Hybrid Off-Road Equipment In-Use Emissions Evaluation

Prepared for:

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Hybrid Off-Road Equipment Pilot Project

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Disclaimer

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Executive Summary

The goal of the Hybrid Off-Road Equipment Pilot Project is to accelerate deployment of commercialized hybrid construction equipment while evaluating the emissions benefits of the equipment in real world applications. The focus of this first of its kind research is to evaluate the emissions impact of existing hybrid technology when used during typical in-use operation. As part of this project, the University of California, Riverside College of Engineering – Center for Environmental Research and Technology (CE-CERT) facilitated the deployment of ten hybrid Caterpillar D7E bulldozers and six hybrid Komatsu HB215LC-1 excavators with eight California-based fleets. Hundreds of hours of in-use D7E dozer and HB215LC-1 excavator activity were observed and logged at six locations to develop typical in-use hybrid dozer and excavator duty cycles. Since exact non-hybrid versions of the hybrid D7E dozer and HB215LC-1 excavator do not exist, emission comparisons were made relative to the most similar non-hybrid dozer and excavator models. Figures ES-1 and ES-2 describe how the hybrid D7E dozer and HB215LC-1 excavator function and identify the most similar non-hybrid equipment chosen for emission comparisons.

This Executive Summary briefly summarizes project activity measurement and duty cycle development, and provides emission testing results for project hybrid equipment relative to its most similar non-hybrid counterparts – the Caterpillar D6T dozer and the Komatsu PC200 excavator. These comparisons provide the closest approximation of the emissions impact of hybridizing the Caterpillar D7E and the Komatsu HB215LC-1. Additional details regarding project activity measurement and duty cycle development, as well as emission comparisons with other conventional dozer and excavator models, can be found in the main report.

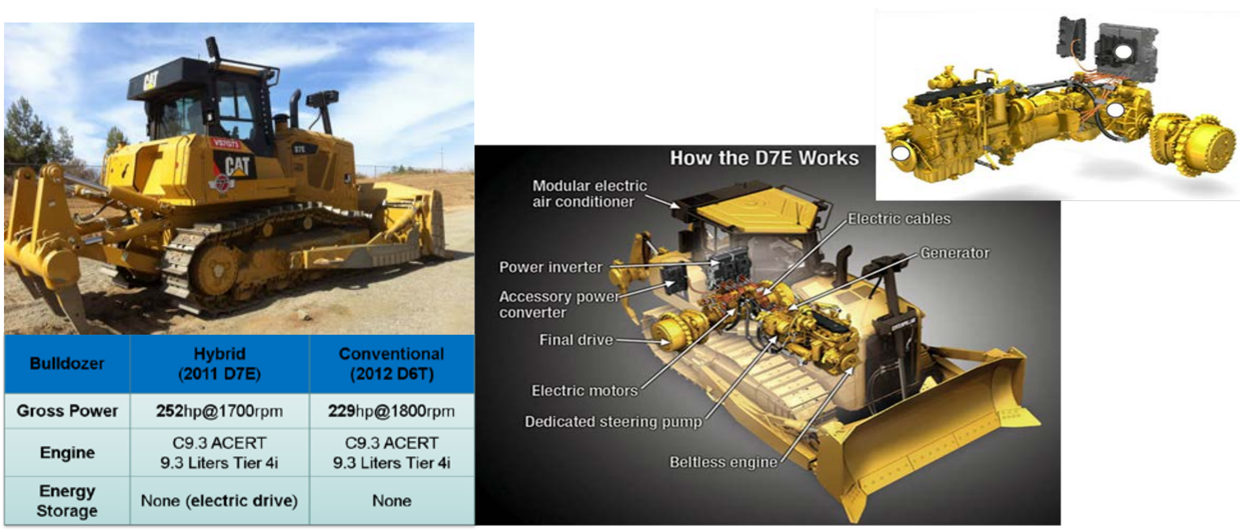

Figure ES-1: Hybrid D7E Caterpillar bulldozer evaluated (source Caterpillar Inc.)

