing	12.58 (7.9, 13.9)	19.3 (6, 23)	317.5 (265, 334)	5.4 (2, 7)	4.2 (2, 6)	89.6 (65, 112)	1.18 (0.8, 1.4)
	Pushing	21.83 (17.6, 26.0)	38.3 (27, 49)	480.1 (419, 557)	18.5 (12, 23)	5.8 (4, 7)	73.8 (62, 73)	2.76 (1.8, 3.3)
	Working	17.79 (11.2, 23.2)	44.8 (25, 60)	422.5 (295, 513)	13.4 (3, 19)	7.9 (6, 10)	81.8 (64, 94)	2.18 (0.9, 2.7)
WL-1	Idling	25.77 (24.7, 26.8)	57.4 (29, 85)	220.2 (215, 226)	6.5 (6, 7)	7.0 (3, 10)	27.1 (25, 28)	0.80 (0.7, 0.9)
	Working	55.95 (46.9, 65.7)	6,395.2 (1300, 8700)	257.5 (186, 300)	117.2 (8, 107)	285.7 (67, 387)	12.6 (9, 15)	5.32 (0.4, 5.1)

	Moving	53.06 (45.9, 60.9)	173.5 (18, 181)	191.3 (161, 218)	22.8 (11, 29)	10.2 (1, 10)	12.1 (8, 17)	1.33 (0.7, 1.6)
WL-2	Idling	27.89 (25.3, 30.4)	48.3 (25, 65)	230.6 (218, 247)	6.8 (5, 7)	5.2 (3, 7)	26.5 (26, 27)	0.76 (0.7, 0.8)
	Working	51.02 (46.2, 55.6)	1033.6 (220, 1230)	252.3 (206, 269)	92.3 (12, 95)	62.6 (13, 78)	15.5 (12, 17)	5.68 (0.7, 5.9)
	Loading truck	50.98 (48.2, 57.4)	1557.1 (460, 2120)	301.2 (232, 361)	101.9 (24, 118)	108.5 (26, 135)	19.8 (13, 22)	10.50 (1.4, 7.7)
	Moving	45.10 (35.5, 58.1)	428.7 (70, 470)	219.9 (160, 250)	43.0 (12, 44)	29.6 (6, 35)	16.6 (11, 19)	2.97 (0.8, 2.8)

CR	Idling	NA	NA	18.1 (17.9, 18.3)	0.08 (0.07, 0.09)	NA	NA	NA
	Working	NA	NA	51.3 (46.9, 55.9)	7.56 (0.8, 10.0)	NA	NA	NA
EX	Idling	4.97 (4.9, 5.1)	NA	48.9 (48, 50)	0.070 (0.06, 0.08)	NA	31.9 (31, 32)	0.045 (0.04, 0.05)
	Working	16.28 (16.0, 16.6)	NA	163.4 (161, 167)	4.30 (3.8, 4.5)	NA	31.2 (31, 32)	0.84 (0.7, 0.9)
TR	Idling	1.15 (1.0, 1.2)	18.7 (10, 29)	12.7 (12, 13)	0.014 (0.01, 0.02)	48.6 (30, 74)	34.3 (32, 36)	0.038 (0.03, 0.04)
	Working	3.51	32.6	33.2	0.54	34.7	32.5	0.56

		(2.9, 4.1)	(12, 46)	(28, 37)	(0.1, 0.4)	(14, 46)	(25, 37)	(0.1, 0.3)
	Moving	2.79 (2.0, 3.5)	29.8 (14, 40)	26.8 (19, 33)	0.45 (0.1, 0.3)	63.4 (33, 80)	31.7 (21, 38)	0.43 (0.08, 0.2)
AC	Working	5.74 (5.6, 5.8)	18.4 (17, 19)	45.2 (43, 46)	1.58 (1.4, 1.7)	10.1 (10, 11)	24.9 (23, 26)	0.87 (0.8, 0.9)
EG	Working	2.04 (2.02, 2.08)	35.0 (34, 36)	35.7 (35, 37)	0.025 (0.02, 0.03)	53.0 (52, 54)	54.1 (54, 55)	0.038 (0.03, 0.04)

[a] Values represent averages whereas the numbers in parenthesis are the 25 and 75 percentiles . Average CO_2 fuel emission factor for all vehicles is 3,120 g/kg-fuel with a 3% standard deviation.

