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Characterization of the emissions impacts of hybrid excavators with a portable emissions measurement system (PEMS)-based methodology

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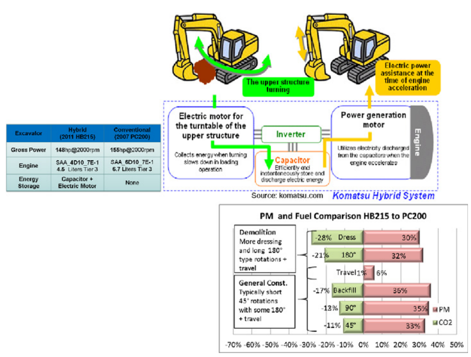
HIGHLIGHTS

- The activities for 4 excavators were characterized using engine control module (ECM) and GPS data, videos, and interviews.
- The activity measurements were used to develop duty cycles for repeatable comparisons.
- A total 7 excavators were evaluated for emissions and fuel consumption over the developed duty cycles using PEMS.
- The hybrid showed reductions in CO_2 emissions (−16%), butincreased PM (+26%) and NOx emissions (+1%).

GRAPHICAL ABSTRACT



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ABSTRACT

Hybrid engine technology is a potentially important strategy for reduction of tailpipe greenhouse gas (GHG) emissions and other pollutants that is now being implemented for off-road construction equipment. The goal of this study was to evaluate the emissions and fuel consumption impacts of electric-hybrid excavators using a Portable Emissions Measurement System (PEMS)-based methodology. In this study, three hybrid and four conventional excavators were studied for both real world activity patterns and tailpipe emissions. Activity data was obtained using engine control module (ECM) and global positioning system (GPS) logged data, coupled with interviews, historical records, and video. This activity data was used to develop a test cycle with seven modes representing different types of excavator work. Emissions data were collected over this test cycle using a PEMS. The results indicated the HB215 hybrid excavator provided a significant reduction in tailpipe carbon dioxide (CO_2) emissions (from −13 to −26%), but increased diesel particulate matter (PM) (+26 to +27%) when compared to a similar model conventional excavator over the same duty cycle.

1. Introduction

The relative contribution of emissions from off-road equipment to emissions inventories has been increasing worldwide, as emissions from on-road engines have declined over the past several decades (Dallmann et al., 2010; Cao et al., 2016a, b). According to the U.S.

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Environmental Protection Agency (EPA)'s recent emissions inventory data, off-road diesel equipment is estimated to be the third largest source for nitrogen oxides (NO_x) emissions and second largest source for particulate matter (PM) emissions, representing 14.5% and 24.3%, respectively, of total NO_x and PM emissions from mobile sources (US EPA, 2013). A European study found that non-road machines made up about 31% and 42%, respectively, of total annual NO_x and PM emissions from diesel power vehicles in Finland in 2014 (Pirjola et al., 2017). Wang et al. (2016) found that in China off-road equipment emitted more $PM_{2.5}$ than all of the on-highway vehicles combined, and suggested that real world emissions and activity data for off-road equipment is "desperately needed". In Korea, Lim et al. (2009) evaluated engine dyno test cell emissions data over the non-road C1–8 mode duty cycle from 445 pieces of older Tier 2 emissions level equipment in an effort to update their emissions factors. They compared these results to the emissions factors being used by EPA at the time.

Thus far, there is limited real-world emissions data for off-road equipment, especially in comparison to the amount of data available for on-road vehicles. Studies of construction equipment have been carried out over the years using different generations of Portable Emissions Measurement Systems (PEMS). The EPA and its collaborators conducted an extensive study of activity patterns and emissions on a fleet of mostly Tier 2 and older construction equipment using a PEMS from Sensors Inc. (Kishan et al., 2012; Giannelli et al., 2010; Warila et al., 2013). These studies included bulldozers, excavators, loaders, concrete saws, cranes, forklifts, graders, drillers, compactors, and a telescopic handlers. A key finding of this work was that they found large differences of in-use emissions factors compared to certification levels. Frey and coworkers measured emissions from off-road construction equipment using a CATI Montana PEMS system (Abolhasani et al., 2008, 2013; Frey et al., 2003, 2008a, 2008b, 2010a, 2010b; Lewis et al., 2009a, 2009b, 2011, 2012; Pang et al., 2009; Rasdorf et al., 2010); the majority of their data was for Tier 0 to Tier 2 equipment. The University of California at Riverside (UCR) has also conducted several studies to characterize emissions and activity patterns of construction equipment (Huai et al., 2005; Cao et al., 2016a). This included activity measurements from 18 pieces of model year 2000 and older non-road equipment (Huai et al., 2005) and activity and emissions measurements from newer Tier 3 and Tier 4i construction equipment with an AVL PEMS (Cao et al., 2016a).