Excavator	Hybrid (2011 HB215)	Conventional (2007 PC200)
Gross Power	148hp@2000rpm	155hp@2000rpm
Engine	SAA_4D10_7E-1 4.5 Liters Tier 3	SAA_6D10_7E-1 6.7 Liters Tier 3
Energy Storage	Capacitor + Electric Motor	None

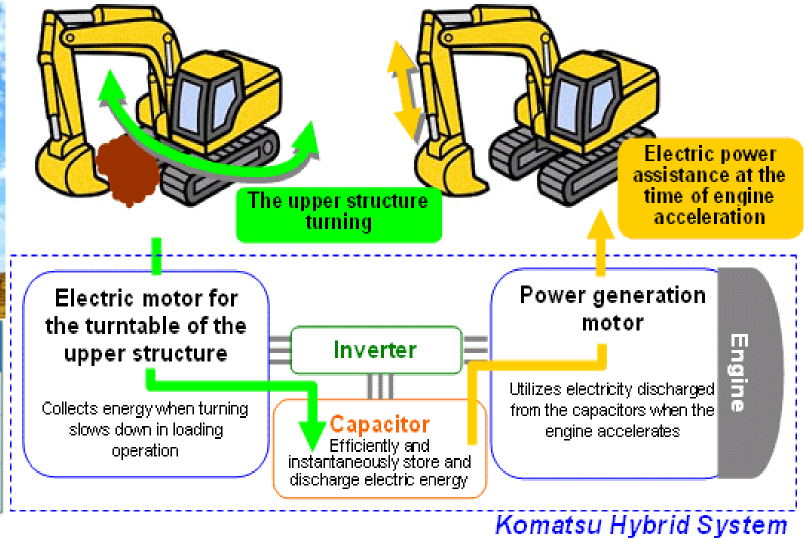

Figure ES-2: Hybrid HB-215-LC-1 Komatsu excavator evaluated (source Komatsu)

Activity measurement

The first phase of this project involved determining the activity (i.e. the types of physical work performed), the loads on the engines, and how much time is spent in each mode. This required a first of its kind comprehensive effort to install time lapse cameras, global positioning systems (GPS), and engine control module (ECM) loggers to fully characterize what work is being performed (see Figure ES-3 for typical installation).

Figure ES-3: Activity measurement setup on the Caterpillar D7E hybrid

Activity measurement highlights include:

- CE-CERT assessed activity by using interviews, historical records, time-lapse video, ECM broadcast data, and real time GPS.
- Activity measurements were made on a subset of six hybrid and various comparable pieces of conventional equipment.
- Activity includes both physical work (P-work) and engine work (E-work).

- P-work represents what is being pushed, lifted, dug, etc. and how.
  - E-work captures engine response to the load imposed by the physical work.
  - P-work dictates the load on the engine, engine speed, and how fast the unit moves.
  - Video data was critical for determining P-work.
- ECM data recorded during known activity from the video was critical in developing the duty cycles for emissions testing.
- ECM fuel flow data was evaluated and found to be relatively accurate. ECM fuel consumption data for the hybrid bulldozer compared within 5 percent to Waste Management's fuel records.

Bulldozer

- Over 160 hours of E-work and over 2000 hours of P-work data was collected for the bulldozers.
- For the bulldozer, P-work ranged from refuse pushing, road building, rock pushing, river bed clearing, to slope repairs. See Figure ES-4 for examples of time lapse pictures, as well as the main report for more details.
- For the bulldozer the video and GPS data were used to determine activity.
- Bulldozer activity consists of forward pushing and backward movement to prepare for next push. See Figure ES-5 for an example of the real time engine data and the report for more details.
- Statistical analysis of over 130,000 events was used as the basis of the proposed duty cycles for the bulldozers.

Figure ES-4: Time lapse video photographs for various operations for the hybrid D7E bulldozer