Table 3. Summary of emissions factors for sampled vehicles with emissions control technology.[a]

Code (Device)	Operation	CO_2 [g/s]	CO [mg/s]	NO_X [mg/s]	BC [mg/s]	CO [g/kg]	NO_X [g/kg]	BC [g/kg]
BH-1 (p-DPF)	Idling	1.58 (1.5, 1.6)	2.2 (2, 3)	48.3 (47, 50)	0.026 (0.02, 0.03)	4.4 (3, 6)	96.2 (88, 103)	0.052 (0.05, 0.05)
	Working with big bucket	5.50 (4.7, 6.4)	11.7 (4, 14)	64.6 (57, 73)	2.90 (0.6, 2.3)	7.6 (2, 8)	38.5 (32, 43)	1.89 (0.3, 1.4)
	Moving	4.35 (3.9, 4.8)	3.5 (2, 5)	65.7 (60, 74)	0.78 (0.5, 0.9)	2.9 (2, 4)	47.6 (42, 50)	0.503 (0.36, 0.57)
BH-2 (p-DPF)	Idling	0.75 (0.5, 0.9)	4.0 (3, 5)	18.6 (13, 24)	0.008 (0.005, 0.010)	16.1 (15, 17)	72.9 (72, 73)	0.037 (0.02, 0.05)

	Ramping (1060-1300)	1.48 (1.4, 1.6)	5.3 (4, 6)	29.2 (25, 33)	0.029 (0.02, 0.04)	9.6 (9,11)	58.0 (52, 65)	0.056 (0.04, 0.07)
	Ramping (1400-1530)	1.86 (1.8, 2.0)	3.7 (2, 5)	32.3 (30, 36)	0.050 (0.04, 0.06)	6.8 (6, 8)	52.9 (48, 58)	0.080 (0.06, 0.09)
	Ramping (1690-1840)	2.02 (1.8, 2.3)	7.3 (4, 11)	32.5 (25, 43)	0.092 (0.06, 0.11)	12.7 (11, 14)	47.3 (36, 60)	0.132 (0.08, 0.14)
	Ramping (1910-1960)	2.89 (2.8, 3.0)	4.0 (3, 5)	28.0 (26, 30)	0.139 (0.13, 0.15)	5.9 (4, 7)	29.0 (26, 32)	0.142 (0.13, 0.15)
	Ramping (2140-2330)	2.81 (2.3, 3.4)	9.8 (4, 13)	41.4 (33, 51)	0.235 (0.16, 0.29)	12.8 (9, 14)	44.6 (31, 62)	0.236 (0.16, 0.27)

BD-1 (DPF)	Idling	3.25 (3.1, 3.3)	3.0 (2, 4)	20.0 (19, 20)	0.018 (0.02, 0.02)	2.8 (2, 3)	18.8 (18, 19)	0.017 (0.02, 0.02)
	Ramping (1250-1280)	7.57 (7.4, 7.6)	6.2 (4, 7)	67.3 (64, 71)	0.005 (0.005, 0.006)	2.8 (2, 3)	26.6 (25, 28)	0.002 (0.002, 0.002)
	Ramping (1600-1630)	12.75 (12.6, 12.8)	9.2 (7, 10)	103.2 (101, 104)	0.012 (0.011, 0.013)	2.2 (2, 2)	24.6 (24, 24)	0.003 (0.003, 0.003)
	Ramping (1860-1865)	17.34 (16.9, 17.5)	10.5 (8, 12)	128.0 (123, 130)	0.032 (0.03, 0.04)	1.8 (1, 2)	22.1 (21, 22)	0.006 (0.005, 0.006)
BD-2 (DPF)	Idling	2.43 (2.3, 2.4)	3.3 (2, 4)	25.1 (15, 35)	0.001 (0.001, 0.001)	4.3 (2, 5)	33.2 (21, 46)	0.001 (0.001, 0.002)