More recently, electric hybrid configurations are being implemented in off-road equipment (Johnson et al., 2013). Very few in-use emission studies have been conducted on hybrid off-road equipment. Sokolsky et al. (2011) evaluated the fuel consumption and productivity of a diesel-electric bulldozer against selected conventional bulldozers; however, no emissions were measured. Block et al. (2012) measured emissions in-use from a hybrid excavator using a Sensors PEMS. Engine control module (ECM) data was not logged in this study; and no data was released. At this early stage of deployment, fuel consumption and emissions evaluations are needed to assess the true in-use emissions and fuel impacts of off-road equipment hybridization.

The goal of this study was to evaluate real-world, in-use emissions and fuel consumption reductions from hybrid off-road construction equipment in comparison to conventional alternatives using a PEMS-based methodology. This included evaluating differences in emissions for hybrid and conventional equipment for different types of in-use operation. Traditionally, off-road engines are certified on engine dynamometers on a brake-specific emissions basis on generalized steady state and transient duty cycles that do not reflect the usage of any particular type of off-road equipment. Evaluating in-use hybrid systems is complex because these systems operate differently from the baseline systems that they are being compared to. As such, there are differences in the amount of fuel used in addition to emissions changes. Many hybrid systems are evaluated on a per unit of activity basis. For heavy duty applications, the activity could be on a ton-mile basis (Code of Federal Regulations, 2015), ton-material basis, or simply on a per time basis where the material moved is kept the same for the different pieces of equipment being tested.

As a case study, UCR's College of Engineering, Center for Environmental Research and Technology (UCR CE-CERT) evaluated the performance of three hybrid and four conventional excavators. The excavators included three Komatsu HB215 hybrids, two Komatsu PC200s, and two Komatsu PC220s. This study was part of a larger evaluation of hybrid off-road equipment that included an evaluation of diesel-electric Caterpillar D7E dozers, which is discussed in detail elsewhere (Johnson et al., 2013). Activity measurements were made on a subset of three hybrids and one comparable conventional piece of equipment in order to characterize the typical operation of different units. Activity data were obtained using real-time ECM broadcast data, and real-time global positioning system (GPS) data, coupled with interviews, historical records, and time-lapse video. The collected activity data were used to develop duty cycles to allow accurate comparisons between the hybrid and conventional equipment. A subset of three hybrid and four conventional excavators were evaluated for emissions and fuel consumption over the developed duty cycles using a 40 CFR 1065 approved PEMS (Code of Federal Regulations, 2011).

2. Methodology

2.1. Test vehicles and fleet selection

A total of seven excavators were recruited for activity measurement and emissions testing. A list of excavators, including their engine information, model year, and fleet owner is provided in Table 1. It should be noted that the equipment covered a range of engine hour accumulation from 245 to 3516 h, so the equipment was more representative of the early stages of equipment life. The test matrix was developed to provide data for conventional excavators that are most comparable to the HB215 hybrid excavator. The hybrid HB215 utilizes an energy storage system that recovers energy that would otherwise be lost as the upper structure slows its rotation. The kinetic energy in the upper body swing is converted to electricity, sent through an inverter, and stored in a capacitor. The energy in the capacitor is available subsequently to power the superstructure swing-motor and to assist the diesel engine under higher engine speed or torque operation. The excavator utilizes short-term energy storage to provide short bursts of power, thus it was not necessary to monitor the capacitor's state of charge. The HB215 is the hybrid version of the conventional PC200, and both are certified to the Tier 3 emissions level. The engines in these excavators are equipped with exhaust gas recirculation (EGR), but not exhaust aftertreatment systems, with the exception of a diesel oxidation catalyst (DOC). This study also included two PC220 excavators. The PC220 excavators have the same engine displacement as the PC200, but are much larger machines than both the HB215 and PC 200 in terms of power, capacity, and exterior dimensions.

The first hybrid excavator was rented to a general construction company performing ground work for a hospital building project near Lancaster, California. The second, third, and fourth excavators were rented to a private general construction company performing ground work at a car wash site near Ft. Hunter Liggett, California. The fifth, sixth, and seventh excavators were rented to a general construction company performing demolition work at a housing project near Escondido, California.