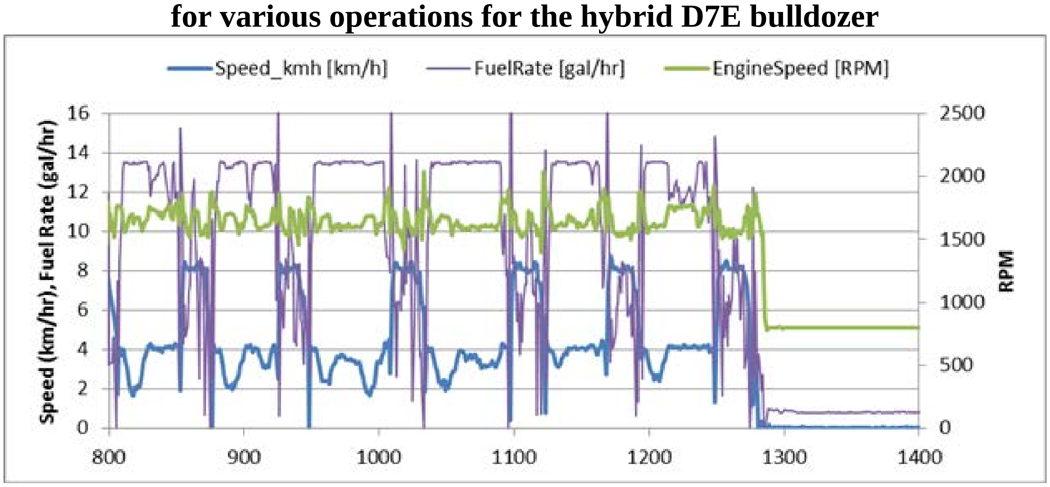

Figure ES-5: Example of real time engine activity logging for the hybrid D7E bulldozer

Excavator

- Over 160 hours of E-work and over 2000 hours of P-work was collected for the excavators.
- Excavator P-work varied significantly and represented over 15 different modes ranging from trenching, dressing (short rotations of excavator turn table to prepare a surface), lifting, holding, hammering, and demolishing. In each mode there were large and small buckets and long and short reaches, and short and long swings. See Figure ES-5 for typical project time lapse data (More detail is provided in the main report).
- For the excavator, activity was determined from video mode data rather than GPS monitoring, since excavator work consists of more stationary operations in which just the vehicle and/or swing arm rotates.
- Statistical analysis of the synchronized video mode data with ECM data reduced P-work work modes from 15 to seven work modes by combining work modes having similar ECM data. These seven work modes adequately characterized in-use excavator emissions.

Figure ES-6: Time lapse video photographs for various operations for the hybrid HB-215LC excavator

Activity results and duty cycle development

The activity logging effort led to the development of real world duty cycles, which are the cornerstone to determining the overall emissions benefit of off-road equipment hybridization. Representative and repeatable comparisons between hybrid and baseline equipment require having the equipment perform the same task under conditions as similar as physically possible. To relate in-use service conditions to controlled test conditions required a statistical analysis of the measured activity data. The duty cycles developed for the bulldozer and excavator are summarized below:

- Activity statistics show that the bulldozer push distance and power varies by operational mode and by fleet facility.
- Based upon the overall bulldozer statistical analysis, 10 meter, 30 meter, and 80 meter push distances at light and heavy loads were selected for the tests cycles. Table ES-1 shows the repeatability of the bulldozer test cycle. Repeatability was close to that of laboratory testing and showed low variability (i.e. less than 2% for engine load and around 5% for representative emissions).

Table ES-1: Repeatability of a bulldozer performance and emissions during cycle testing

	Power	Torque	Fuel	Vel GPS	Time Specific Emissions (g/hr)			
	bhp	ft-lb	kg/hr	km/h	CO_2	NOx	THC	mg PM 3
	196.8	516.5	36.5	3.7	115450	202	2.5	43.8
	197.3	521.5	35.4	4.0	112089	197	2.5	41.5
	198.2	518.6	38.2	3.6	120765	199	2.0	45.1
	197.0	516.4	35.9	3.7	113479	211	2.3	41.8
	204.8	536.0	37.4	3.8	118201	212	1.8	43.8
	195.0	510.2	35.9	3.8	113654	202	2.0	39.3
	203.4	533.3	36.9	3.5	116617	206	2.1	44.1
ave	198.9	521.8	36.6	3.7	115751	204.2	2.2	42.8
std	3.7	9.4	1.0	0.2	3026	6.0	0.3	2.0
cov	1.8%	1.8%	2.6%	4.8%	2.6%	2.9%	12.3%	4.7%

[1] The average "ave" and single standard deviation "std" are based on seven measurements. Variability is described by the term "cov" which is the coefficient of variation as defined by a single standard deviation divided by the average.

- Based upon recorded excavator activity data, UCR developed a representative test cycle that drew heavily upon one previously proposed by Komatsu to evaluate the emissions and fuel economy of Komatsu hybrid and conventional excavators.
- Specific events evaluated over the representative cycle were: travel, idle, dress, trench with 45° swings, backfill, ditch with 90° swings, and dig with 180° swings. These modes represent both general construction and demolition type activity as recorded. Excavator swings are identified by the rotation of the upper structure with the base unit remaining in one position (i.e. not traveling).
- Two specific excavator vocations were identified, 1) general construction and 2) demolition. General construction includes shorter swings (trench 45 degrees) with some travel operation, and demolition includes dressing mode operation, longer rotations (180 degrees), and some travel.