	Ramping (960-965)	3.74 (3.6, 3.8)	2.2 (1, 3)	46.3 (43, 48)	0.002 (0.002, 0.002)	1.8 (1, 2)	39.0 (36, 40)	0.002 (0.001, 0.002)
	Ramping (1020-1050)	4.11 (3.9, 4.2)	3.6 (3, 4)	37.7 (34, 37)	0.002 (0.002, 0.003)	2.8 (2, 4)	28.8 (27, 28)	0.002 (0.001, 0.002)
	Ramping (1500-1510)	7.15 (7.3, 7.5)	6.7 (5, 8)	44.0 (37, 44)	0.003 (0.003, 0.004)	3.1 (2, 4)	19.8 (15, 21)	0.002 (0.001, 0.002)
	Ramping (1750-1800)	9.60 (9.8, 10.4)	8.9 (5, 10)	55.8 (40, 65)	0.008 (0.007, 0.008)	3.0 (2, 3)	19.3 (13, 23)	0.003 (0.002, 0.003)
	Ramping (2190-2210)	14.48 (14.4, 15.3)	22.1 (5, 17)	93.0 (56, 115)	0.024 (0.02, 0.03)	5.2 (1, 3)	21.5 (12, 23)	0.005 (0.004, 0.006)

WL-1 (DPF)	Idling	5.69 (5.6, 5.8)	6.2 (5, 8)	55.2 (44, 55)	0.004 (0.004, 0.005)	3.5 (3, 4)	30.2 (25, 30)	0.002 (0.002, 0.003)
	Ramping (1190-1220)	10.35 (10.1, 10.7)	12.5 (10, 15)	97.7 (90, 106)	0.010 (0.01, 0.01)	3.9 (3, 5)	29.8 (28, 32)	0.003 (0.002, 0.003)
	Ramping (1505-1510)	15.09 (14.9, 15.3)	15.6 (12, 19)	229.3 (180, 297)	0.012 (0.01, 0.01)	3.2 (3, 4)	47.8 (37, 63)	0.002 (0.002, 0.003)
	Ramping (1790-1815)	21.55 (21.3, 21.8)	21.1 (19, 24)	347.1 (326, 370)	0.039 (0.03, 0.04)	3.1 (3, 3)	50.8 (47, 54)	0.006 (0.005, 0.006)
WL-2 (DPF)	Idling	5.95 (5.6, 6.4)	4.7 (3, 6)	46.5 (44, 48)	0.005 (0.004, 0.006)	2.6 (2, 4)	24.5 (23, 25)	0.003 (0.002, 0.003)

	Ramping (1210-1230)	9.51 (8.6, 10.5)	17.4 (10, 18)	64.0 (57, 71)	0.011 (0.01, 0.01)	5.8 (3, 6)	21.3 (19, 22)	0.004 (0.003, 0.004)
	Ramping (1265-1275)	12.24 (11.5, 13.3)	43.1 (17, 52)	128.1 (124, 138)	0.056 (0.04, 0.05)	10.6 (4, 12)	32.9 (31, 35)	0.015 (0.01, 0.02)
	Ramping (1490-1500)	14.04 (12.9, 15.4)	30.3 (12, 23)	90.9 (85, 99)	0.022 (0.02, 0.03)	6.9 (2, 6)	20.5 (19, 20)	0.005 (0.004, 0.006)
	Ramping (1515-1545)	15.13 (14.8, 16.1)	13.3 (9, 14)	176.0 (173, 195)	0.223 (0.14, 0.28)	2.9 (2, 3)	36.2 (32, 40)	0.044 (0.03, 0.05)
	Ramping (1790-1805)	21.13 (19.7, 22.4)	61.3 (15, 55)	140.0 (123, 153)	0.387 (0.32, 0.46)	9.5 (2, 7)	21.2 (18, 22)	0.057 (0.05, 0.06)

