UC Riverside
UC Riverside Electronic Theses and Dissertations

Title

Evaluation of Greenhouse Gas and Criteria Emissions From Conventional and Hybrid Off-Road Equipment

Permalink
https://escholarship.org/uc/item/6z7935b0

Author
Cao, Tanfeng

Publication Date
2014

Peer reviewed|Thesis/dissertation

eScholarship.org Powered by the California Digital Library
University of California

UNIVERSITY OF CALIFORNIA
RIVERSIDE

Evaluation of Greenhouse Gas and Criteria Emissions From Conventional and Hybrid Off-Road Equipment

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Chemical and Environmental Engineering

by

Tanfeng Cao

August 2014

Dissertation Committee:
Dr. David R. Cocker III, Chairperson
Dr. J. Wayne Miller
Dr. Akua Asa-Awuku
Dr. Kent C. Johnson

Copyright by
Tanfeng Cao
2014

The Dissertation of Tanfeng Cao is approved:

____

____

____

____

Committee Chairperson

University of California, Riverside

Acknowledgements

The author would like to thank the entire dissertation committee members: Dr. David R. Cocker III, Dr. J. Wayne Miller, Dr. Akua Asa-Awuku and Dr. Kent C. Johnson, proposal committee members: Dr. Xin Ge and Dr.Marko Princevac for their guidance during course this research and school work at the University of California at Riverside's (UCR) College of Engineering – Center for Environmental Research and Technology (CE-CERT).

The author would like to thank the CE-CERT's diesel team staff: Don Pococha, Edward O'Neil, and Joe Valdez for their support on the entire field testing campaigns.

The author would also like to acknowledge the co-authors on each of the projects, all of them have played important role in each of the project. The author would also like to acknowledge the funding agencies for their generous support. The co-authors and funding agencies for each project are listed below.

Chapter Two: A Comprehensive Evaluation of a Gaseous Portable Emissions Measurement System with a Mobile Reference Laboratory

Co-authors: Kent C. Johnson[1], Thomas D. Durbin[1], David R. Cocker III[1], Roland Wanker[2], Thomas Schimpl[2], and Volker Pointner[2], and Karl Oberguggenberger[2]

[1]University of California, College of Engineering, Center for Environmental Research and Technology (CE-CERT), Riverside, CA 92521

[2]AVL List GmbH, Hans-List-Platz 1, A-8020 Graz, Austria

Funding Agency: AVL List GmbH

Chapter Three: Evaluations of In-Use Emission Factors from Off-Road Construction Equipment

Co-authors: Kent C. Johnson[1], Thomas D. Durbin[1], Robert L. Russell[1], David R. Cocker III[1], and Hector Maldonado[2]

[1]University of California, College of Engineering, Center for Environmental Research and Technology (CE-CERT),1084 Columbia Ave, Riverside, CA 92507, USA

[2]California Air Resources Board, 1001 I Street, P.O. Box 2815, Sacramento, CA 95815, USA

Funding Agencies: California Air Resources Board, CalTrans

Chapter Four: A Generalized Approach for Characterizing Emissions Benefits of Hybrid Off-Road Equipment via Physical Activity and Engine Work: A Case Study for Bulldozers

And

Chapter Five: A Generalized Approach for Characterizing Emissions Benefits of Hybrid Off-Road Equipment via Physical Activity and Engine Work: A Case Study for Excavators

Co-authors: Kent C. Johnson[1], Robert L. Russell[1], Thomas D. Durbin[1], George Scora[1], David R. Cocker III[1], Andrew Burnette[2], Joseph Calavita[3], and Hector Maldonado[3]

[1]University of California, College of Engineering, Center for Environmental Research and Technology (CE-CERT),1084 Columbia Ave, Riverside, CA 92507, USA

[2] InfoWedge, 4903 Alondra Ct, El Dorado Hills, CA 95762, USA

[3]California Air Resources Board, 1001 I Street, P.O. Box 2815, Sacramento, CA 95815, USA

Funding Agency: California Air Resources Board

Dedication

I dedicate this work to my parents Xiangli Tan and Shunliang Cao, my extended American family Duane and Kimberly Legg, and Jiwon Kim for their love, encouragement, and support all through my life.

ABSTRACT OF THE DISSERTATION

Evaluation of Greenhouse Gas and Criteria Emissions From Conventional and Hybrid Off-Road Equipment

by

Tanfeng Cao

Doctor of Philosophy, Graduate Program in Chemical and Environmental Engineering
University of California, Riverside, August 2014
Dr. David R. Cocker III, Chairperson

Hybrid technologies on both on-road and off-road applications offer potential in reducing both GHG emissions and criteria emissions by using sophisticated vehicle designs with multiple power sources. Environmental regulations today are starting to shift from criteria emissions to include GHG emissions. However, criteria emissions are still significant contributors to local air pollution in many populous areas throughout the United States. Many different designs for hybrid applications have emerged within the last decade, but reliable studies on their performance, efficiency, and emissions are limited for on-road vehicles and non-existent for off-road hybrid equipment. Unexpectedly, some on-road hybrid vehicles studies have shown a considerable increase in criteria emissions while achieving the desired fuel economy benefits. The research presented in this dissertation evaluates the criteria and GHG emissions benefits of hybrid technologies in off-road bulldozers and excavators. Measurements of power duty cycle and emissions hybrid within this dissertation greatly improve our understanding of the emission inventories of off-road engines, and also offer a new approach on evaluating real world benefits of hybrid off-road engines. Additionally, this dissertation investigates the latest portable emissions measurement equipment (PEMS) technologies which are critical for determining in-use emissions. Finally, in-use emissions rates from a variety of conventional off-road equipment are

evaluated for off-road equipment such as backhoe loaders, dozers, excavators, motor graders, wheel tractor-scrapers, and wheel loaders.

Table of Contents

List of Tables

List of Figures

Acronyms and Abbreviations

AB .... Assembly Bill (California)
AEO .... annual energy outlook
AER .... annual energy review
AQMP .... Air Quality Management Plan
ARB .... Air Resources Board
AVL .... Anstalt für Verbrennungskraftmaschinen List (an Austrian based automotive engineering firm)
bs .... brake specific
CAFE .... Corporate Average Fuel Economy
CAT .... Caterpillar Inc.
CalTrans .... California Department of Transportation
CARB .... California Air Resources Board
CE-CERT .... College of Engineering-Center for Environmental Research and Technology (University of California, Riverside)
CFR .... Code of Federal Regulations
CO .... carbon monoxide
CO_2 .... carbon dioxide
CVS .... constant volume sampling
CRT .... continuously regenerative trap
DOC .... diesel oxidation catalyst
DPF .... diesel particulate filter
ECM .... engine control module
EFM HS .... exhaust flow meter high speed
EGR .... exhaust gas recirculation
EO .... executive order
EPA .... United States Environmental Protection Agency
EIA .... United States Energy Information Administration
ECS .... emissions control systems
E-work .... engine work
FID .... flame ionization detector
GHG .... greenhouse gas
g/hp-hr .... grams per brake horsepower hour
g/kw-hr .... grams per brake kilowatt hour
HDVs .... heavy-duty vehicles
LDVs .... light-duty vehicles
MA .... Measurement Allowance
MEL .... CE-CERT's Mobile Emissions Laboratory
M.O.V.E. .... Mobile On-Board Vehicle Evaluation
NDIR .... nondispersive infrared
NDUV. .... nondispersive ultraviolet
NG .... natural gas
NHTSA .... National High Traffic Safety Administration
NIST .... National Institute of Standards and Technology
NMHC .... non-methane hydrocarbons
NTE .... not-to-exceed

NO_x .... nitrogen oxides
OEM.. original equipment manufacturer
PEMS.. portable emissions measurement systems
PM.. particulate matter
ppm .... parts per million
P-work... physical work
RPM.. revolutions per minute
SCR... selective catalytic reduction
THC .... total hydrocarbons
UCR .... University of California at Riverside
VERL.. Vehicle Emissions Research Laboratory (CE-CERT)
VMT... vehicle miles traveled (annual)

Chapter One: Introduction

Climate change is an ongoing worldwide issue. Scientists have predicted that if no action is taken to reduce future greenhouse gas (GHG) emissions, global climate change will have a profound effect on sea levels, weather patterns, and negatively impact human society (IPCC 2014). According to the 2010 Annual Energy Review published by U.S. Energy Information Administration (EIA), a total of 6.58 billion metric tons of GHG emissions were emitted to the atmosphere in the U.S. alone in the year of 2009. Combustion of fossil fuel such as petroleum contributed about 37% of that number, the largest of all major sources. The transportation sector by itself have accounted for about 71% of the total petroleum consumption in the U.S. (AER 2010). Thus, improving fuel efficiency of engines and vehicles has become a central focus in reducing GHG emissions from the transportation sector.

The incentive to reduce fuel consumption is primarily driven more by energy security than climate change (Johnson 2010). Regulatory Agencies around the world are starting introducing more stringent regulations to reduce GHG emissions under various international and local agreements. Under powers granted by the Clean Air Act and the Energy Policy and Conservation Act, the U.S. Environmental Protection Agency (EPA) and the National High Traffic Safety Administration (NHTSA) have jointly issued GHG emissions standards calling for high efficiency of vehicles and engines in effect as soon as model year (MY) 2014 for heavy duty vehicles and MY 2017 for light duty vehicles (Federal Register 2010, 2011). Locally, the State of California Air Resources Board (CARB) has adopted a greenhouse gas standard called AB32, which aims for higher efficiency of the California state fleet by year 2020 with a long term goal of 80 percent reduction of GHG emissions by year 2050 (AEO 2013). In order to achieve these goals, hybrid engine technologies are growing in popularity as government agencies and manufactures strive to reduce petroleum consumption and GHG emissions. Hybrid technologies offer potential in reducing both GHG emissions and other criteria emissions by cutting engine fuel consumption using sophisticated designs with multiple power sources. Many different designs of hybrid configurations have emerged within the last decade, but reliable studies on the hybrid in-use performance, GHG and emissions benefit are limited and non-existent in many cases. Thus, comprehensive evaluations of real-world benefits from hybrid technologies have become critical for manufacturers to optimize their systems for different applications, and important for governmental agencies to strategically allocate their limited resources for promoting hybrid technologies in the transportation sector.

Hybrid technologies for on-road applications have been in development over the two decades, with the market shares for hybrid technologies constantly increasing. The U.S. EIA estimates that various types of light duty vehicle (LDV) hybrid technologies will play an important role in meeting more stringent future GHG emissions and fuel economy regulations, with the market share of hybrid LDVs increasing from 4% in 2012 to 40% by 2040 (AEO 2014). Several studies have shown that the true benefits for the on-highway heavy-duty hybrid can vary significantly, and highly depend on their application and hybrid system design. Hallmark et al. (2013) measured hybrid transit buses study while in-use and found GHG emission benefit for the hybrid bus. However, the authors also noted an "unexpectedly" higher nitrogen oxide (NO_x) emissions compared to NO_x emissions from a conventional bus. The National Renewable Energy Laboratory (NREL) performed a 13-month long study of fuel economy and emissions benefits for a fleet of hybrid and conventional class 8 heavy duty trucks. The NREL study observed 0%-30% fuel economy improvements; however NO_x increases of 5%-101.3% were observed. The incased in NO_x were attached to certification level of the selected engine in the hybrid bus (Walkowicz

2013). Similar to the NREL study, an evaluation by the University of California, Riverside (UCR) found up to a 60% reduction in GHG emissions but higher CO emissions and mixed NO_x emissions for hybrid class 8 heavy duty trucks in comparison to a conventional truck (Russell 2012).

Recently, hybrid configurations have been introduced for non-road engines as part of additional effort to meet the overall GHG emissions reduction goals. At this stage, non-road engines remains one of the most significant sources of nitrogen oxides (NO_x), particulate matter (PM), and diesel fuel consumption both nationally and within California (AQMD 2007). Although increasingly more stringent engine standards are being implemented for off-road engines, there is a still a delay between the implementation of non-road emissions standards compared to similar standards for on-road vehicles. Additionally, off-road engines are also known have relatively long lifespan, due to their inherent durability, and can sometimes remain in-service for several decades. Further, it is anticipated that the relative contribution of these sources will continue to increase as on-road emissions continue to be reduced. These combined factors make the control of GHG emissions and criteria emissions from off-road equipment a critical need for reducing emissions inventories and protecting public health.

As of today, the number studies on off-road engines are limited; studies on hybrid off-road engines are even more scarce. Jayaram et al. (2010) evaluated the emissions benefits from hybridization of a tug boat. In this study, the hybrid tug boat showed significant benefits of the for $CO_{2,}$ NO_x, and PM emissions. However, the vast majority of these benefits were attached to advanced management of the main/auxiliaries engines operation rather than the hybrid system itself. Sokolsky et al. (2011) evaluated the fuel consumption and productivity of a diesel-electric (hybrid) bulldozer against conventional bulldozers; however, no emissions were measured. Block et al. (2012) measured emissions in-use from a hybrid excavator using a portable emissions measurement system (PEMS), but no data was released and engine parameter was not logged. At this early stage of hybrid deployment in off-road applications, in-use fuel consumption and emissions evaluations are necessary to assess the actual GHG and criteria emissions benefits.