2.2. Activity characterization methods

Excavator activity measurements were made at all three facilities on a subset of three hybrid units and one conventional unit (Table 1). Two time-lapse cameras were mounted on each unit, and a GPS and an ECM logger were placed in the cab for the in-use data collection. One camera was mounted on the front of the equipment and the other on the rear. The two cameras provided views of both front and rear operations to

Table 1
Detailed excavator model, fleet owners, model year, and engine information of excavators studied in this paper.

ID	Unit model	Site[b]	Eng model	Disp	Year	Eng hr[a]	Gross power[c]		Activity	Emissions
#	n/a	n/a	n/a	Liters	n/a	hr	kW	r/min	n/a	n/a
1	HB215	Hospital (RM)	SAA4D107E-1	4.5	2011	245	110	2000	Yes	Yes
2	PC200	Car wash (DD)	SAA6D107E-1	6.7	2007	2097	116	2000	Yes	Yes
3	HB215	Car wash (DD)	SAA4D107E-1	4.5	2011	245	110	2000	Yes	Yes
4	PC220	Car wash (DD)	SAA6D107E-1	6.7	2006	2228	134	2000	No	Yes
5	PC220	Housing (CE)	SAA4D107E-1	6.7	2006	3516	134	2000	No	Yes
6	HB215	Housing (CE)	SAA4D107E-1	4.5	2011	280	110	2000	Yes	Yes
7	PC200	Hospital (RM)	SAA6D107E-1	6.7	2010	1228	116	2000	No	Yes

[a] Nominal hours during testing (varies by day used).
[b] The car wash site was located in Ft. Hunter Liggett, CA operated by Diamond D (DD) private construction company. The hospital site was located in Lancaster, CA operated by rental company Road Machinery (RM). The housing demolition project was located in Escondido, CA operated by rental company Claremont Equipment (CE).
[c] Gross power ratings are from published materials.

identify the type of work being performed. The GPS was used to characterize unit speed, location, and grade. The ECM data was used to evaluate engine load and engine speed. The cameras (PlotWatcher Pro) were battery operated, and were programmed to record one frame every 1 to 10 s depending on the location. The video data was critical for determining the activity performed. The excavator activity included digging utility trenches, backfilling trenches, compacting dirt, lifting objects, carrying debris, grabbing items, and dressing dirt.

The ECM tool used in this study was a beta version of the UniCAN Pro and a GPS data logging system from CSM Product Inc. This system is a self-contained J1939 ECM interface and data logging tool. It was configured to start logging when the key was turned on and stop logging with key-off. The UniCAN was upgraded to provide specific J1939 request messaging so that it worked at 100% reliability with the Komatsu excavators. This tool greatly improved the data capture success in comparison to other ECM tools that existed on the market at the time.

The activity information from the video and direct measurements of engine and GPS data was supplemented by interviews with regular operators and industry experts. The interview questions included details on the exact application of the equipment, what other types of operation the equipment might be used for, as well as operator's opinion on the hybrid *vs.* conventional excavators. Fuel consumption logs were also evaluated as part of the activity records. The expert opinions and feedback helped in the development of the duty cycles for the emissions testing and allowed us to incorporate activity estimates that may not have been captured in the activity measurements due to the relatively small sample size.

2.3. Approach to duty cycle development

The development of the excavator duty cycle required defining micro-trips and typical operation patterns. Excavators of this size are used for many types of work, including types of work that were not readily identifiable in the ECM/GPS data for the three study sites. Thus, the video data played a large role in the duty cycle development, where event identification was critical, as shown in Fig. 1. Excavator videos were reviewed frame by frame so that work modes for a specific date/time could be assigned. Engine idle was the only mode identified by ECM data, and it was later parsed into either “stop low idle” or “stop high idle” based upon the corresponding engine speed data. Idle events were defined as when the engine was operating at idle speeds for over 5 s. The first mode of a typical day was often a “Move”, as the excavator was moved to a specific location and positioned to begin work. Next, the excavator stopped and waited to begin work. Later, the excavator began some type of work activity, and the date and time was noted. For each day, a spreadsheet with three columns (date, time and mode) was developed. The time data were aligned with the ECM data using a cross-correlation function in MATLAB®.