EX (DPF)	Idling	8.13 (8.0, 8.3)	5.6 (4, 8)	78.4 (72, 86)	0.005 (0.004, 0.007)	2.1 (1, 3)	30.3 (28, 33)	0.002 (0.002, 0.003)
	Working	18.24 (17.2, 19.4)	6.7 (3, 13)	147.3 (138, 154)	0.033 (0.02, 0.04)	1.2 (0.4, 2)	25.6 (24, 26)	0.005 (0.003, 0.007)
	Moving	19.83 (18.3, 21.3)	5.5 (4, 7)	145.4 (130, 160)	0.028 (0.02, 0.03)	0.8 (0.5, 1)	23.5 (22, 24)	0.004 (0.003, 0.005)
TR (p-DPF)	Idling	1.02 (0.9, 1.0)	5.3 (1, 10)	11.2 (11, 12)	0.012 (0.01, 0.01)	16.1 (3, 32)	33.6 (33, 35)	0.035 (0.03, 0.04)
	Working	2.69 (2.1, 3.2)	4.1 (1, 4)	24.3 (21, 28)	0.670 (0.12, 0.58)	5.2 (1, 5)	29.2 (26, 32)	0.642 (0.10, 0.43)

	Moving	2.19 (1.7, 2.6)	6.7 (2, 7)	20.7 (17, 24)	0.308 (0.06, 0.23)	17.6 (6, 19)	28.8 (23, 33)	0.379 (0.06, 0.20)
EG (p-DPF)	Working	2.11 (2.0, 2.2)	36.4 (36, 37)	36.4 (36, 37)	0.018 (0.02, 0.02)	53.0 (52, 54)	53.1 (53, 53)	0.026 (0.02, 0.03)

[a] Values represent averages whereas the numbers in parenthesis are the 25 and 75 percentiles . Average CO_2 fuel emission factor for all vehicles is 3,050 g/kg-fuel with a 3% standard deviation.

Table 4. Comparison of average fuel-based emission factors [g/kg-fuel] with other studies.

	Tier	**This study** [d.]				**Frey et al., (2008)**				**Durbin et al., (2013)**			
		MY	**NO_X**	**CO**	**BC**	**MY**	**NO_x**	**CO**	**PM** [a]	**MY**	**NO_x**	**CO**	**PM**
Backhoes	0					1997	35.2	25	0.35				
	1					1999	31.4	12	0.35				
						1999	52.1	19	0.25				
						2000	26	7.3	0.67				
						2001	33.7	11	0.35				

						2004	39.4	21	0.06	2006	29.7	8.7	0.72
	2	2007	32.2	16.4	4.83	2004	54.6	3.5	0.25	2006	26.7	11	0.68
		2007	59.0	9.4	1.75	2004	53.3	8.6	0.29	2007	27.4	13	0.79
	3									2010	17.6	7.2	5.06
Bulldozers	0					1988	57.2	19	0.41				
						1995	64.8	18	NA				
	1					1998	67.9	16	0.32				
						200	37.8	17	0.19				

						2							
	2					2003	52.4	39	0.48	2003	27	4.9	0.96
						2005	29.8	13	0.25				
	3	2008	22.4	40.6	2.87								
		2008	81.8	7.9	2.18								
		2008[c]	22.1	1.8	0.01								
		2008[c]	21.5	5.2	0.01								
	4i									2011[b]	10.1	2.3	0.002
										2011[b]	9.7	-0.5	0.001

							2012[b]	7.6	-0.4	0.002
							2012[b]	9.5	-0.7	0.006
							2012[b]	8.5	-0.7	0.001
Wheel loaders	1		2002	41.9	13	0.29	2004	24.7	11	0.67
			2002	56.8	12	0.19				
			2002	46	4.1	0.32				
	2		2004	36.2	14	0.29				