The research presented within this work mainly focuses on developing a methodology to evaluate the real-world emissions and fuel consumption benefits from hybrid off-road construction equipment. The first phase of this research focuses on evaluation of gaseous portable emission measurement systems (PEMS) and sensors, which are essential in quantifying in-use emissions and to assure proper performance of engine and after-treatment technologies. The second phase of this research is to use the PEMS qualified in the first phase of this study to evaluate in-use emissions from newer and high-use off-road equipment. The last phase of this research is to use the tools and experiences from first two phases to perform a comprehensive evaluation of the real-world emissions and fuels consumption benefit from hybrid bulldozers and hybrid excavators.

Chapter 2 presents the in-lab and on-road emissions comparisons made between a new gaseous AVL PEMS and the UCR mobile emissions laboratory (MEL). The main purpose of this study is to determine the feasibility of the newly improved PEMS for use on modern ultra-low emission vehicles. Three engines were tested for emissions comparison, a high emission model year (MY) 2000 heavy duty diesel engine with no gaseous aftertreatment system; a mid-level emission MY 2006 heavy duty diesel engines equipped with exhaust gas recirculation (EGR); and an ultra-low emission MY 2011 heavy duty diesel engine equipped with the latest exhaust gas aftertreatment systems including EGR, diesel oxidation catalyst (DOC), and selective catalytic reduction (SCR) systems. The outcome of this study validates the main measurement tool used throughout this research for in-use emissions measurement.

Chapter 3 investigates the in-use emissions from high-use off-road construction equipment using CFR 1065 compliant PEMS instruments to provide more accurate estimates of emissions. The gas-phase and PM exhaust emissions and engine work were measured on a second-by-second basis for twenty-seven pieces of construction equipment, while their activity was capture by video. The units tested included seven pieces of Tier 2 engines with model years ranging from 2003 to 2007, with horsepower ranging from 92 to 540 hp, and engine hours ranging from 946 to 17,149. The other thirteen pieces of equipment tested were Tier 3 engines with model years ranging from 2006 to 2011, with horsepower ranging from 99 to 520 hp, and engine hours ranging from 242 to 5,233. The results of this study will be used to provide a framework for better understanding emissions from off-road construction equipment under typical operating conditions.

Chapter 4 presents the core of this research, which is the development of a methodology for evaluating emissions and fuel consumption benefits from hybrid off-road equipment via characterizations of physical activity and engine work. As a case study, a total of six hybrid and conventional bulldozers were studied for physical activity and tested for emissions. In order to characterize the typical operation of different units, activity measurements were made on a subset of three hybrid and one comparable conventional pieces of construction equipment. Activity data were obtained from interviews, historical records, and in-use activity measurements obtained from time-lapse video, engine control module (ECM) broadcast data, and GPS data. From the activity study, duty cycles representing in-use activity were developed. Both the hybrid and conventional bulldozers were tested for GHG and criteria emissions on the developed cycle. The results provided insights into in-use NO_x and CO_2 emissions comparisons between the hybrid and conventional bulldozer. This study provides a plausible explanation for the observed emissions differences between the engines and offers future recommendations for improved hybrid systems designs as well as a generalized approach for measuring off-road hybrid emissions. This chapter found that hybrid bulldozer did achieve some fuel economy benefit, however, the NO_x emissions has increased, and this increase is possibly attached to complexity in engine ratings with in off-road engine family.

Chapter 5 uses a similar approach as that developed in Chapter 4 to evaluate emissions and fuel benefits from hybrid excavators. The various different types of observed work application of the excavators are provided within this chapter. A novel approach for duty cycle development for the excavator is also report in Chapter 5. This study provides estimates on overall emissions benefits for switching two different conventional excavator models with hybrid excavator model. This chapter found that although the hybrid excavator has achieved significant fuel consumption savings, but the hybrid components has caused higher PM emissions due to more frequent engine speed variations.

Chapter 6 summarizes the major findings of this dissertation and Chapter 7 provides recommendations for future work

1.1 References

1. Climate Change 2014: Mitigation of Climate Change (2014), Intergovernmental Panel on Climate Change (IPCC), April 2014 http://www.ipcc.ch/report/ar5/wg3/
2. Annual Energy Review 2010, US Department of Energy, Energy Information Administration, www.DOE.EIA.gov
3. Johnson, T V, (2010) "Review of CO2 Emissions and Technologies in the Road Transportation Sector", SAE Technical Paper 2010-01-1276, 2010
4. Light-Duty Vehicle Greenhouse Gas Emissions Standards and Corporate Average Fuel Economy Standards; Final Rule, Federal Register, May 7, 2010, vol. 75, No. 88.
5. Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles; Final Rule, Federal Register, September 14, 2011, vol. 76, No. 179.
6. Annual Energy Outlook 2013, US Department of Energy, Energy Information Administration, www.DOE.EIA.gov
7. Annual Energy Outlook 2014, US Department of Energy, Energy Information Administration, www.DOE.EIA.gov
8. Hallmark, L. S., Wang, B., Sperry. R., (2013) Comparisons of On-road Emissions for Hybrid and Regular Transit Buses, J. Air & Waste Mange. Assoc., Volume 63, Issue 10, 2013, DOI: 10.1080/10962247.2013.813874
9. Walkowicz, K., Lammert, M. Curran, P., (2012) Coca-Cola Refreshments Class 8 Diesel Electric Hybrid Tractor Evaluation: 13-Month Final Report, final report prepared by National Renewable Energy Laboratory. Contract No. DE-AC36-08GO28308. < http://www.nrel.gov/docs/fy12osti/53502.pdf>

10. Russell, R., Johnson, K., Durbin, T. D., (2012) Assessment of the Emissions and Fuel Economy of a Class 8 Conventional and Class 8 Hybrid Truck Chassis Dynamometer Testing. Final report prepared for CALSTART, July.

11. Jayaram, V., Khan, M.Y., Miller, J.W., Welch, W.A., Johnson, K., and Cocker, D. (2010) "Evaluating Emissions Benefits of a Hybrid Tug Boat", Final Report by the University of California Riverside for the California Air Resources Board, October 2010.

12. Sokolsky, S., Presentation by CALSTART, "Joint Military Evaluation of the Benefits of an Electric-Drive Bulldozer", Presented to Ventura County Naval Base, Port Hueneme, CA, November 2011.

13. Block, M., Abolhasani, S., Toscano, F., Persson, E., Presentation by EMISSTAR LLC. "PEMS Testing – Applications and Lessons Learned", Presented to V2012 PEMS Conference and Workshop, Riverside, CA, March 2012.

14. "Final 2007 Air Quality Management Plan" (2007), South Coast Air Quality Management District, June 2007.http://www.aqmd.gov/aqmp/07aqmp/index.html

15. 40 CFR Part 1065 on-line version http://www.ecfr.gov/cgi-bin/text-idx?c=ecfr&tpl=/ecfrbrowse/Title40/40cfr1065_main_02.tpl

Chapter Two: A Comprehensive Evaluation of a Gaseous Portable Emissions Measurement System with a Mobile Reference Laboratory

2.1 Introduction

The United States Environmental Protection Agency (EPA) and California Air Resources Board (CARB) have implemented a series of regulations to control oxides of nitrogen (NO_x) and particulate matter (PM) emissions, from diesel engines during "in-use" conditions. [1] The purpose of the regulations is to ensure that emission standards are maintained throughout the course of the engine's useful lifetime. One of the most important US regulations with respect to controlling in-use emissions is the Not-To Exceed (NTE) standard. The US NTE standard sets limits for gaseous and PM pollutants that are emitted during operation in a defined portion of the engine map and specifies the protocols required to make those measurements.[2] The European Union and other international agencies are also preparing similar in-use regulations with slightly different measurement approaches. The European Union approach will consider emissions over a work based window (WBW).[3, 4] In either case, Portable Emissions Measurement Systems (PEMS) are critical for the implementation of these in-use regulations.

In the US, regulators agreed PEMS measurement uncertainty could be larger than that for laboratory measurements, and thus conducted a study to evaluate the "Measurement Allowance" (MA) for PEMS.[5] The allowance accounts for PEMS measurement uncertainty and adds to the in-use standard for a Not-To-Exceed combined standard. EPA, CARB, and the Engine Manufacturers Association (EMA) formed a heavy duty in-use testing measurement allowance steering committee (HDIUT-MASC) to develop these MA values.[2,5] The University of California at Riverside's (UCR) College of Engineering – Center for Environmental Research and Technology (CE-CERT) was part of this study, and used its mobile reference laboratory (MEL) to validate the developed MAs for in-use conditions for both gaseous and PM PEMS MA programs.[10,16] The in-use validation study found PEMS measurement uncertainties were higher during in-use conditions. In particular, PEMS NO_x were biased high by as much as 0.47 g/hp-hr, or +9 to +25% of the measured point.[7, 8] As a result of this study, a NO_x allowance of 0.60 g/kW-hr (0.45 g/hp-hr) were adopted for 2007-2009 MY engines, which is around 25% of the 2007 standard. The NO_x allowance for Post 2010 MY engines was estimated to be 0.20 g/kW-hr (0.15 g/hp-hr), which is over 75% of the 2010 standard.[9,10]

During the MA program and since its conclusion, PEMS manufacturers have been continuously improving the designs of the PEMS. Testing conducted by Southwest Research Institute (SwRI) near the end of the MA showed that the accuracies of gaseous PEMS improved over the course of the MA program for fixed laboratory testing.[11] However, studies that have focused on in-use comparisons between the Federal Reference methods (FRMs) and gaseous PEMS have been essentially non-existent since the conclusion of the MA program. With the recent implementation of more stringent on-road and non-road emission standards, the emissions levels of the new engines have dropped significantly compared to the emission levels that were evaluated during the MA program. Thus, the in-use accuracy of PEMS needs to be evaluated at today's lower emissions levels.

As today's engine technologies rapidly evolve, manufacturers, regulators, and scientists worldwide are looking to use PEMS to generate in-use emissions and engine performance data to aid their research and development. AVL, an Austrian based PEMS manufacturer released the new 493 gaseous PEMS in late 2011 that incorporated a number of new features to address the issues found with earlier PEMS with accuracy, repeatability, and reliability.[12] The goal of this study is to provide information on the accuracy and measurement capability of the new AVL

PEMS at the high, mid, and low emissions levels. This study was conducted as part of a verification testing program on this PEMS system for approval under the U.S. HDIUT program, and to quantify the new PEMS's in-use uncertainties using UCR's mobile reference laboratory. A comprehensive 40 CFR Part 1065 audit and evaluation was performed on the AVL 493 gas PEMS system.[13] This included laboratory audits, comparison against National Institute of Standards and Technology (NIST) traceable sources, and engine dynamometer correlation testing against a reference laboratory. Additionally, UCR performed two unique in-use comparisons between the PEMS and the UCR MEL utilizing a high NO_x and a low NO_x heavy-duty on-road vehicle. Understanding the PEMS measurement bias relative to the reference method under in-use conditions is a necessary first step to want deploying the PEMS in future studies.

2.2 Experimental

2.2.1 Test engines and vehicles

Three correlation exercises were performed as part of the PEMS audit evaluation. One utilized UCR's engine dynamometer, the second utilized UCR's in-house 2001 Freightliner heavy-duty truck, and the third utilized a 2010 compliant SCR equipped low NO_x heavy-duty on-road truck.

A list of the engines and vehicles tested and their certification ratings are shown in Table 2–1. The range of engines tested includes brake specific NO_x ($bsNO_x$) emissions levels from a high of 5.4 g/kW-hr represent of MY early 2000s certification to a low of < 0.3 g/kW-hr represent the latest MY 2010+ certification. The selected emissions levels thus provide PEMS users a comprehensive evaluation of the PEMS performance over a wide range of NO_x operating conditions. The main comparisons were based on the NTE points, where a NTE point is defined when an engine enters a predefine speed and torque zone for more than 30 seconds. The three tests generated anywhere from 145 NTE points to 174 NTE points.

Table 2–1: Engine dynamometer and in-use vehicle test matrix showing testing location, engine make and displacement, engine power and torque ratings, emission control systems (ECS), NO_x certification levels and total number of NTE test points.