A total of 19 different operating modes were identified from the time-lapse video and ECM data. For the cycle development, the number

Fig. 1. Time lapse video photographs for various operations for the hybrid HB-215 excavator.

of modes was reduced from the original 19 operation modes to facilitate constructing a reasonable test duty cycle. Mode reduction was performed by combining modes with similar ECM power and engine speed behaviors. An analysis of variance (ANOVA) using "Sysstat" was performed on the 50th percentile distributions to assist in determining significant differences between modes. Due to the complex nature of engine power, engine speed, and the shape of the distributions for each of the modes, additional analysis with the video tape was performed to support the ANOVA analysis. The details of this analysis can be found in the supporting information section. The final combined modes after the ANOVA analysis were reduced from 19 to 7 (including Idle).

For additional input into mode development, an excavator test cycle developed by Komatsu was reviewed (Block et al., 2012). The Komatsu cycle shows what the manufacturer considers to be important modes of operation for the purposes of emissions testing the hybrid excavator. Prominent modes that Komatsu included in their cycle are several digging modes with various ranges of swing (45°, 90°, and 180°). They also included a "dirt leveling" mode (similar to a "dress" mode as described below), an extended idle mode, and a mode they called "traveling" (what is called "move" in our activity data). So, although some of the digging modes of the Komatsu cycle were not observed in the video data at the sites tested, they were included in the list of modes for our cycle development because they are widely used in the industry. Some of these modes (*e.g.*, digging with a 180° swing) were probably not observed in the activity data due to the limited range of excavator projects sampled.

2.4. PEMS description

The PEMS equipment utilized in this research was compliant with federal test methods for in-use testing (Code of Federal Regulations, 2011). Both the gaseous and PM PEMS were manufactured by AVL (Graz, Austria). The AVL 493 gaseous PEMS measures oxides of nitrogen (NO and NO_2) using non-dispersive ultraviolet radiation (NDUV), carbon monoxide (CO) and carbon dioxide (CO_2) using non-dispersive infrared radiation (NDIR), and total hydrocarbons (THC) using flame ionization detection (FID) (Cao et al., 2016b). The NO_x value is calculated from NO and NO_2, and is reported on a NO_2-equivalent basis. PM was collected with an AVL 494 PM PEMS system, which includes a dilution sampling system and a real-time AVL 483 Micro Soot Sensor (MSS), in conjunction with AVL's integrated gravimetric filter module (GFM) option. A more detailed discussion of comparisons between PEMS and laboratory grade gaseous emissions equipment is provided in U.S. EPA (2008) and Johnson et al. (2009), with similar comparisons for PM PEMS provided in Khan et al. (2012). The exhaust flow meter (EFM) used with the PEMS was a Sensors Inc.'s High Speed EFM (HS-EFM). The EFM is based on a differential pressure principle. The EFM is designed to have a wide dynamic range to measure exhaust flows over the full range that would be found for testing under transient conditions. It has a reported accuracy of $\pm$2%, but previous experience suggests the accuracy might be more closer to $\pm$10% (U.S. EPA, 2008). A 5" EFM was selected to match the displacements of the engines tested in this study. The EFM sampling was done from the end of the tailpipe through heated lines. The instruments were calibrated daily and zeroed hourly in keeping with the 40 CFR 1065 protocols.

2.5. Excavator emissions testing

A total of seven different hybrid and conventional excavators were tested for emissions at two different locations. The excavators were tested over the seven-mode test cycle developed in this paper (see results section for the cycle details). The test sites were carefully selected, as ground materials can have an important impact on engine loads. The terrain was evened and prepared prior to testing, as travel effort can be significantly impacted by uneven terrain. The area for the digging cycles required homogeneous and uniform material, along with enough area for digging. A single 24 in. (61 cm) wide tooth bucket was used for all test modes to provide testing consistency between the three different models of excavators. The test area was prepared by marking out locations where the travel mode and other modes would be performed. The equipment operators conducted one warm up cycle before testing. Each test was conducted in triplicate. For the digging modes, the dimensions of the trench dug during each mode were measured to determine the volume of material removed. The final volume of the trench was calculated as its length times its average cross-sectional area. Soil samples were collected at different locations at each of the site to determine the material density. See the supporting information for more details on the test setup.

3. Results

3.1. Duty cycle results

Based on the consolidated modal data, supported with a statistical analysis of the logged activity data, and operator input from the three sites that were monitored, a duty cycle with 7 different work modes was developed. The duty cycle was designed to represent the operation of excavators approximately the same size as the Komatsu hybrid HB215 and conventional PC200. Table 2 lists the sequence of events of the test cycle as they were conducted during emissions testing. Trenching modes with three different swing angles (45, 90, and 180) were a key component of the duty cycle. The pile of material from the trenching (180 swing) was then dressed into an even pile. The material was then returned to the trench in the backfill mode. The duty cycle also included a travel mode to represent the equipment being taken to the work site, and idle mode for various waiting periods.