Emissions of off-road hybrids

The emissions and fuel consumption for the hybrid equipment were measured in-use during real world operation with AVL's federally compliant M.O.V.E portable emission measurement systems (PEMS). The AVL's M.O.V.E PEMS system includes measurements for carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO and NO_2), total hydrocarbons (THC) and particulate matter (PM). Fuel consumption is measured using the carbon balance method similar to how vehicle fuel economy measurements are made. The PEMS system was installed on each of the units tested as shown in Figure ES-7 while performing the duty cycles developed as part of this project. The emissions findings are summarized below:

- Emission measurements were successfully performed for both the hybrid and conventional bulldozer and excavator while performing the typical in-use duty cycles developed for this project.
- The emissions and fuel consumption performance evaluations were primarily based on the mass of emissions per ton of earth moved.
- Idle, travel, and non-earth moving actives were factored into the overall emissions comparison on a grams per hour basis with a weighting function derived in this project.
- Emissions on a per brake horse power hour, per fuel use, and per yard basis were also performed (More detail is provided in the main report). Brake horse power was determined from ECM data and published lug curves for each engine.
- The final emissions and fuel consumption performance benefit for the hybrid D7E Tier 4 interim bulldozer are based on a comparison to the D6T Tier 4 interim conventional bulldozer.
- The final emissions and fuel consumption performance benefit for the hybrid HB215LC-1 Tier 3 excavator are based on a comparison to the PC200 Tier 3 conventional excavator.
- CO_2 emissions are directly related to fuel usage. Thus, a reduction in CO_2 emissions translates to a reduction in fuel consumption and improved fuel economy (FE).
- Hybrid emission and performance results are based on a comparison to the hybrid unit. Thus, negative numbers indicate a hybrid benefit (i.e. hybrid results are less than the conventional results) and positive number indicate a hybrid dis-benefit.

Figure ES-7: PEMS in-use measurement example for the bulldozer and excavator units

Caterpillar hybrid D7E emission testing

- Two hybrid D7E bulldozers and one conventional D6T bulldozer were evaluated during both controlled pull and in-service testing at two different locations. As mentioned earlier, the D6T is the conventional bulldozer model most similar in power, size and other key parameters to the hybrid D7E. Figure ES-8 shows the average emission comparisons to the D6T conventional bulldozer for different types of work performed. Emission comparisons between the hybrid D7E and other (less similar) conventional bulldozers are presented in the main report.

- The CO_2 emissions benefit ranged from a 28% benefit to a 2% dis-benefit and depended on push distance and push effort (See Figure ES-8).
- Fuel consumption is based on CO_2 emissions and thus its fuel savings also ranged from a 28% benefit to 2% dis-benefit and depended on push distance and push effort. In general, lighter, shorter pushes resulted in greater fuel economy benefit and heavier, longer pushes resulted in less fuel economy benefit. Typically heavy pushes are found in large excavation, landfills, and rock quarry operations, and lighter pushes are found in slope repairs, maintenance, fine trim type work, and road repair work.
- The hybrid bulldozer had an overall NO_x emissions dis-benefit of 7% to 21%, depending upon work performed (See Figure ES-8).
- No benefit or dis-benefit could be quantified for PM, CO, and THC due to the low emission levels from the aftertreatment system (ATS) equipped engines on both the D7E and D6T units.