Test Units	Location	Test Engine	Power Torque	ECS [1]	NO_x Certif. g/kW (hp)-hr	Number NTE Points
1	Engine Lab	2006 Cummins ISM 10.8L	370 hp 1450 ft-lb	EGR	2.7 (2.0)	150
2	In-Use	2000 Caterpillar C15 15.0L	475 hp 1650 ft-lb	CRT-retrofit	5.4 (4.0)	145
3	In-Use	2011 Cummins ISX 11.9L	425 hp 1650 ft-lb	OEM DOC, DPF, SCR	0.3 (0.2)	174

[1] Diesel oxidation catalyst (DOC), diesel particulate filter (DPF), original equipment manufacturer (OEM), selective catalytic reduction (SCR), exhaust gas recirculation (EGR), continuously regenerative trap (CRT)

2.2.2 PEMS description

The PEMS evaluated is part of AVL's new Mobile On-Board Vehicle Evaluation (M.O.V.E.) system. The gaseous PEMS includes the 493 gaseous PEMS hardware with a system controller, post processor, and exhaust flow meter. This gaseous PEMS uses heated flame ionization detection (HFID) for total hydrocarbon measurement, non-dispersive ultraviolet (NDUV) for NO and NO_2 measurements, and non-dispersive infrared (NDIR) for carbon monoxide (CO) and carbon dioxide (CO_2), measurements. The design emphasis for the instrument on high accuracy and long term stability and includes some new features, such as internal damping, climate control, and a multi-stage water removal system.[12] The AVL 494 PM PEMS was already validated in some earlier studies thus not included in this study.

The PEMS was first installed in an engine test cell and subjected to variations in test cell temperature. The PEMS was installed outside the tractor cab for several on-road testing and exposed to ambient conditions. The PEMS was secured to a shock absorbing plate provided by the PEMS manufacturer which was mounted to a custom frame located behind the passenger side fuel tank. The electrical power and necessary operating gases for the PEMS were provided by the UCR MEL. A PEMS weather probe was installed inside of a weather shield mounted on the rear of the cab away from any obvious heat sources. As per typical in-use test operating procedures, the PEMS was calibrated at the beginning and the end of the day. The PEMS was automatically zero checked hourly using zero air gas.

2.2.3 UCR Mobile Emissions Laboratory (MEL) description

The reference laboratory used for this PEMS study correlation was the UCR Mobile Emissions Laboratory (MEL). The UCR MEL was the validation laboratory used during the federal PEMS MA program, making this correlation study directly comparable to previous PEMS studies.[7,8] The MEL consists of a number of operating systems typically found in a stationary certification laboratory. However, the MEL is a 53 foot trailer that can be hauled under typical driving conditions, and used to measure the emissions directly from the vehicle towing the MEL.[14,15]

The MEL is a qualified mobile reference laboratory for performing any PEMS validations. A 40 CFR Part 1065 audit for the gaseous and constant volume sampler (CVS) related measurements was successfully completed in the MEL prior to performing the correlation testing with this PEMS study. The UCR MEL has also previously performed cross correlations with several certification laboratories throughout the United States. In 2006, the UCR MEL has cross-correlated with SwRI on two separate trips and California Air Resources Board's (CARB's) heavy duty chassis laboratory.[9, 1] In addition, the UCR MEL successfully completed a blind audit by CARB during an internal biodiesel research project.[5, 10]

2.2.4 Interferences, validation, and accuracy

The main purpose of this study was to characterize the in-use uncertainty of the latest PEMS technology for high, mid, and low emission level environments. Therefore, several steps were performed prior actual emissions testing to characterize and quantify the PEMS measurement capabilities. These included NDIR interference checks, NDUV interference checks, measurement linearity, etc. for both the PEMS and reference laboratory. This combined effort resulted in over 100 experiments (interference checks, accuracy checks, and linearity verifications) on both systems. In all cases the comparisons showed excellent agreement where interferences and accuracies were within 2% for all measurements except exhaust flow, which had uncertainties in the range of 5% and varied by installation and application (2.3.3).

2.3 Results

As first part of this study, the new PEMS passed all the requirements of a 40 CFR Part 1065 audit, and met those requirements during in-use testing. This paper focuses on the correlation results of the gaseous PEMS system with the UCR MEL. Brake-specific emission factors for NO_x, non-methane hydrocarbon (NMHC), CO, CO_2 were calculated using the ECM and J1939 broadcast speed and torque.

2.3.1 NO_x emission results

The comparisons in this report are expressed in either absolute delta, which is defined as the absolute change in difference of PEMS to MEL in units of g/kW-hr, or in relative delta, which is defined as the relative error of PEMS compared to MEL in unit of percentages. The PEMS's NO_x deltas as a function of MEL emission level for the engine dynamometer and on-road comparisons are displayed in Figure 2-1.

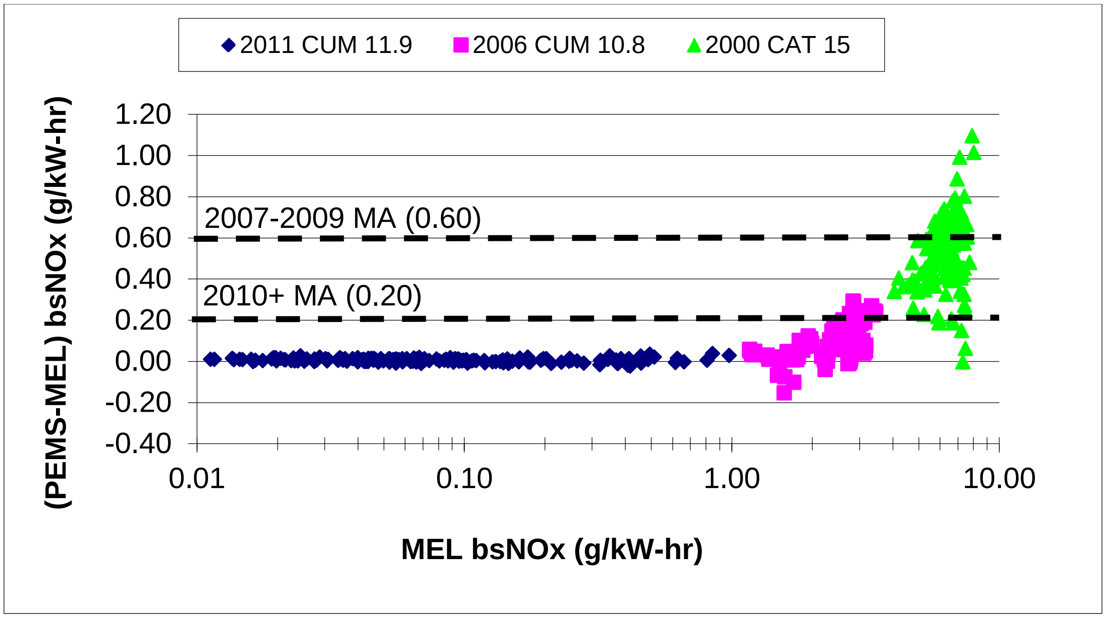

Figure 2-1: bsNOx NTE test points comparison summary shown in absolute deviation for the 2000 Caterpillar engine (NO_x certification 5.4 g/kW-hr), the 2006 Cummins engine (NO_x certification 2.7 g/kW-hr), and the 2011 Cummins engine (NO_x certification 0.3 g/kW-hr) to MEL measured $bsNO_x$ emission levels.

The 2000 MY Caterpillar engine had higher $bsNO_x$ emission levels and showed higher $bsNO_x$ deltas compared to the other two engines tested in this study. However, the validation of the ability of PEMS measurement to maintain a specific delta relative to the MA is heavily dependent on emission level. Therefore, the relative error is more important to evaluate higher emission levels while absolute error is more important to evaluate lower emission levels (e.g. post 2010 MY engines). The relative error of the 2000 MY engine is approximately 5% relative error overall, similar to the 2006 MY engine (Figure 2-2).

The $bsNO_x$ relative error for the 2000 engine and 2011 engine (above 0.10 g/kW-hr) tested in-use is similar overall to that for the 2006 engine tested on an engine dynamometer suggesting that the PEMS NO_x measurement is robust down to 0.10 g/kW-hr regardless of sources (Figure 2-2). PEMS NO_x relative error is observed to be approximately +5% to -10% from 1.0 to 7.0 g/kW-hr and +15% to -15% from 0.1 to 1 g/kW-hr, respectively. The PEMS NO_x

relative error increases below 0.1 g/kW-hr as the emission level approaches the detection limit of both the PEMS and the MEL measurement methods.

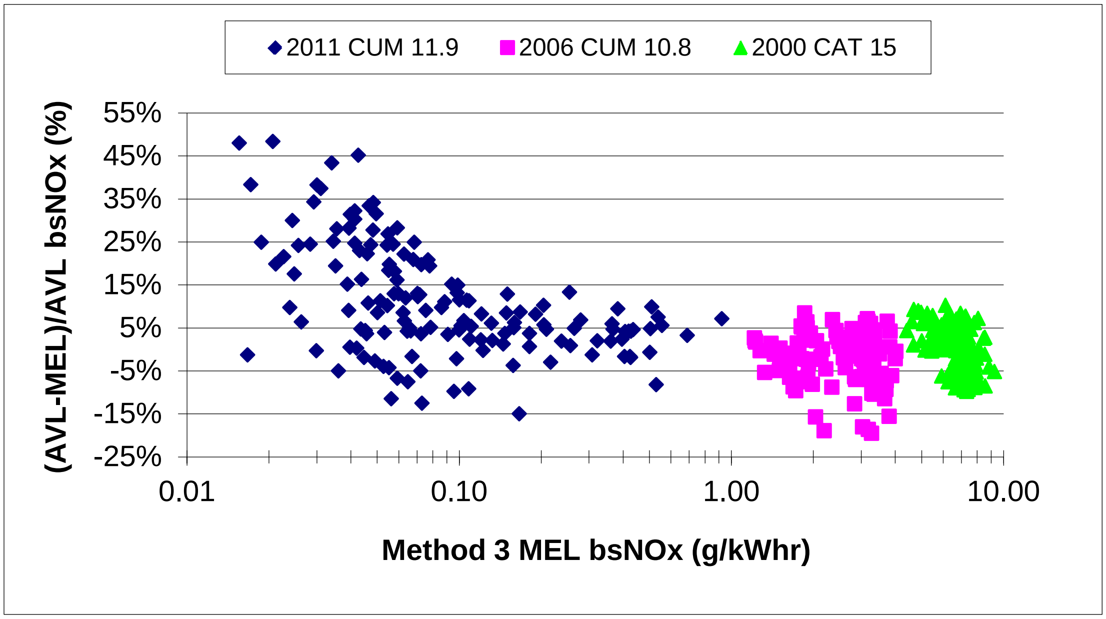

Figure 2-2: bsNO_x NTE test points comparison summary shown in relative percent deviation for the 2000 Caterpillar engine (NO_x certification 5.4 g/kW-hr), the 2006 Cummins engine (NO_x certification 2.7 g/kW-hr), and the 2011 Cummins engine (NO_x certification 0.3 g/kW-hr) to MEL measured bsNO_x emission levels.

The observed PEMS NO_x concentration measured during the three comparison tests (engine dynamometer and the two in-use vehicles) increases linearly with measured MEL bsNO_x emissions (Figure 2-3). The raw PEMS NO_x concentration observed varied from 1000 ppm for the MY 2000 engine down to a few ppm for the MY 2011 engine. The PEMS manufacturer specified drift criteria of the NDUV analyzer is 2 ppm per 8 hours for both NO and NO_2, which equates to 4 ppm / 8hr NO_x.[12] Based on in-use zero drift evaluation of this study, the NDUV analyzer showed a max 1.67 ppm drift at the 90th percentile (Table 2–3). The lowest NO_x measurements observed by the PEMS are near the instruments drift specifications and possibly the PEMS detection limit during in-use testing. Thus, in conclusion, any NO_x measurements below 0.10 g/kW-hr are subjected to higher levels of uncertainty and appear to be higher than the reference method by 50% in some cases (Figure 2-2).

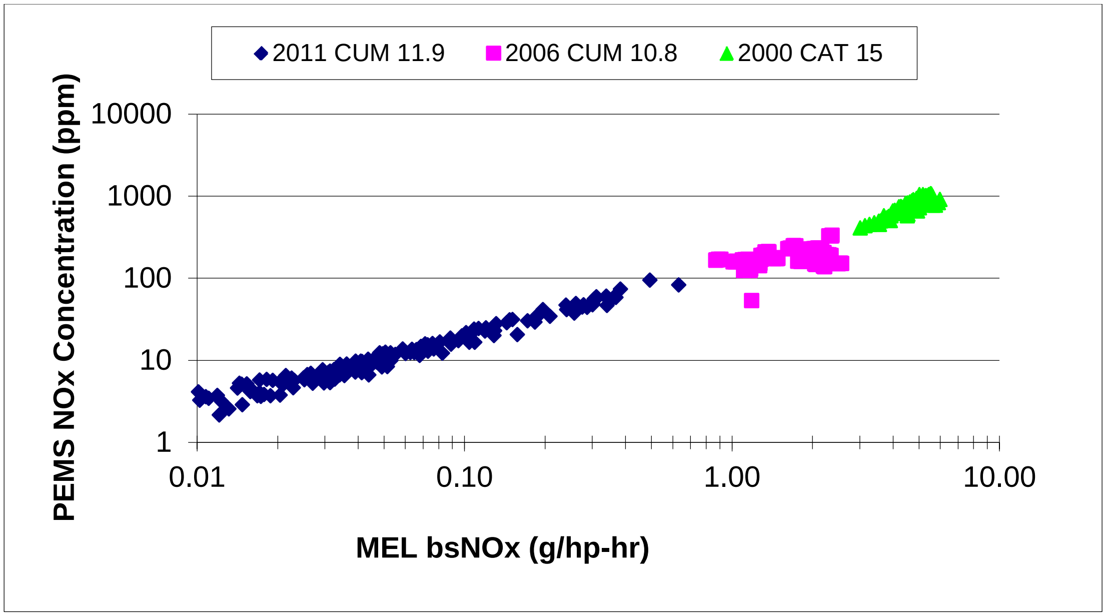

Figure 2-3: Observed PEMS raw NO_x concentration averaged per NTE testing point versus the MEL bsNO_x for the 2000 Caterpillar engine (NO_x certification 5.4 g/kW-hr), the 2006 Cummins engine (NO_x certification 2.7 g/kW-hr), and the 2011 Cummins engine (NO_x certification 0.3 g/kW-hr).