To help estimate the overall potential benefit for the hybrid excavators, weighting factors were developed for each of the test modes. This analysis was based on measured activity data, an excavator population database, and interviews with stakeholders such as local dealers, project participants, and the manufacturer. The purpose of this paper is not to develop emissions inventory weighting factors, but to understand how the selected excavators are typically used and what fraction of excavators are represented by this power category. By combining the observed modal fractions, an estimate of how this class of excavator is typically used was made. This required an assumption of the average of the type of work done by these excavators as a fraction of engine-on time. In talking to the participants in the project and the manufacturer of the excavators, it was estimated that about 20% of engine time is for demolition work and the rest is for construction. A summary of the weighting factors for the different modes is provided in Table 3.

The idle speeds for the conventional and hybrid equipment were significantly different, as suggested by the manufacturer's literature. The

Table 2
Details of the UCR proposed excavator test cycle.

Cycle mode	Description
1	**Travel** in a predetermined 91 m (100-yd) line, back and forth for about 3 laps. *Idle for 30–60 s.
2	**Trench 45** (trench with 45° swing) to single bucket width and 1.2 to 1.5 m (4 to 5 ft.) depth for 8 min. *Idle for 30–60 s.
3	**Trench 90** (trench with 90° swing) to same depth with width for 8 min. *Idle for 30–60 s.
4	**Trench 180** for 8 min (trench with 180° swing) a pit of same depth and width. *Idle for 3 min.
5	**Dress** the "trench with 180° spoils into a level pile about 0.3 m (1 ft.) high until the entire pile is finished. Idle for 30–60 s.
6	**Backfill** the spoils from the "trench 45" (mode 2) trench back into the same trench. Idle for 30–60 s.
7	**Idle** mode was assembled during post processing from the delay between test modes.

hybrid's low-idle is 700 r/min and the conventional low-idle is around 1000 r/min. Table 4 shows the percent of time the excavators idled for both the high and low-idle classifications. The idle time ranged from 35% for some conventional excavators being used for construction work at the Ft. Hunter Liggett site to 8.4% for the hybrid excavator being used for demolition work at the Escondido site.

3.2. Emissions comparisons: HB215 vs PC200 vs PC220

The emissions comparison was performed on a per hour basis as compared to traditional load or fuel consumption basis. Time was chosen over work and fuel consumption because the hybrid system is expected to influence load and fuel in a way that can complicate determining the true emission increase or decrease. Specifically, for a given task, the work performed by the hybrid equipment is split between the work performed by the diesel engine and that performed by the electric motor. So, the reduction in the amount of work being done by the diesel engine due to the electric motor for the hybrid equipment must be accounted for. Estimates of the tons of earth moved were also measured, but in order to incorporate idle and travel time, a time basis was selected for this analysis. Comparisons on a time and per ton earth moved basis were very similar as the conventional and hybrid construction equipment completed specific tasks/test modes in a similar amount of time. This suggests that time based analysis was reasonable method for doing the comparisons between the different excavator types. See the supporting information for emission factors on a per work, per fuel, and per ton basis. Additional information on comparisons based on amounts of material moved is provided in Johnson et al. (2013).

Comparing the combined, averaged results for each mode shows the differences in fuel consumption and emissions for each model of excavator. The comparisons for this study focused on the results for average CO_2, NO_x, and PM emissions for each model, THC and CO emissions were generally low. The unit averaged CO_2, PM, and NO_x emissions for each test mode and each model of excavator are provided in Figs. 2–4, respectively. The three figures compare excavator models side by side for each mode. The left (blue) column represents the conventional PC200 result, the middle (red) column represents the hybrid HB215, and the right (green) column represents the conventional PC220. The error bars in these graphs show the 90% confidence interval for each mean.

CO_2 emissions serve as an analog of fuel consumption, as practically all of the carbon in the fuel is converted to CO_2. For CO_2 emissions, the hybrid HB215 is consistently more efficient than either of the conventional excavators, except during the travel mode. In the travel mode, the hybrid HB215 consumed about the same amount of fuel as the conventional PC200. Since the travel mode is not prevalent in typical excavator work, these results indicate that the hybrid excavator will use consistently less fuel for a given period of work. This translates to less fuel per job for the hybrid, because the productively levels for these excavators are similar. The PC220 had the highest CO_2 emissions, as it was a much larger machine than the other two and has the highest fuel consumption rate per hour.