			2005 33 11 0.19	
	3	2010 12.6 286 5.34 2010 15.5 62.6 5.68		2007 25 16 0.71 2009 29 19 4.73 2011 31.3 15 1.77 2011 17.6 8.1 0.99 2011 16.8 8.6 1.66
Excavators	1		1998 41.9 8.3 0.25 2001 46 7.3 0.32	
	2		2003 23.2 8.6 0.22	

	3	2010 31.2 NA 0.84		2006 15.3 5 1.52 2007 15.3 5.8 0.63 2008 17.1 18 2.23 2011 18.8 5.7 0.93

[a] Particle matter values were obtained with light-scattering (opacity) measurements and thus are semi-quantitative.

[b] These vehicles were equipped with DPFs and SCR.

[c] Values obtained for maximum RPM ramping conditions with DPF installed (no SCR).

[d.] Without using emissions control devices, except as noted in c.

Table 5 Corresponding adjusted NSCR fuel-based emission factors for the vehicle types in this study.

Vehicle type	CO (g/kg)	NOx (g/kg)	PM (g/kg)
Backhoe 1	33.1	28.0	1.4
Backhoe 2	33.2	28.0	1.4
Bulldozer 1	13.3	15.7	1.2
Bulldozer 2	14.3	15.7	1.3
Wheel loader 1	13.6	18.2	1.0
Wheel loader 2	13.6	18.2	1.0
Excavator	0.3	15.7	0.9

Tractor	13.8	15.7	0.9
Air compressor	5.0	18.2	1.5
Generator	8.6	34.5	1.1

Figure 1. Time-based CO_2, CO, NO_X, and BC emissions rates and corresponding engine speed (RPM) for a bulldozer (BH 2) during a pushing and moving material operation task. F: Pushing forward; B: Moving backward.

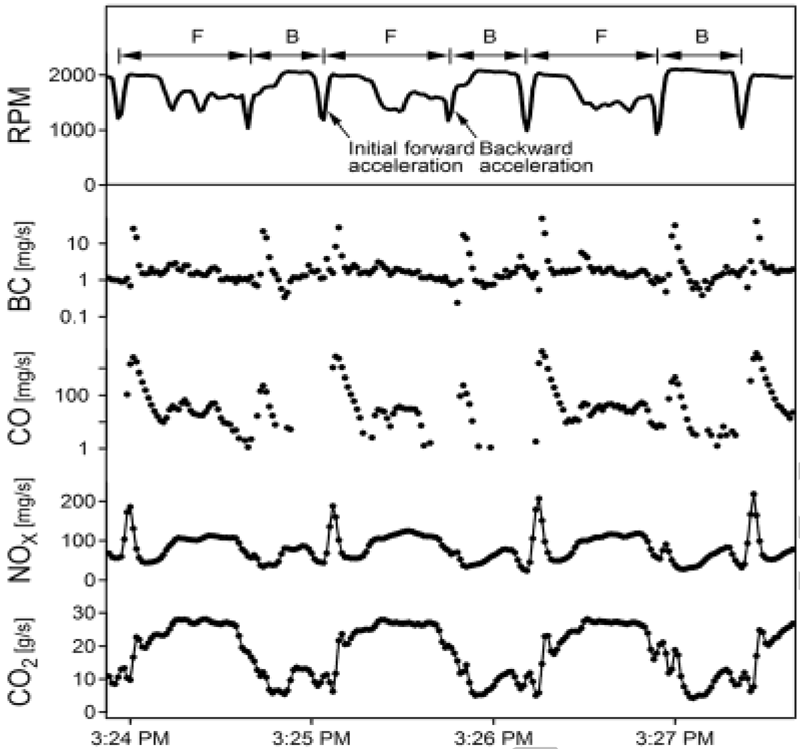

Figure 2. Time-based (grey-filled bars, bottom axes) emission rates and fuel-based (dark transparent bars, top axes) emission factors frequency distributions for CO_2, CO, NO_X, and BC of Bulldozer 2 during an earth pushing working task.