2.3.2 NMHC and CO emissions summary

The engine dynamometer and on-road NMHC and CO emission absolute deltas as a function of MEL emission level are presented in Figure 2-4 and Figure 2-5. The NMHC and CO emission deltas were well below their respective MAs, as denoted by the dashed lines. In particular, the 2006 MY engine's CO and NMHC emission levels were relatively high compared pervious MA study.[5] This is because the current study's 2006 MY engine was not equipped with a DOC/DPF aftertreatment system, whereas the vehicles/engines used in the earlier MA study were. Relatively low NMHC and CO emissions were observed during the on-road testing since the 2000 MY engine utilized a continuously regenerative trap (CRT) system and the 2011 MY engine utilized a DOC/DPF plus SCR system (Table 2–1).

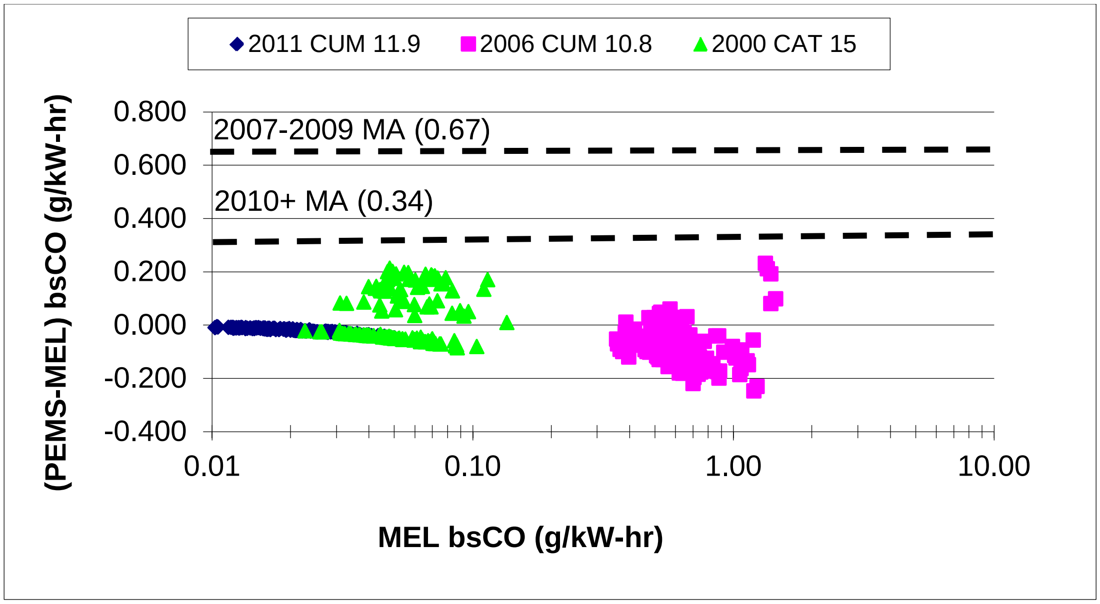

Figure 2-4: Absolute deviation of bsCO emission (g/kW-hr) between PEMS and MEL versus MEL bsCO (g/kW-hr).

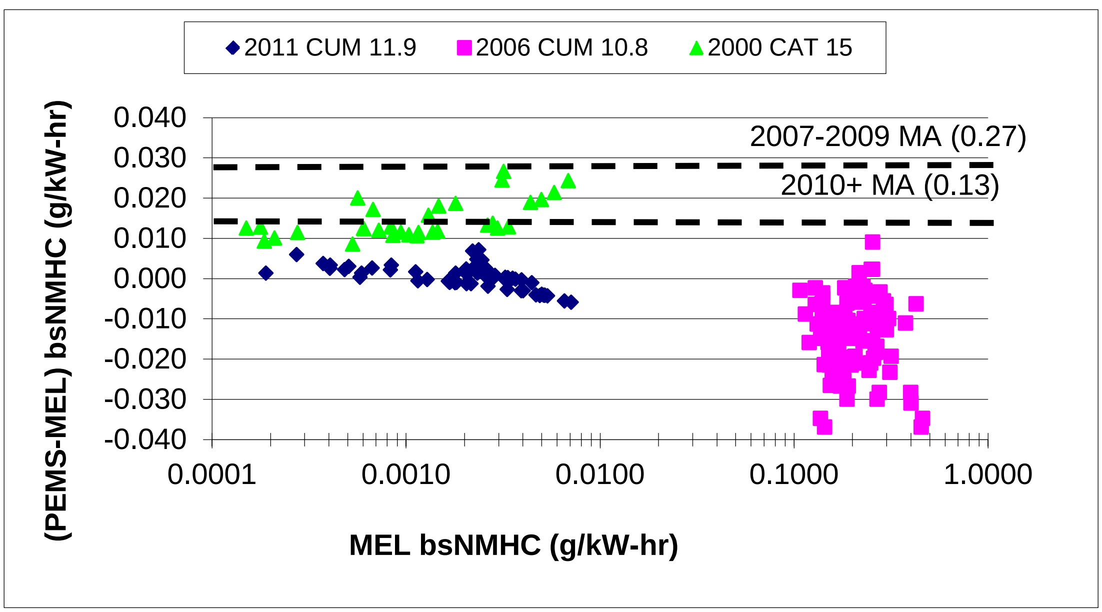

Figure 2-5: Absolute deviation of bsNHMC emission (g/kW-hr) between PEMS and MEL versus MEL bsNMHC (g/kW-hr).

2.3.3 CO_2 emission s and exhaust flow summary

The $bsCO_2$ relative error between the PEMS and the MEL for both engine dynamometer and in-use testing is shown in Figure 2-6. Overall, the PEMS $bsCO_2$ had a +2% average bias relative to the MEL, with the engine dynamometer testing showing the highest positive deviation (+1.9%) and the in-use vehicles with lower bias (-2.3% for MY 2011 engine and +1.8% for the MY 2000 engine). The range of $bsCO_2$ deviations varied from +10% to -5% for all tests (Figure 2-6). The $bsCO_2$ deviations are attributed to uncertainties in exhaust flow measurement.

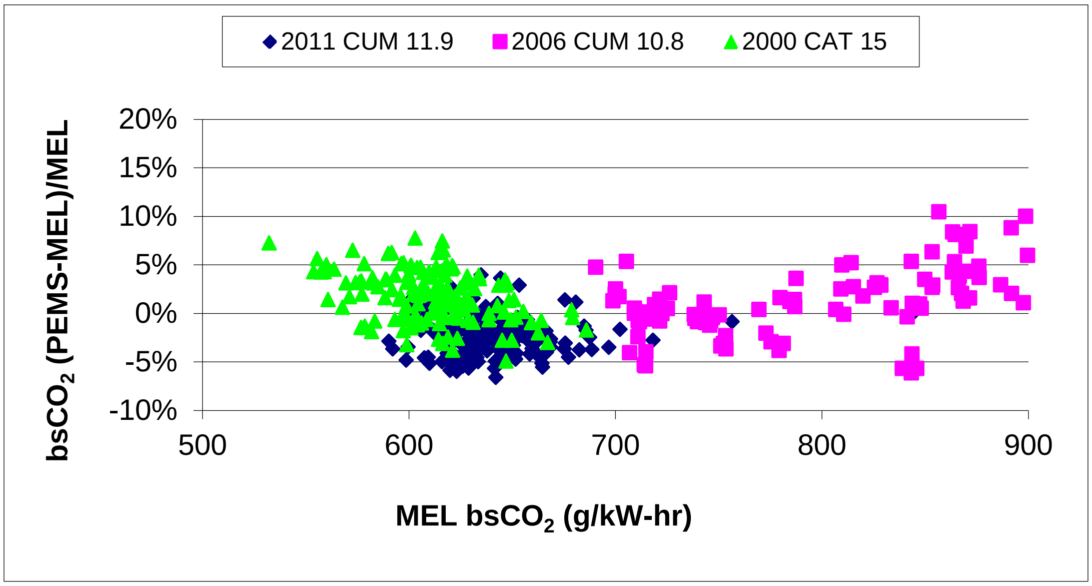

Figure 2-6: Percent $bsCO_2$ deviation between PEMS and MEL versus MEL $bsCO_2$.

The PEMS exhaust flow relative error ranged from +10% to -6% (+2% overall) for all the comparison tests (Figure 2-7). The MEL exhaust flow is calculated by the difference between the two CVS venturis (total flow minus dilute flow) in the CVS system. The MEL venturis were shown to be accurate during the MA studies and are routinely verified by propane verifications ensuring robust measurement.[10]

The MEL diluted venturi exhaust flow calculation is a very stable and reliable measurement on an integrated NTE basis and is not subject to the rapid transients that occur in the raw exhaust. The PEMS exhaust flow is measured using differential pressures sensors corrected for density using the static pressure and temperature in the exhaust line. It is difficult to accurately estimate the exhaust density because of the rapid temperature changes observed in the exhaust. Additionally, the measured dynamic pressure must be correlated with exhaust flow using a constant correction factor "K" as part of the Bernoulli equation that the flow measurement is based on. This "K" constant is a function of Reynolds number (Re), and thus impacted by uncertainty in exhaust parameters. More analysis outside the scope of this work is required to understand these differences; the magnitude of these uncertainties is on the order of ± 10%.

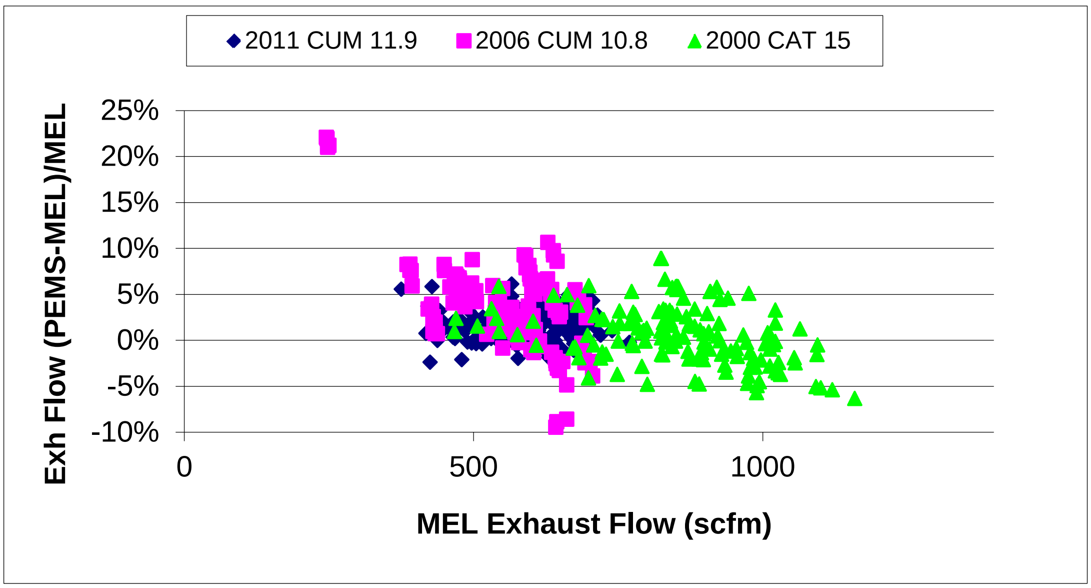

Figure 2-7: Relative error in exhaust flow measurement (scfm) between NEL and PEMS relative to total exhaust flow (scfm) measured by MEL.