Table 4
Excavator idle time measured during activity assessment.

Description	Carwash (DD) hybrid[a]		Carwash (DD) conventional[b]		Housing (CE) hybrid[a]		Hospital (RM) hybrid[a]	
	hr	%	hr	%	hr	%	hr	%
Total idle	9.2	28.1%	9.2	35.1%	4.7	8.4%	2.2	24.5%
Low idle	8.5	26.0%	6.7	25.5%	4.1	7.5%	2.0	22.3%
High idle	0.7	2.1%	2.5	9.6%	0.5	0.9%	0.2	2.2%
Total time	32.8		26.1		55.3		8.8	

[a] Hybrid low idle = 680–720 r/min, high idle = 1150–1175 r/min.
[b] Conventional low idle = 1000–1050 r/min, high idle = 1350–1400 r/min.

Particulate emissions from the hybrid HB215 are consistently higher than those from either of the conventional excavators for all modes of work, except for the idle mode. There results were confirmed by visual observation of the smoke plume from the exhaust pipes of these units. The hybrid HB215 models all had more visible smoke plumes than the two conventional units.

NO_x emissions from the hybrid HB215 and the conventional PC200 are similar for the different modes of work. NO_x emissions for the PC220 are consistently higher than those from either the hybrid HB215 or the conventional PC200, as the conventional PC220 is a much larger machine than the other two.

3.3. CO_2 emissions variability over the duty cycle

The CO_2 emissions measurements were evaluated in greater detail to evaluate the repeatability of the duty cycle. Since all seven excavators were tested on the same duty cycle, the results are directly comparable for all activities and modes evaluated. Moreover, multiple units of each model of excavator were tested to evaluate variability due to the influence of unit to unit, operator to operator, and site to site differences. Table 5 summarizes the time specific CO_2 emissions for all of the units tested. CO_2 emissions can further be directly correlated to fuel consumption rate, which can be an effective indicator as to how consistently an excavator is being operated.

The three hybrid HB215s had very similar CO_2 emission rates for the same job, except in a few instances, such as the “dress” mode. Two were tested at the car wash site (operated by different persons) and the third was operated by a third operator at the housing demolition site. The coefficient of variation (COV) ranged from 4% to 13% over test runs on the HB215s, with a COV of 2% for overall weighted average for all modes. Two were tested at the car wash site (operated by different persons) and the third was operated by a third operator at the housing demolition site. This result is interesting since the techniques of the operators and the material they were working with seemed to be more different than these results imply. The conventional PC220 results were very similar in terms of CO_2 variability to those for the hybrid HB215, with the

Table 3
Summary of observed mode fractions and final weighting factors.

Mode no.	Mode name	Construction (DD)		Demolition (DD)		Final weighting factors	
		Total hours	Fraction	Total hours	Fraction	Wtd. avg.[a]	Adjusted wtd. avg.[b]
1	Travel	4.0	5%	3.2	10%	6%	6%
2	Trench 45	40.1	52%	4.5	14%	44%	40%
3	Trench 90	0	0%	0	0%	0%	5%
4	Trench 180	0	0%	0	0%	0%	2%
5	Dress	1.7	2%	20.8	66%	15%	16%
6	Backfill	13.2	17%	0	0%	14%	10%
7	Idle	18.4	24%	3.0	10%	21%	21%
	Total	77.4		31.5			

[a] Weighted average based on 80% constructions and 20% demolition activities.
[b] Final weighted average were adjusted based on industry expert inputs.

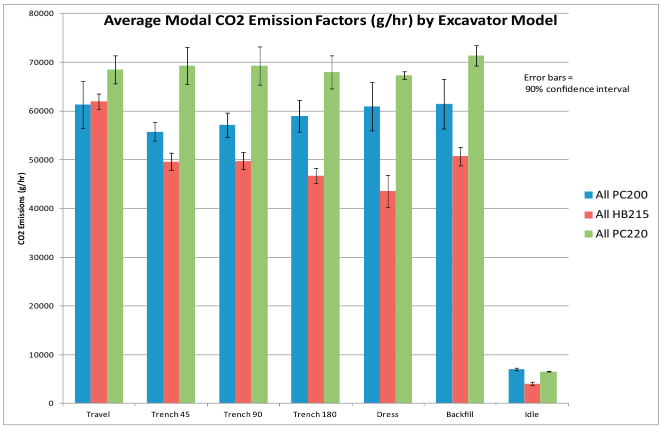

Fig. 2. Average modal CO_2 (fuel consumption) differences between excavator models.

highest COVs being 9–10% for the trenching modes. While we hesitate to draw too broad of conclusions from such a small data set, these tests seem to indicate that in spite of differences in operator technique, there is a general consistency in the comparisons from test to test. The relative consistency of the results could be due in part to the hydraulic pump system inherent to excavators, which acts to stabilize the engine power supply in most cases.