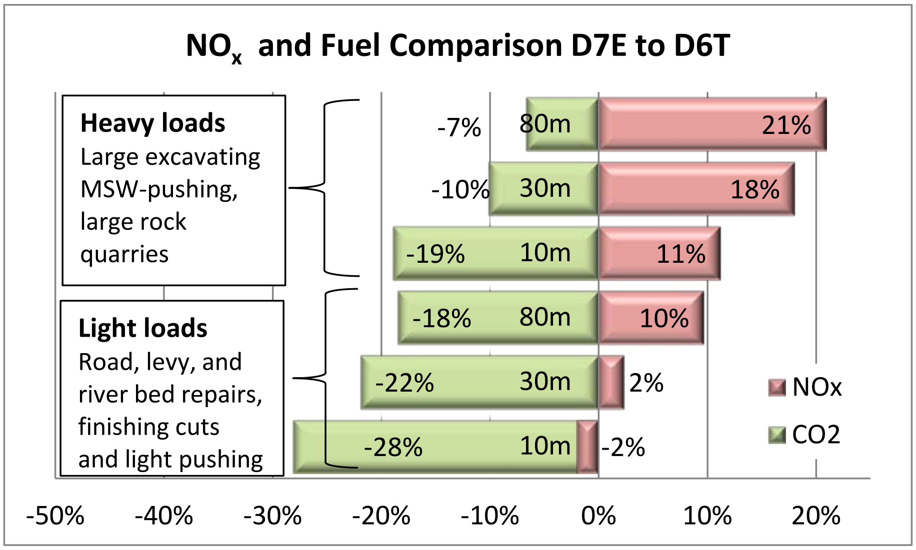

Figure ES-8: Hybrid D7E NO_x and FE benifit for typical dozer vocations

[1] Negative values mean hybrid benefit and positive values mean dis-benefit

[2] PM, THC, and CO emission rates were very low for both the D7E and D6T and thus were not able to be quantified as a hybrid benefit or dis-benefit.

[3] Idle emissions showed a similar trend, with the hybrid emitting less CO_2 (-15%) and more NO_x (+15%)

- Overall average weighted emission and fuel consumption impacts identified in Table ES-2 are based on a best estimate of typical activity for similar large, California-based dozers, based upon fleet surveys, dealer information, and ARB's Diesel Off-Road On-Line Registration System (DOORS) data base (See main report for details).
- Our weighted activity estimates resulted in the hybrid excavator having an overall CO_2 emissions and fuel consumption benefit of 14% and an overall NO_x emissions dis-benefit of approximately 13%. (See main report for details).
- Brake specific and fuel specific analysis confirmed the NO_x dis-benefit for the in-service testing, in-use testing, and controlled pull tests for all modes.
- The engine lug curves showed that the engine speed range of the D7E is very narrow relative to the D6T and this may be causing the higher in-use NO_x emissions.

Table ES-2: Hybrid D7E weighted emission comparison to the D6T conventional

D7E Weighted Comparison to the D6T				
CO_2	NO_x	PM	THC	CO
-14%	**13%**	n/a	n/a	n/a

[1] Negative values mean hybrid benefit and positive values mean dis-benefit
[2] Calculated using best estimate of the typical operating mode

- Measured NOx levels were below engine emission certification standards. See the main report for actual values and difference relative to the emissions certification standards.

Komatsu hybrid HP215LC-1 emission testing

- Two PC200 excavators and three HB215LC-1 hybrid excavators were evaluated using the representative test cycle developed for this project. Figure ES-9 and ES-10 summarizes the hybrid weighted-average emissions comparisons to the typical conventional excavator. Results utilizing a different conventional excavator model (PC220) are presented in the main report.

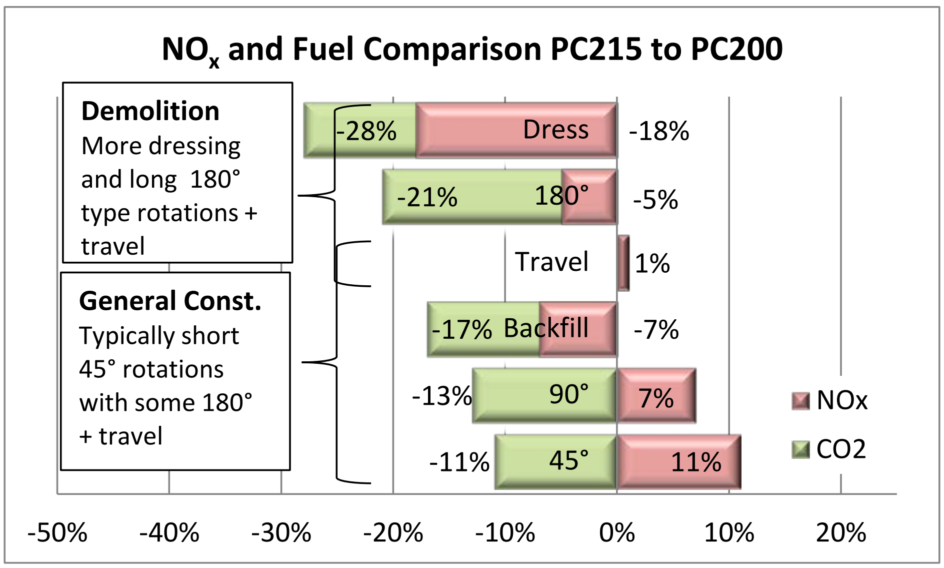

Figure ES-9: Hybrid PC2015 NO_x and FE benefit for typical excavator vocations

[1] Negative values mean hybrid benefit and positive values mean dis-benefit
[2] CO was mixed and ranged from -5% to +21%. THC was lower and ranged from -48% to -73%, see report for details.
[3] The hybrid idle emissions showed a lower CO_2, PM, CO and THC emissions of -43%, -85%, -66%, and -75% respectively and no difference in NO_x emissions (0%).