2.3.4 Measured absolute concentration

NTE brake specific emissions and concentrations for NO_x, CO, NMHC, and CO_2 are summarized in Table 2–2 for both the PEMS and MEL. The concentrations represent average measured values where the MEL is for diluted CVS measurements while the PEMS is for raw exhaust measurements. Therefore, the concentrations between the PEMS and the MEL are not expected to be similar; rather they provide a magnitude of the concentrations of each species measured. The MY 2000 vehicle had the highest NO_x concentrations, the MY 2011 vehicle the highest CO_2 concentrations, and the MY 2006 engine had the highest CO and NMHC concentrations. The THC and CO concentrations were only a few ppm for both the MY 2000 and MY 2011 vehicles. The average NO_x concentrations were lowest for the 2011 vehicle and averaged 19 ppm for the PEMS and 5 ppm for the MEL. The PEMS correlated well with MEL over the wide range of average emission concentrations for the 3 engines in this study.

Table 2–2: Averaged concentration levels and bsEmission level measured by MEL and PEMS in this study for the 3 different MY engines.

		Averaged Emission Concentrations				bsEmissions (g/kW-hr)			
Vehicle/Engine	Test	CO ppm	CO_2 %	NO_x ppm	THC ppm	CO	CO_2	NO_x	NMHC
2006 CUM 10.8	PEMS	79.8	7.0	191.8	52.4	0.582	867	2.54	0.212
2006 CUM 10.8	MEL	24.4	2.0	53.7	13.6	0.660	851	2.43	0.220
2000 CAT 15	PEMS	16.6	7.5	799.0	6.4	0.086	622	6.87	0.016
2000 CAT 15	MEL	3.7	2.5	247.4	2.2	0.056	611	6.36	-0.0028
2011 CUM 11.9	PEMS	0.5	8.9	19.1	1.2	0.001	622	0.145	0.002
2011 CUM 11.9	MEL	2.1	2.7	5.1	1.3	0.026	638	0.139	-0.0006

2.4 PEMS in-use experience

This section addresses additional issues related to the applicability of the AVL PEMS system for on-road applications. These observations are based on the PEMS installation and in-use testing for the two on-road vehicles, as discussed previously. The additional environmental conditions to be considered for in-use testing include variations in temperature, humidity, pressure, and vibration level.

2.4.1 Temperature, humidity, pressure, and vibration affects

No additional noticeable drift of the PEMS analyzer or operational issues were encountered during in-use operations due to temperature, humidity, pressure, and vibration variations. The PEMS was operated in temperatures ranging from 9ºC to 29ºC, in ambient relative humidities ranging from 20% to 90%, and at elevations ranging from sea level to 1,500 meters. Although ambient variations are not extreme, the gaseous PEMS is subjected to much higher temperatures when it is installed on the vehicle due to direct sun radiation, radiation from the engine, and low speed/stationary operation from test vehicle.

2.4.2 Analyzer drift

Determining analyzer drift is critical for stable and repeatable emission measurements. The 40 CFR Part 1065 test requirements include analyzer drift limit, that force a PEMS test to be repeated if the required specifications are not met (drift < ±5%).[17] In-use operation subjects to greater vibration and changes in barometric pressure and temperature that may increase PEMS analyzer drift compared with stationary laboratory conditions. The AVL M.O.V.E's PEMS drift was evaluated during one day of engine dynamometer testing and four days of in-use testing. The testing intervals ranged from a 6 hours to 8 hours per day.

The average, standard deviation, 50th percentile, and 90th percentile statistics for the 16 in-lab and 49 in-use zero deltas for the PEMS and MEL are shown in Table 2–3. PEMS zero calibration was only performed at the beginning of each day, with subsequent zeros audits done once per hour thereafter. For the MEL, on another hand, zero and span calibrations were done before and after each test cycle. Thus to provide a fair comparison to the PEMS, the MEL zero results are shown as the zero deviations from the first calibration of each test day. Overall, the MEL showed significantly less zero drift compared to the PEMS due to the more frequent calibration (hourly) as well as the more accurate and stable overall sampling system.

Table 2–3: Statistical summary of PEMS zero drift results versus MEL for the one engine dyno test and two in-use tests.

	# of zeros		CO_2		CO		NO_x		THC	
	n/a		vol%		ppm		ppm		ppmC	
	PEMS	MEL	PEMS [1]	MEL	PEMS	MEL	PEMS	MEL	PEMS	MEL
Dyno. Ave.	16	14	0.00	-0.001	7.8	-1.4	0.77	0.03	3.1	0.1
Dyno. Stdev.			0.00	0.005	4.0	0.7	0.47	0.06	1.9	1.0
Dyno. 50^{th}			0.00	0.000	9.8	-1.6	0.91	0.03	3.6	0.3
Dyno. 90^{th}			0.00	0.001	10.9	-0.4	1.19	0.04	5.4	1.1
In-use Ave.	49	35	0.00	0.000	10.5	-0.9	0.26	0.09	1.2	0.6
In-use Stdev.			0.00	0.002	18.0	0.8	1.53	0.14	1.8	0.9
In-use 50^{th}			0.00	0.000	3.7	-0.9	0.70	0.01	0.2	0.0
In-use 90^{th}			0.00	0.002	47.3	0.0	1.67	0.29	4.4	1.9

[1]The PEMS CO_2 zero drift was small and only recorded to two decimal points, and is thus shown as zeros.

The span percent changes for the PEMS and MEL gaseous species are summarized in Table 2–4 and Table 2–5. Due to the nature of PEMS operation, like the zero calibration, span calibration was only performed at the beginning and end of the day. In the case of the MEL, span calibrations are performed every hour along with zero calibrations typical for MEL operation. For PEMS span drift, all deviations are less than 2% over a full day of operation except for NO_2 on the low emitting MY 2011 vehicles. The MEL's span drifts, as expected were less than the PEMS. The MEL is a reference laboratory with a full flow CVS system with analyzers sampling in more ideal environmental conditions. On the other hand, the PEMS was sampling in raw transient conditions while exposed outside of the truck cab.

Table 2–4: Summary of in-use PEMS span percent change results for the one engine dyno test and two in-use tests.

Results	Test Dur.	CO_2	CO	NO	NO_2	THC
n/a	hrs	vol%	ppm	ppm	ppm	ppmC
2006 CUM 10.8 (dyno)	6.7	0.0%	0.1%	-0.1%	-0.2%	0.2%
2000 CAT 15 (in-use)	6.1	0.3%	1.3%	-1.5%	-0.4%	-1.7%
2000 CAT 15 (in-use)	7.5	-0.3%	0.0%	-0.2%	-0.6%	-1.7%
2011 CUM 11.9 (in-use)	8.1	-0.1%	0.0%	-0.3%	-4.0%	-0.9%
2011 CUM 11.9 (in-use)	6.3	0.0%	0.0%	0.0%	-0.8%	0.1%

Table 2–5: Statistical summary of MEL span drift for the one engine dyno test and two in-use tests.

Results	# of spans[1]	CO_2	CO	CH_4	NO_x	THC
n/a	n/a	vol%	ppm	ppm	ppm	ppmC
Dyno. Ave.	14	0.7%	-0.3%	0.5%	-0.3%	0.4%
Dyno. Stdev.		0.7%	0.3%	0.6%	0.3%	1.0%
Dyno. 50th		1.0%	-0.2%	0.5%	-0.2%	0.5%
Dyno. 90th		1.2%	-0.1%	1.2%	0.1%	1.4%
In-use Ave.	35	-0.6%	-1.5%	-3.0%	0.2%	-1.5%
In-use Stdev.		2.1%	1.6%	2.8%	0.8%	2.2%
In-use 50th		-0.4%	-1.1%	-2.3%	-0.1%	-0.6%
In-use 90th		2.1%	0.5%	0.1%	1.3%	0.4%

[1]The MEL is span calibrated hourly thus more calibration points than the PEMS.

2.5 Overall Discussion

The goal of this study was to provide insight into the capabilities of a PEMS representing the latest commercially available technology for making measurements at today's ultra-low emissions levels. Overall, the AVL gaseous PEMS solution met and exceeded the verification acceptance criteria for in-use emissions measurements. The results from this study showed that the latest PEMS have evolved over time and have similar accuracies to those of fixed laboratories for pre-2010 emission levels. Further, PEMS are now more versatile in-use applications compared to the fixed reference laboratories, which are much larger in size and cost.

The correlation between the AVL PEMS and MEL ranges depending on emission level and of specific pollutant. In summary, the PEMS have relatively high accuracy for higher NO_x emission levels down to 0.1 g/kW-hr where the PEMS measured nominal NO_x concentration are between 10 ppm and 1000 ppm. However, for the ultra-low bsNO_x emission levels below 0.1 g/kW-hr, the PEMS started to lose accuracy as the very low NO_x concentrations approaches its in-use analyzer drift.

The bsCO_2 emissions agreed to within 2% overall, with the measurement differences being largely related to uncertainties in exhaust flow measurements. The PEMS exhaust flow measurement is subject to greater variations due to the more transient nature of the raw exhaust PEMS measurements. The NMHC and CO PEMS absolute deltas were low for all configurations and below the MA levels for each engine and after treatment tested in this program.

2.6 References

1. 40 CFR 86.1370-2007, Not-To-Exceed Test Procedures, 65 Federal Register 59958, Oct. 6, 2000.
2. Federal Register, 2005. Control of Emissions of Air Pollution From New Motor Vehicles: In-use Testing for Heavy-duty Diesel Engines and Vehicles, Federal Register, June 14, 2005, vol. 70 No. 113.
3. Provenza, A., Bonnel, P., Weiss, M., Perujo, A. (2012) In-Use Emissions Testing Developments in the New and Future European Motor Vehicle Emissions Regulations, presentation at the 2nd UCR PEMS conference and workshop, Riverside, CA
4. Shade, B., Carder, D., Thompson, G., and Gautam, M., "A Work-Based Window Method for Calculating In-Use Brake-Specific NOx Emissions of Heavy-Duty Diesel Engines," *SAE Int. J. Engines* 1(1):778-793, 2009, doi:10.4271/2008-01-1301
5. EPA, 2008. Determination of PEMS Measurement Allowances for Gaseous Emissions Regulated under the Heavy-duty Diesel Engine In-use Testing Program. Revised Final Report EPA420-R-08-005. United States Environmental Protection Agency, Arlington, USA
6. Miller, J.W., Durbin, T.D., Johnson, K.J., Cocker, D.R., III, (2006) Evaluation of Portable Emissions Measurement Systems (PEMS) for Inventory Purposes and the Not-to-Exceed Heavy-Duty Diesel Engine Regulations; final Report for the California Air Resources Board, July.
7. Feist, M.D., Sharp, C.A., Spears, M.W., 2009. Determination of PEMS measurement allowances for gaseous emissions regulated under the heavy-duty diesel engine in-use testing program Part 1-project overview and PEMS evaluation procedures. SAE International Journal of Fuels and Lubricants 2 (1), 435-454

8. Sharp, C., Feist, M., Laroo, C., and Spears, M., "Determination of PEMS Measurement Allowances for Gaseous Emissions Regulated Under the Heavy-Duty Diesel Engine In-Use Testing Program Part 3 – Results and Validation," *SAE Int. J. Fuels Lubr*. 2(1):407-421, 2009, doi:10.4271/2009-01-0938
9. Johnson, K., Durbin, T.D., Miller, J.W., Cocker III, D.R., Sharp, C., Maldonado, H., Laroo, C., and Spears, M. (2007) On-road Comparisons between a PEMS and a full CFR Dilution Tunnel System on a Mobile Platform as Part of the Measurement Allowance Program, presentation at the 17th CRC On-Road Vehicle Emissions Workshop, San Diego, CA
10. Johnson K.C., Durbin T.D., Cocker III D.R., Miller W.J., Bishnu D.K., Maldonado H. Moynahan N, Ensfield C., Laroo C.A. (2009) On-Road Comparison of a Portable Emission Measurement System with a Mobile Reference Laboratory for a Heavy Duty Diesel Vehicle, Atmospheric and Environment, 2009. http://eprints.cert.ucr.edu/338/
11. Bougher, T., Khalek, I., Trevitz, S., and Akard, M., "Verification of a Gaseous Portable Emissions Measurement System with a Laboratory System Using the Code of Federal Regulations Part 1065," SAE Technical Paper 2010-01-1069, 2010, doi:10.4271/2010-01-1069.
12. AVL M.O.V.E GAS PEMS 493 User Manual
13. Johnson, K., Cao, T., Durbin, T.D., Oberguggenberger, K., Wanker, R., Schimpl, T., Pointner, V. (2012) Comprehensive Evaluation of AVL's 1065 Compliant Gaseous PEMS, presentation at the 22nd CRC On-Road Vehicle Emissions Workshop, San Diego, CA
14. Cocker, D.R., Shah, S.D., Johnson, K.C., Miller, J.W., and Norbeck, J.M. (2004a) Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 1. Regulated Gaseous Emissions. Environ. Sci. Technol. 38, 2182. http://eprints.cert.ucr.edu/510/

15. Cocker, D.R., Shah, S.D., Johnson, K.C., Zhu, X., Miller, J.W., and Norbeck, J.M. (2004b) Development and Application of a Mobile Laboratory for Measuring Emissions from Diesel Engines. 2. Sampling and Toxics and Particulate Matter. Environ. Sci. Technol. 38, 6809. http://eprints.cert.ucr.edu/511/

16. Johnson, K.C., Durbin, T.D., Jung, H., Cocker III, D.R., Giannelli, R., Bishnu, D., (2011). Quantifying In-Use PM Measurements for Heavy Duty Diesel Vehicles. Environ. Sci. Technol, 45, 6073-6079, 2011.