The two PC200 units showed more significant differences in CO_2 emissions for all seven modes, particularly during the "travel" mode and the modes that involved a lot of maneuvering (dress and backfill). Two PC-200 excavators were tested, one at the car wash site and the other at the housing demolition site (Table 5). There are several possible reasons that these two excavators had such different CO_2 emissions. First, they were tested at different locations and operated by different operators. Additionally, the conventional PC200 used at the car wash (DD) site was a 2007 model, while the PC200 used at the housing site (RM) was a newer 2010 model. Furthermore, the operator did notice that the tracks for the older DD PC200 unit needed maintenance, which could contribute to the observed differences in the travel mode. Upon reviewing the data, it was found that the DD PC200 also traveled significantly slower than all the other excavators.

3.4. Overall analysis

The results of the hybrid HB215 comparison to the conventional PC200 and conventional PC220 are summarized in Table 6. This includes the CO_2, NO_x, and PM results that are discussed above, as well as HC and CO emissions results that are provided in greater detail in the

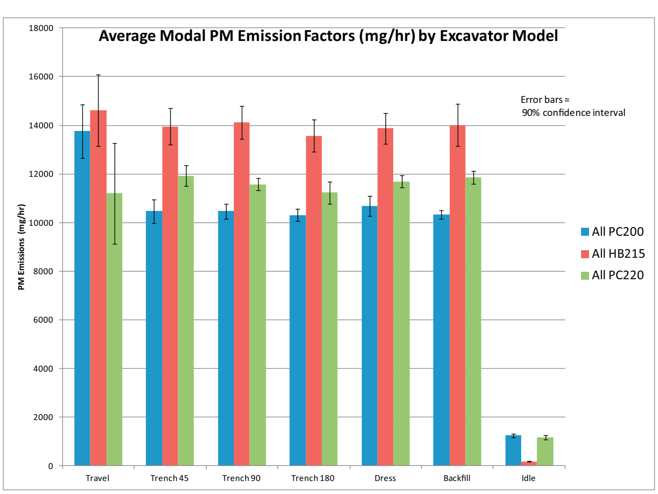

Fig. 3. Average modal PM differences between excavator models.

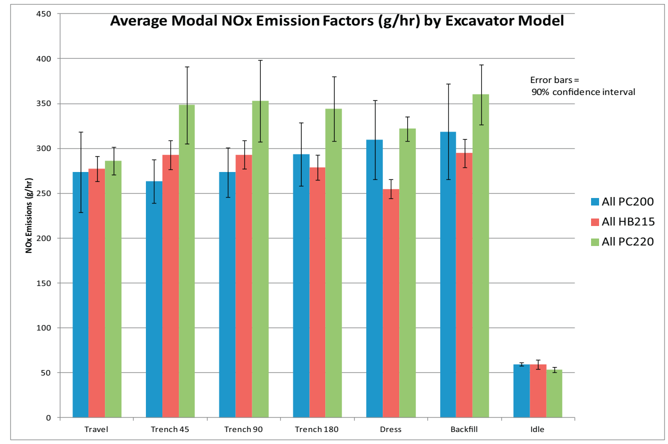

Fig. 4. Average modal NO_x differences between excavator models.

Supporting Information. The overall weighted benefit of the hybrid HB215 is based on comparisons with the PC200s, and assumes 80% construction activity and 20% demolition activity. The ranges in the emissions impacts at the top of Table 6 are based on the average results for the construction and demolition activity based on the weighting factors given for each activity in.