- The CO_2 benefit of the hybrid varied from a 28% benefit to a 1% dis-benefit, where the highest benefit was for dressing mode (i.e. light surface work with short rotations of the upper structure). The dis-benefit was for the travel mode.
- Demolition type work averaged about a 23% benefit (demolition work typically uses longer swings of the arm, which captures/releases more energy). General construction consists of more trenching and backfilling which resulted in a lower average of about a 13% benefit.
- The hybrid NO_x emissions impact varied from an 18% benefit for demolition work to an 11% dis-benefit for general construction work. (See Figure ES-9).

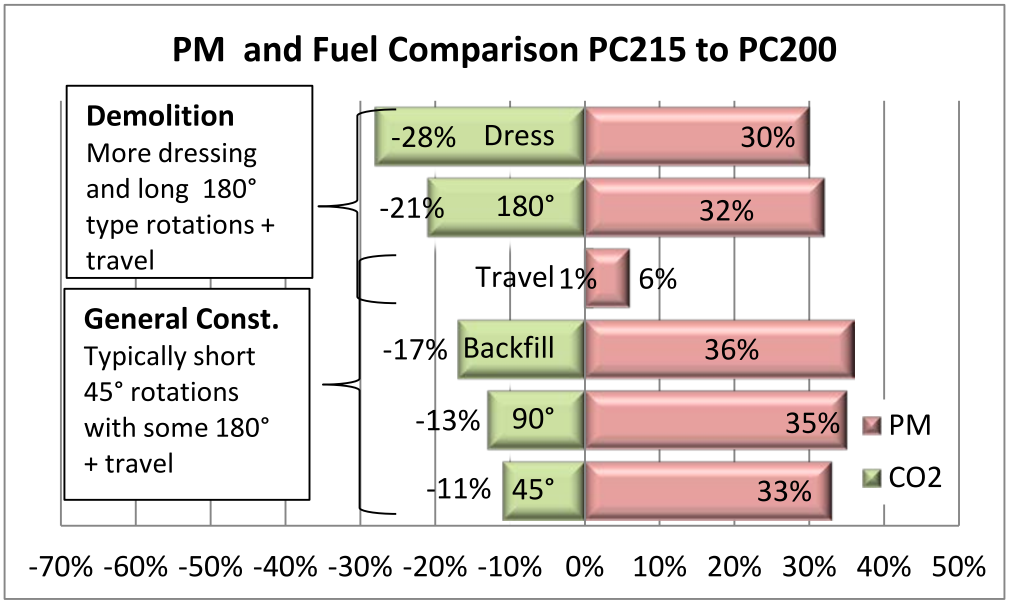

Figure ES-10: Hybrid PC2015 PM and F.E benefit for typical excavator vocations

[1] Negative values mean hybrid benefit and positive values mean dis-benefit
[2] The hybrid idle emissions showed a lower PM at around -85%

- The hybrid PM dis-benefit was around 27% for all types of work and ranged from 6% for travel to 36% for backfill. (See main report for details).
- Table ES-3 provides the overall weighted emissions and fuel consumption estimates developed, based on activity data, fleet surveys, dealer information, and ARB's DOORS data base. Additional details are provided in the main report.
- Using the weighting estimates, the hybrid excavator had an overall fuel consumption, CO_2, and THC emissions benefit of 16%, 16%, and 70% respectively and a NO_x, PM and CO emissions dis-benefit of approximately 1%, 27%, and 8% respectively (See report for details).

Table ES-3: Hybrid PC215 weighted emission comparison to the PC200 conventional

HB215LC-1 Weighted Comparison to the PC200				
CO_2	NO_x	PM	THC	CO
-16%	**1%**	**27%**	-70%	**8%**

[1] Negative values mean hybrid benefit and positive values mean dis-benefit
[2] Calculated using best estimate of the typical operating mode

- During heavy work the engine speed variation for the hybrid was much larger compared to the conventional, which may be the reason for the PM and CO dis-benefits.

Summary

The full report also contains a detailed list of lessons learned regarding activity measurements, data analysis, duty cycle development, and emissions testing. Additionally the final report identifies possible causes of higher emissions from the hybrid equipment and provides recommendations for reducing hybrid construction equipment emissions in next generation models.