Chapter Three: Evaluations of In-Use Emission Factors from Off-Road Construction Equipment

3.1 Introduction

Off-road equipment is one of the most significant sources of nitrogen oxides (NO_x) and particulate matter (PM). According to U.S. Environmental Protection Agency (EPA) emissions inventory, off-road diesel equipment is estimated to be the 3rd largest source for NO_x emissions and 2nd largest source for PM emissions among all of the mobile sources, representing 14.5% and 24.3% of total mobile NO_x and PM emissions, respectively (EPA, 2011). Although increasingly more stringent engine standards are being implemented for off-road engines, there is a still lag between the implementation of these standards compared to similar standards for on-road vehicles (Federal Register 2004, 2005). Off-road engines also have relatively long lifespans, due to their inherent durability, and can remain in use for several decades. It is anticipated that the relative contribution of these sources will continue to increase as on-road emissions continue to be reduced. These factors make the control of emissions from off-road equipment one of the more critical areas in terms of reducing emissions inventories and protecting public health.

Developing emissions factors and emissions inventories for off-road equipment has inherently been more challenging than on-road vehicles. Off-road engines are typically certified via engine dynamometer tests that are not necessarily representative of the engine's in-use operation. Prior to about 2000, emissions from off-road engines were quantified based on steady-state engine dynamometer tests, which did not represent real-world activity. More recently, EPA introduced a non-road transient test cycle along with the Tier 4 emissions standards to more accurately represent the real-world off-road equipment activity (Federal Register 2004). Although a number of studies have measured in-use emissions from off-road equipment (e.g., Abolhassani et al. 2008, 2013), the available data for off-road equipment is still considerably more limited compared to on-road mobiles sources, which have been studied extensively for decades. Additionally, data on in-use activity patterns is scarce for off-road equipment to identify typical equipment operating modes that's needed to identify the greatest contributors to emissions.

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

Studies of construction equipment have been carried out over the years using different generations of PEMS technology. Gautam et al. (2002) measured in-use emissions using non-CFR compliant prototype portable analyzer on a street sweeper, a rubber-tired front-end loader, an excavator, and a track-type tractor in the field in an effort to develop test cycles for subsequent engines dynamometer testing. Scora et al. (2007) and Barth et al., (2008, 2012) also measured gas phase (NO_x, CO, CO2) and PM emissions from heavy-duty construction equipment using a non-

CFR compliant portable gas analyzer and gravimetric based PM from a self-designed mini-dilution tunnel, respectively. The EPA and its collaborators have also conducted an extensive study of construction emissions in EPA region 7 using CFR compliant PEMS from Sensors Inc. (Kishan et al. 2010; Giasnnelli et al. 2010; Warila et al. 2013). Frey and coworkers conducted emisson studies of construction equipment and studies of how to model their emissions impact using non-CFR compliant PEMS system (Abolhasani et al. 2008, 2013; Frey et al. 2003, 2008a, 2008b, 2010; Lewis et al. 2009a, 2009b, 2011, 2012; Pang et al. 2009; Rasdorf et al. 2010). Huai et al. (2005) also measured the activity for different fleets of off-road diesel construction equipment.

The primary purpose of this paper is to obtain gaseous and PM emissions from high-use off-road construction equipment using a CFR compliant PEMS to provide accurate estimates of emissions from off-road construction equipment under real-world scenarios. Further, the goal of this work is to sample a sufficiently wide range of engine hours to permit deterioration of emissions estimates as function of engine operational hours. The gaseous and PM exhaust emissions and the engine work were measured using CFR compliant PEMS on a second-by-second basis for twenty-seven pieces of construction equipment. Videotaping and on-site observation were used to determine the type of construction activity (e.g. digging, pushing, idling, moving, etc.) that the equipment was performing.

Table 3–1: Detailed information of the off-road equipment tested during in-use operation.

No.	Date Tested	UCR Name ID	Equipment Type	Engine Mfg	Model	Year	Tier	Dis. (L)	Rated Power (bhp)	Rated Speed (RPM)	Engine Hours	ECM	Work Performed
1	12/03/10	1_410J	Backhoe	Deere	410J	2007	2	4.5	99	2200	1182	yes	Digging and backfilling
2	12/07/10	2_310SJ	Backhoe	Deere	310SJ	2010	3	6.8	99	2250	242	yes	Digging and backfilling
3	12/08/10	3_644J	Wheel loader	Deere	644J	2007	3	6.8	225	2200	1735	yes	Digging and backfilling
4	12/09/10	4_310SG	Backhoe	Deere	310SG	2006	2	4.5	92	2300	2599	yes	Digging and backfilling
5	12/10/10	5_410G	Backhoe	Deere	410G	2006	2	4.5	99	2200	946	yes	Digging and backfilling
6	02/09/11	6_WA470-6	Wheel loader	Komatsu	WA470-6	2009	3	11.04	273	2000	900	no	Loading trucks
7	02/10/11	7_928G	Wheel loader	Caterpillar	928G	2004	2	6.6	156	2300	2294	yes	Loading and smoothing asphalt
8	3/17/2011	8_345D	Excavator	Caterpillar	345D	2008	3	12.5	520	2100	tbd	no	Loading trucks
9	4/20/2011	9_637E	Scraper	Caterpillar	637E	2006 (Rebuild)	2	8.8	280	2200	>10000	yes	Scraping dirt
10	04/21/11	10_637E	Scraper	Caterpillar	637E	2006 (Rebuild)	2	15.2	540	2100	>10000	yes	Scraping dirt
11	05/04/12	11_EC360B	Excavator	Volvo	EC360B	2006	3	12.1	269	1700	5233	yes	Loading trucks
12	05/14/12	12_D8R	Bulldozer	Caterpillar	D8R	2003	2	14.8	338	2000	17149	yes	Pushing trash
13	10/16/12	13_120M	Grader	Perkins	120M	2008	3	6.6	163	2200	3815	yes	Grading shoulder
14	10/17/12	14_928Hz	Wheel loader	Caterpillar	928Hz	2011	3	6.6	171	2200	289	yes	Cleaning ditch
15	10/18/12	15_120M	Grader	Caterpillar	120M	2010	3	6.6	163	2200	1308	yes	Grading dirt road
16	10/22/12	16_120M	Grader	Perkins	120M	2008	3	6.6	163	2200	2706	yes	Grading dirt road
17	10/23/12	17_120M_DPF	Grader	Caterpillar	120M_DPF	2010	3	6.6	168	2200	952	yes	Grading dirt road
18	10/29/12	18_928Hz	Wheel loader	Caterpillar	928Hz	2011	3	6.6	171	2200	345	yes	Digging dirt
19	10/30/12	19_613G	Scraper	Caterpillar	613G	2010	3	6.6	193	2200	439	yes	Scraping dirt
20	10/31/12	20_928Hz	Wheel loader	Caterpillar	928Hz	2011	3	6.6	171	2200	242	yes	Grading road shoulder
21	11/13/12	21_D6T_JM	Bulldozer	Caterpillar	D6T	2012	4i	9.3	223	2000	24	yes	Pushing Rock
22	12/04/12	22_D7E_WM	Bulldozer	Caterpillar	D7E	2011	4i	9.3	296	2200	296	yes	Pushing trash
23	12/06/12	23_D8T_JM	Bulldozer	Caterpillar	D8T	2012	4i	15	316	2000	32	yes	Pushing Rock
24	12/11/12	24_D6T_OC	Bulldozer	Caterpillar	D6T	2012	4i	9.3	223	2000	44	yes	Building slope, pushing dirt
25	12/12/12	25_D7E_OC	Bulldozer	Caterpillar	D7E	2011	4i	9.3	296	2200	589	yes	Building slope, pushing dirt
26	03/01/13	26_PC200	Excavator	Komatsu	PC200	2007	3	4.5	155	2000	2097	yes	Digging Trench
27	02/28/13	27_HB215	Excavator	Komatsu	HB215	2012	3	6.7	148	2000	245	yes	Digging Trench

3.2 Methodology

3.2.1 Test Matrix

Emission measurements were made for the following equipment: four backhoes, six wheel loaders, four excavators, three scrapers (one with two engines tested), six bulldozers, and four road graders. The six different types of equipment tested in this study make up about 80% of the equipment population in State of California. The tested off-road equipment used this paper are summarized in Table 3–1. The twenty-seven pieces of equipment included seven pieces of Tier 2 equipment with model years ranging from 2003 to 2007, with horsepower ratings ranging from 92 to 540 hp, and engine hours ranging from 946 to 17,149 hours. The other twenty pieces of equipment were Tier 3 and Tier 4i equipment with model years ranging from 2006 to 2012, horsepower ratings ranging from 99 to 520 hp and engine hours ranging from 242 to 5,233 hours.

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

The six bulldozers tested were working in either a landfill or a riverbed; their operations included idling and pushing trash and/or dirt. The four graders were used for grading (scraping) dirt roads; and their operations included idling, moving, and grading.

3.2.2 *PEMS Description*

Two different gaseous PEMS systems were utilized over the course of the test campaign for the measurement of gaseous emissions. For the first ten pieces of equipment, the gaseous emissions were measured with a SEMTECH DS PEMS, and the last seventeen pieces of equipment were measured with an AVL 493 PEMS. Both systems measure NO_x using a non-dispersive ultra-violent (NDUV) analyzer, total hydrocarbons (THC) using a heated flame ionization detector (HFID), carbon monoxide (CO), and carbon dioxide (CO_2) using a non-dispersive infrared (NDIR) analyzer. Both system collected raw exhaust through a sample line heated to 190°C, consistent with the conditions for regulatory measurements for THC. Therefore, the two systems were similar, notwithstanding minor differences in design and packaging. The reason for the analyzer switch was solely based on PEMS availability at the time of testing.

The PM analyzer used for all twenty-seven units was an AVL Micro Soot Sensor (MSS) with a prototype gravimetric filter box (GFB). The MSS measures soot concentration on a second–by-second basis using the photo-acoustic principle (Schindler 2004). The gravimetric filter box measurement is used to calibrate the time resolved MSS soot measurements by comparing the accumulated soot signal from the MSS with the total mass from the filter. The range of calibration factors observed varied from 1.15 to 1.25 for this testing project.

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

3.2.3 PEMS Installation

The complex design of off-road equipment required a unique installation approach for each equipment type. A custom steel frame instrument package with gaseous PEMS, PM PEMS, EFM, data logging equipment, batteries, battery charger, and other necessary operating auxiliary items was built as a single unit complete package. This PEMS package was warmed up and calibrated prior to installation it onto the off-road equipment. Once the PEMS package was secured with heavy duty ratcheting straps, only the routing of the exhaust pipes to the EFM, logging of the ECM signals, and installing the auxiliary generator for power was required.

Depending on the equipment type, the CE-CERT PEMS package generally fit best on the roof or large section of the hood due its relative large footprint. Vibration isolation mounts installed onto the steel frame along with six inch thick high-density foam pad between the frame and the vehicle provided vibrational dampening. Weather shielding protected the PEMS package from direct provides real-time instruments status.

Table 3–2: Overall time specific, fuel specific, and brake specific non-idle emissions summary for each of the 27 units tested.