Table 3. For example, the hybrid HB215 can provide savings from 13% to 23% in CO_2 emissions or fuel consumption, but would emit from 26% to 27% more PM in doing so. The expected ranges depend upon whether the excavators would be used more for construction or demolition type of work. It should be noted that the broader observations of reduced CO_2 and increased PM emissions were seen for nearly all the test modes, which provides an initial indication that the method was successful in providing comparisons between the conventional and hybrid technologies. As previously stated, Komatsu considers their conventional PC200 to be the unit directly comparable to the hybrid HB215, as both engines are from the same family and are similar in configuration, as shown in Supporting Information Table SI-1. By assuming that an average mix (80% construction and 20% demolition) of work would be done by the excavators, a 16% fuel consumption reduction is estimated, along with a 27% increase in PM. For future studies, these estimates can be refined to more accurately reflect either a specific work site or more regional impacts, as additional activity data is obtained for either a specific type of work or for a broader range of excavator activity as a whole.

The results indicate that control dynamics are important factors in determining the potential emissions and fuel economy impacts for hybrid equipment. This includes control dynamics for engines with multiple systems or combinations of internal combustion engines with an electric motor in the case of the hybrid. These dynamics can be unique for different operating conditions, and will likely continue to evolve as diesel engine and hybrid technologies continue to advance. Further investigations of such systems under real-world conditions will likely provide addition insights into potential hybrid benefits, and perhaps provide a better understanding of how such systems can be optimized. The more information that can be gathered on activity for either a specific work site or a larger region, the more accurately duty cycles can be developed to characterize the emissions impacts for either specific applications or for a broader implementation. The hybrid manufacturers today are able to achieve significant fuel savings, which is appealing to the end customers and helps reduce tailpipe GHG emissions. The unexpected increases in criteria emissions need to be accounted for, however. In this case, it is anticipated that the observed increase in PM emissions could be eliminated with further development work on the engine control strategy or with additional exhaust after treatment. While there is not an active effort to tighten off-road PM standards in the U.S., the European Stage V non-road mobile machinery (NRMM)

Table 5
Average and variance in CO_2 emissions for the same types of excavator tested.

Time specific CO_2 emissions (g/h)								
	Operator	Travel	Trench 45	Trench 90	Trench 180	Dress	Backfill	Working avg.
PC200 RM	CE1	67,737	57,467	60,128	62,881	67,479	68,181	63,945
PC200 DD	DD1	54,949	54,030	54,234	55,120	54,255	54,723	54,617
Avg.		61,343	55,749	57,181	59,001	60,867	61,452	59,281
COV		15%	4%	7%	9%	15%	15%	11%
HB215 DD	DD1	62,683	49,018	46,911	48,360	41,112	46,905	51,024
HB215 CE	CE1	64,198	46,474	49,254	43,507	50,142	51,352	52,418
HB215 RM	DD2	59,164	43,422	53,013	48,197	39,496	53,909	52,503
Avg.		62,015	49,638	49,726	46,688	43,583	50,722	51,982
COV		4%	7%	6%	6%	13%	7%	2%
PC220 DD	DD2	65,067	73,925	74,009	72,386	66,565	73,927	71,064
PC220 CE	CE1	71,890	64,636	64,612	63,570	67,958	68,866	66,916
Avg.		68,479	69,281	69,311	67,978	67,262	71,397	68,990
COV		7%	9%	10%	9%	1%	5%	4%

Note that the coefficient of variation (COV) is based on the average of all runs for all excavators that were the same model.

emissions standards impose particle number (PN) limits that are essentially forcing the implementation of DPFs. Additional in-use testing, such as in this study, could provide valuable information for optimizing emissions while maintaining the fuel economy improvement for the hybrid.

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Appendix A. Supplementary data

Additional supporting information can be found in the companion document to this manuscript and in the detailed final report submitted to ARB (see link below): *http://www.arb.ca.gov/msprog/aqip/off-road%20hybrid/offrd_hybrid_final_report.pdf*. Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.04.011.

Table 6
Range of overall benefits of hybrid HB215 relative to conventional PC200 and PC220.

	CO_2	NO_x	PM	THC	CO
Ranges of benefit as "construction" only or "demolition" only					
PC200 tier 3[a]	−23% or −13%	−12% or 4%	26% or 27%	−70% or −68%	7% or 10%
PC220 tier 3[a]	−31% or −28%	−18% or − 15%	15% or 19%	−74% or −73%	−12% to 0%
Overall weighted comparison (80% construction and 20% demolition)					
Weighted. PC200 tier 3	−16%	1%	27%	−70%	8%

Note that for the ranges for the PC200 and PC220 given in the first two rows, the value on the left is based on the construction activity weighting factors and the value on the right is based on the demolition activity factors from Table 3.
[a] Negative value means decrease in fuel and emissions and positive values mean increase, weighting factor from Table 3.

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