MY	Tier	Hours	Unit ID	Fuel [2]	Power [3]	eLoad	eSpeed	Time Specific Emissions (g/hr)					Fuel Specific Emissions (g/kgfuel)					Brake Specific Emissions (g/hp-h)				
	Level		#	kg/hr	bhp	%	RPM	kg CO2	CO	NOx	THC	PM [5]	CO2	CO	NOx	THC	mg PM [5]	CO2	CO	NOx	THC	mg PM [5]
2003	2	17149	12_D8R	29.6	214.5	72.8	1744	93.3	145	798	20.8	28.4	3152	4.9	27.0	0.70	961	435	0.68	3.72	0.10	133
2004	2	2294	7_928G	8.3	42.4	29.8	1377.2	26.5	90.1	205	11.9	5.6	3192	10.9	24.7	1.4	670	624	2.12	4.8	0.28	131
2006	2	2599	4_310SG	5.9	33.7	40.4	2066	18.8	51.0	175	10.8	4.2	3184	8.7	29.7	1.84	719	557	1.51	5.19	0.32	126
2006	2	946	5_410G	7.3	38.8	44.2	1865	23.1	76.6	193	24.9	4.9	3188	10.6	26.7	3.43	677	596	1.97	4.99	0.64	126
2006	2	10000	9_637E[1]	25.9	161.3	61.1	1596	81.8	493	288	45.7	20.7	3164	19.1	11.1	1.77	804	507	3.06	1.78	0.28	129
2006	2	10000	10_637E[1]	38.3	274.6	54.5	1631	121.2	518	535	27.0	38.1	3164	13.5	14.0	0.71	996	441	1.88	1.95	0.10	139
2006	3	5233	11_EC460B	25.1	134.5	55.0	1650	78.9	124	384	28.8	36.9	3142	5.0	15.3	1.15	1515	587	0.93	2.86	0.21	274
2007	2	1182	1_410J	5.0	25.8	32.6	1712	15.9	64.9	138	17.5	4.0	3167	12.9	27.4	3.50	794	615	2.51	5.33	0.68	154
2007	3	1735	3_644J	14.6	81.2	41.0	1665	46.4	236	365	6.6	10.4	3181	16.2	25.0	0.45	713	572	2.91	4.50	0.08	128
2007	3	2097	26_PC200	12.0	69.0	49.2	1663	37.8	69.3	183	11.7	7.5	3150	5.8	15.3	0.98	628	547	1.00	2.65	0.17	109
2008	3	tbd	8_345D[4]	28.4				90.0	502	487	18.3	63.4	3169	17.7	17.1	0.64	2230					
2008	3	3815	13_120M	10.6	51.8	34.1	1668	33.2	108	220	15.3	18.9	3141	10.2	20.8	1.45	1792	641	2.08	4.24	0.29	365
2008	3	2706	16_120M	8.4	45.0	32.2	1525	26.1	137	162	11.8	22.1	3123	16.3	19.3	1.41	2649	581	3.04	3.59	0.26	491
2009	3	900	6_WA470-6	15.5	87.1		1296	49.4	296	450	9.7	7.3	3182	19.1	29.0	0.63	4731	567	3.39	5.16	0.11	84.2
2010	3	242	2_310SJ	8.6	45.3	52.3	1718	27.4	62.2	152	10.9	4.4	3178	7.2	17.6	1.26	5064	606	1.37	3.35	0.24	97.0
2010	3	1308	15_120M	7.4	38.6	28.2	1353	23.2	96.2	146	11.6	18.4	3128	13.0	19.6	1.57	2493	601	2.49	3.78	0.30	478
2010	3	952	17_120M_dpf	12.1	68.4	42.8	1774	38.0	131	198	11.1	2.0	3133	10.8	16.3	0.92	165	555	1.91	2.89	0.16	29.1
2010	3	439	19_613G	19.9	100.7	58.4	1638	62.6	137	315	5.0	14.3	3142	6.9	15.8	0.25	718	622	1.36	3.13	0.05	142
2011	3	289	14_928Hz	5.8	31.9	26.0	1159	18.3	85.1	182	9.6	10.3	3134	14.6	31.3	1.64	1774	573	2.67	5.71	0.30	324
2011	3	345	18_928Hz	16.0	89.9	56.1	1650	50.2	130	282	13.4	15.8	3138	8.1	17.6	0.84	989	558	1.45	3.14	0.15	175
2011	3	242	20_928Hz	11.3	56.1	36.0	1625	35.6	97.7	191	13.9	18.7	3136	8.6	16.8	1.22	1655	634	1.74	3.39	0.25	333
2011	3	245	27_HB215	9.3	55.6	43.9	1347	30.1	52.9	175	4.0	8.7	3152	5.5	18.4	0.42	907	527	0.93	3.07	0.07	152
2011	4i	2528	22_D7E_WM	19.9	106.7	35.3	1466	62.9	45.4	201	9.7	0.04	3157	2.3	10.1	0.49	1.91	590	0.43	1.89	0.09	0.36
2011	4i	589	25_D7E_OC	14.4	82.2	27.6	1466	45.6	-7.1	140	3.1	0.01	3162	-0.5	9.7	0.21	1.01	555	-0.09	1.70	0.04	0.18
2012	4i	24	21_D6T_JM	19.1	90.7	40.6	1553	60.3	-6.8	145	3.4	0.03	3162	-0.4	7.6	0.18	1.57	665	-0.08	1.60	0.04	0.33
2012	4i	32	23_D8T_JM	23.4	104.0	39.4	1548	74.1	-15.6	222	6.0	0.73 [6]	3162	-0.7	9.5	0.26	31.2 [6]	712	-0.15	2.14	0.06	7.03 [6]
2012	4i	48	24_D6T_OC	14.2	74.5	34.5	1370	45.0	-10.5	121	3.3	0.02	3162	-0.7	8.5	0.23	1.37	605	-0.14	1.62	0.04	0.26

[1] Rebuilt engine

[2] Fuel calculated from carbon balance method

[3] Power estimated from lug curve work sheet

[4] No ECM information was collected

[5] Total PM using gravimetric span method and not the model alpha methods

[6] DPF regen occurred for about 50 mins, if remove DPF regen data, PM emissins will be 0.12 g/hr, 5.51 mg/kg fuel, and 1.21 mg/hp-h gaseous emissions would reduce only slightly (< 5%)

3.3 Results

Results from emissions testing of off-road equipment are usually expressed in units of grams of pollutant per horsepower-hour (or per kilowatt-hour) of work done by the engine - the reporting units for certification purposes. However, emissions can also be expressed in units of grams of pollutant per hour (g/hour) or in units of grams of pollutant per kilogram of fuel consumed (g/kg-fuel). Emissions results will be reported using all three metrics in this paper for comparative purposes. The overall non-idle emissions results for the twenty-seven units tested are presented in Table 3–2. Valid work values were not obtained for unit 8_345D (excavator) so no brake specific emission values are available for that unit; emissions for this excavator was limited to 30 minutes due to failure of the exhaust boot connecting the stock to the EFM, Nevertheless, observation of the unit throughout the work day indicated that this unit was repeating the same operation throughout the full work day, so the data on a g/hr and g/kg of fuel basis to represent valid measurements.

The results presented in units of g/hp-hr provide for a 'high level' comparison against the certification standards. It should be noted that in contrast to the 8-mode steady-state engine dynamometer certification test cycle for Tier 2 and Tier 3 diesel off-road engines, actual in-use engine/equipment operation is highly transient, with rapid and repeated changes in engine speed and load. In addition, the average engine 'load factors' (a measure of how hard the engine is working) can be different than the certification test cycle load factor. Thus, results are not expected to be directly comparable to the certification test results, but nevertheless provide an indication of how emissions from actual, in-use diesel engines compare against their engine certification standards.

3.3.1 *Idle Emissions*

Idle emissions represent a large fraction of all equipment usage (by time). Idle emissions for each pollutant are summarized in Table 3–2 in g/hr and g/hr-L, where L is the engine displacement in liters. Overall, the idle emissions for CO_2 correlate with engine displacement, as large engines require more fuel during engine idle. Load-specific idle emissions are not presented because the load during idle is near zero.

Table 3–3: Low RPM idle emissions for each unit tested vs. engine displacement

			Idle Emissions (g/hr)					Idle Emissions (g/hr-L)				
Unit ID	% Idle	Disp (L)	CO2	CO	NOx	THC	PM	CO2	CO	NOx	THC	PM
1_410J	31.7	4.5	4234	18.9	47.4	7.03	1.082	941	4.21	10.53	1.56	0.240
2_310SJ	25.3	6.8	4740	15.8	52.3	3.62	0.522	697	2.33	7.69	0.53	0.077
3_644J	28.4	6.8	7815	38.5	93.2	4.24	0.903	1149	5.66	13.71	0.62	0.133
4_310SG	11.1	4.5	6486	32.9	129.8	6.73	0.274	1441	7.31	28.84	1.49	0.061
5_410G	21.5	4.5	4328	36.6	44.2	5.76	0.650	962	8.14	9.83	1.28	0.145
6_WA470-6	22.4	11.04	10832	56.8	119.0	6.53	1.226	981	5.15	10.78	0.59	0.111
7_928G	23.0	6.6	7734	30.2	99.0	4.13	0.699	1172	4.58	15.00	0.63	0.106
8_345D		12.5	17528	160.8	199.4	8.05	n/a	1402	12.86	15.95	0.64	n/a
9_637E	18.3	8.8	7322	32.8	111.5	13.98	0.906	832	3.72	12.67	1.59	0.103
10_637E	16.5	15.2	21352	85.7	162.9	9.30	1.825	1405	5.64	10.71	0.61	0.120
11_EC360B	18.8	12.1	9590	8.2	90.0	3.48	1.227	793	0.67	7.44	0.29	0.101
12_D8R	13.1	14.8	11978	6.0	146.2	5.55	1.248	809	0.40	9.88	0.38	0.084
13_120M	17.7	6.6	7335	30.2	130.1	4.54	0.853	1111	4.57	19.72	0.69	0.129
14_928Hz	39.2	6.6	6276	27.0	120.1	4.60	2.128	951	4.09	18.19	0.70	0.322
15_120M	28.4	6.6	6645	23.9	101.1	5.73	0.278	1007	3.63	15.33	0.87	0.042
16_120M	23.6	6.6	5693	29.5	86.9	4.00	0.179	863	4.48	13.17	0.61	0.027
17_120M_DPF	14.2	6.6	7028	30.1	106.9	3.38	0.029	1065	4.56	16.19	0.51	0.004
18_928Hz	10.4	6.6	6524	22.1	100.6	4.38	1.040	989	3.35	15.24	0.66	0.158
19_613G	28.9	6.6	7060	12.7	111.9	1.98	0.761	1070	1.92	16.96	0.30	0.115
20_928Hz	14.3	6.6	6707	17.6	112.7	4.43	0.895	1016	2.66	17.07	0.67	0.136
21_D6T_JM	27.5	9.3	10643	-3.7	98.0	0.86	0.009	1144	-0.39	10.54	0.09	0.001
22_D7E_WM	18.6	9.3	9027	4.3	89.1	2.83	0.006	971	0.46	9.58	0.30	0.001
23_D8T-JM	29.5	15.3	11412	-6.6	97.4	0.74	0.013	746	-0.43	6.37	0.05	0.001
24_D6T_OC	44.5	9.3	9548	1.6	98.5	3.71	0.005	1027	0.17	10.59	0.40	0.001
25_D7E_OC	31.2	9.3	6933	-5.0	83.7	0.74	0.005	746	-0.54	9.00	0.08	0.001
26_PC200	32.6	6.7	6589	16.4	53.8	5.55	1.112	983	2.45	8.02	0.83	0.166
27_HB215	28.5	4.5	3735	4.4	55.4	1.21	0.156	830	0.98	12.31	0.27	0.035

3.3.2 *In-Use Load Factor*

The overall in-use brake power was typically light (Table 3–2): 9 units with rated hp's between 97 to 171 had average in-use hp's <50 loading to average engine loads between 26.0 to 52.3%; 11 units with rated hp's between 148 to 296 had average in-use hp's between 50 to 100 with average engine loads between 27.6 to 56.1%; 5 units with rated hp's between 193 to 316 had average in-use hp's between 100 to 150 with average engine loads between 35.3 to 66.1%, and 3 units with rated hp's between 280 to 540 had average in-use hp's between 161 to 275 with average engine loads between 54.5 to 72.8 %.

The California Air Resources Board's 2011 Inventory Model for off-road diesel equipment provides a reference load factors (LF) for each type of off-road equipment. A load factor is used to adjust the rated horsepower of a give equipment to reflect actual operation conditions. Table 3–4 below provides averaged measured LFs in this study in comparison to the current inventory model. The measured LFs were lower than model for bulldozers and graders, higher for excavators and scrapers, and about on par for backhoes and wheel loaders.

Table 3–4: Comparisons of current inventory model and measured load factors from current study.

ARB Offroad 2007		Measured			
Equipmet Type	**Renference LF**	**Unit Tested**	**Ave. Percent Load**	**Ave. LF**	**% Diff.**
Bulldozers	42.88	6	41.70	39.04	-9.0%
Excavators	38.19	3	49.37	44.03	15.3%
Graders	40.87	4	34.33	30.91	-24.4%
Wheels Loaders	36.18	4	39.77	35.10	-3.0%
Scrapers	48.24	3	58.03	53.54	11.0%
Backhoes	36.85	4	42.39	36.91	0.2%

3.3.3 NO_x Emissions

The overall NO_x emissions for each of the units tested are provided in Figure 3-1. The top figure shows the time specific results, the middle figure shows the fuel specific results, and bottom figure shows the brake specific results. The results are sorted by MY where the leftmost results represents the older MYs tested. Comparisons with certification limits can provide a rough estimate of how the emissions from different equipment compare. It should be noted that the NMHC+NO_x certification value decreased between Tier 2 and Tier 3 engines and the split occurred roughly around MY 2007 in the presented data. Seven of the twenty-seven units tested were Tier 2, fifteen were Tier 3, and five were Tier 4i. The NMHC+NO_x certification limits varied from 5.6 g/hp-hr for Tier 2 in the 75-100 hp categories to 3.0 g/hp-hr for Tier 4i in the 175–300 hp categories. It should be emphasized that the PM certification limits are based on engine dynamometer measurements over a specific test cycle, so any comparisons with emissions from the real-world operation are not meant to imply that an individual piece of equipment may or may not be operating within certification limits. As observed, in-use NO_x for Tier 2 units were below their certification standards, and above for Tier 3 and Tier 4i units. None of the test units were exceeding the emissions standards as there is no current in-use emissions regulation for off-road equipment.

The NO_x emissions showed generally lower emissions for the Tier 4i units on a g/kg fuel and g/hp-hr basis. However, the NO_x emissions for the Tier 2 and 3 units do not show a similar trend that correlates with certification MY. For example, the highest fuel specific NO_x ($fsNO_x$) and $bsNO_x$ emissions were from a 2011 wheel loader (#14, Tier 3, Table 3–2). This is attributed to the differences in the type of work being done by each test unit; this wheel loader had the lowest engine load of any engine tested. Further, the other two wheel loaders (#18 and #20) have similar engine hours, MYs, and engine displacements, but showed almost 50% less $bsNO_x$ and $fsNO_x$ emissions. The average power over the time of operation was 56% and 36%, respectively, for these two units with lower NO_x emissions compared to the average percent load of 26% for unit #14 (Table 3–2). The percent engine load threshold for Not-to-Exceed (NTE) in-use compliance testing is 30%, thus, operation below 30% is excluded from compliance testing. However, operation below 30% occurs during in-service operation and can even represent the overall average for some in-service operations, as shown by unit #14.

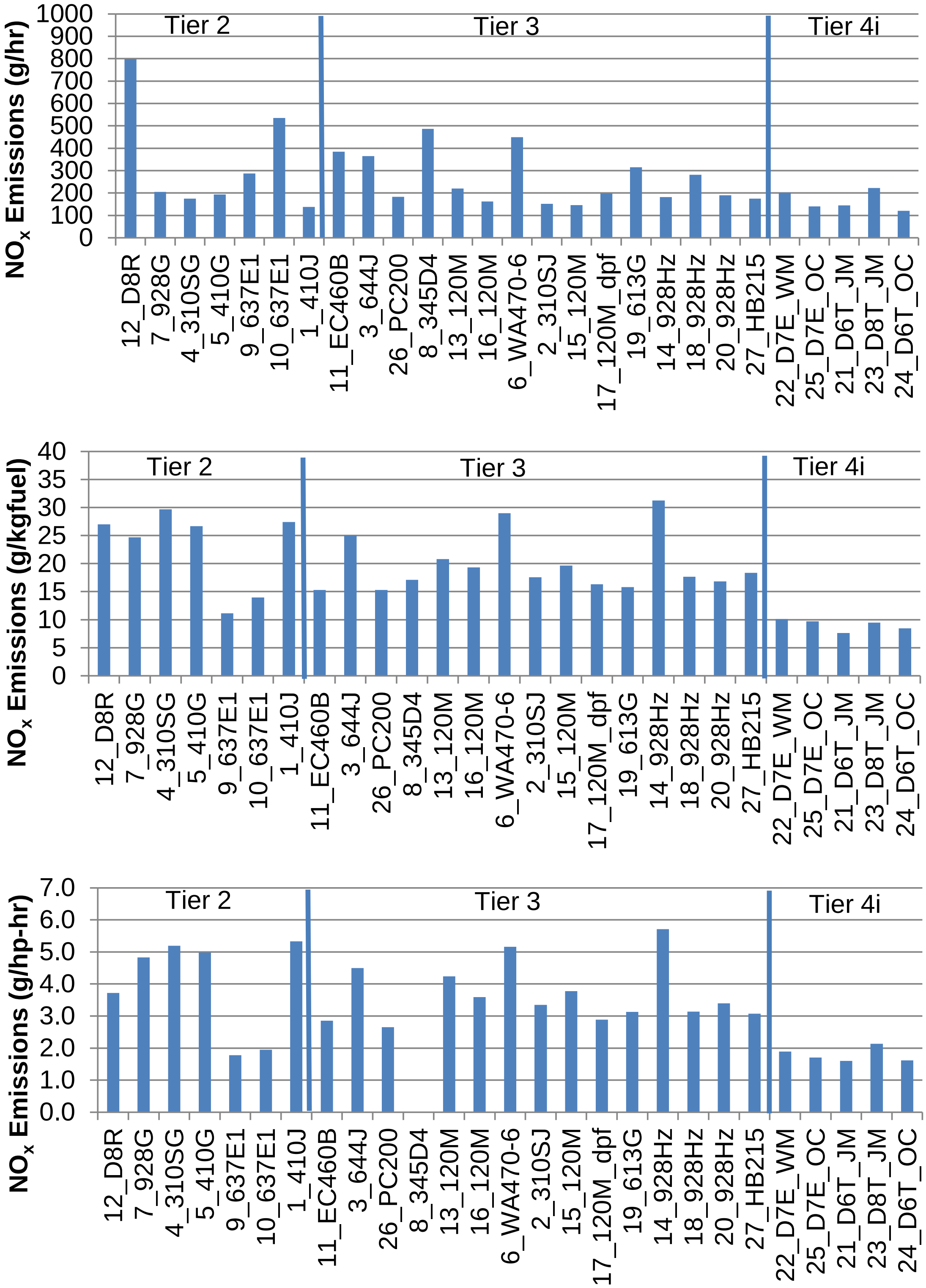

Figure 3-1: Overall average NO_x emissions for 27 units tested.
(Top – g/hr; Middle – g/kgfuel; Bottom – g/hp-h)

The oldest MY tested (#12) did not show the highest load specific emissions, but did show the highest time-specific emissions. The oldest MY unit had an average of 798 g/hr, 20.3 kg/kgfuel, and 3.72 g/hp-h NO_x emissions. The lowest $fsNO_x$ and $bsNO_x$ emissions, for units with more than 250 hours of operation, were for the front engine on a 2006 rebuilt scraper (#9). The $fsNO_x$ and $bsNO_x$ emissions were 11.1 g/kgfuel and 1.78 g/hp-hr, respectively. The actual hours were not available on unit #9 due to an engine rebuild, but the hours were estimated at more than 10,000 due to typical rebuild time recommendations. The 2006 scraper (#9) was one of seven engines tested with power ratings over 275 hp, and also one of seven engines with an average percent load over 50%. The $fsNO_x$ and $bsNO_x$ on the engines with percent loads over 50% averaged 16.9 g/kgfuel and 2.8 g/hp-h. The $fsNO_x$ is 10% lower and the $bsNO_x$ is 20% lower than the average for the less than 50% average power tests, and both are as much as 100% lower than the lowest percent load test from unit #14. The higher power operation appears to have a more significant effect on the emission factors on a work basis than engine hours or MY. Again, this suggests the type of work being performed is critical in characterizing and understanding the emission impacts from construction equipment.

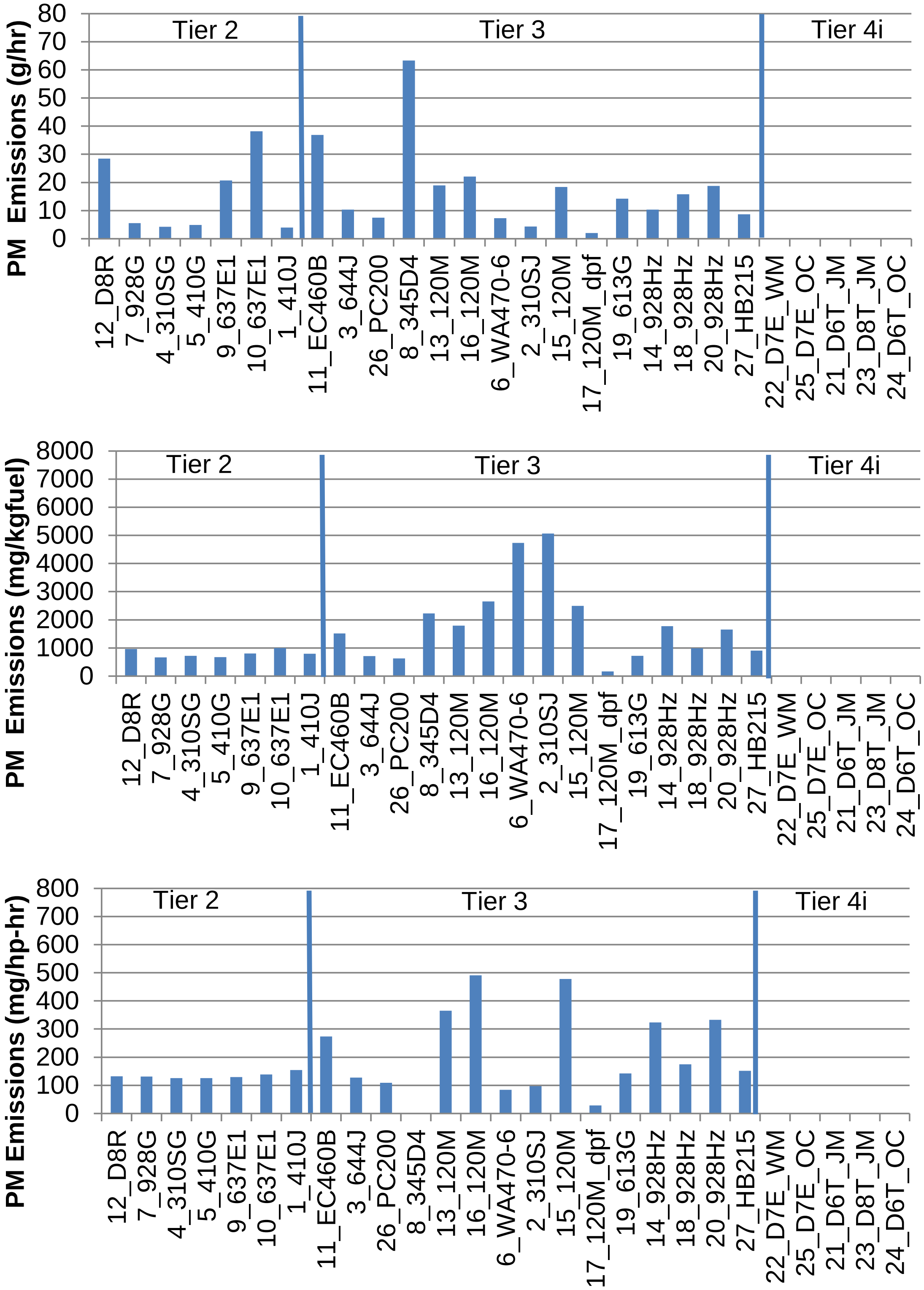

Figure 3-2: Overall average PM emissions for 27 units tested.
(Top – g/hr; Middle – g/kgfuel; Bottom – g/hp-h)

3.3.4 PM Emissions

The overall PM emissions results for each of the units tested are provided in Figure 3-2. The top figure shows the time-specific results, the middle figure shows the fuel-specific results, and the bottom figure shows the brake-specific results. The units with DPFs all showed significant reductions (>90%) in PM in comparison with those units without aftertreatment. There is a slight trend of lower brake specific PM (bsPM) emissions for older MYs when comparing units without aftertreatment (Figure 3-2) although any such trend is complicated by differences in the operational work between units. It is also possible that the engine calibration differences needed to achieve $bsNO_x$ emissions for the newer equipment could lead to increases in bsPM, although this is likely a secondary factor compared to the engine load differences.

Comparisons with certification limits can provide a rough estimate of how the emissions from different equipment compare. The PM certification limits are 300 mg/hp-h for Tier 2 and 3 in the 50-100 hp category, 220 mg/hp-h for Tier 2 and 3 in the 100 to 175 hp category, 150 mg/hp-h for Tier 2 and 3 for the 175 to 600 hp category, and 15 mg/hp-h for Tier 4i. Twenty-one of the twenty-seven units with measured brake specific emissions showed bsPM emissions lower than the certification levels. The six units that showed higher bsPM emissions were engine operations at lower power or with high engine hours. All but two of the tier 2 and tier 3 units with bsPM emissions of less than 200 mg/hp-h had power levels over 36% load, indicating that higher power levels were generally associated with lower emissions on a brake- or fuel-specific basis. The one unit that showed emissions greater than 200 mg/hp-hr bsPM with a relatively high load was the excavator (#11), it showed an average percent load of 55% and a bsPM emission of 274 mg/hp-hr (Table 3–2) One of the units (#17, a 2010 grader) was equipped with an aftermarket DPF. The bsPM emissions from this unit averaged 29.1 mg/hp-hr overall and ranged from 100.8

to 2.4 mg/hp-hr depending on the activity mode. The average bsPM for five Tier 4 interim unit was 1.1 mg/hp-hr, suggesting the particular aftermarket DPF is not as efficient as the ones on the Tier 4 interim machines.

3.3.5 Other Criteria Emissions

The overall THC emissions results for each of the units tested are summarized in Table 3–2. The THC certification levels are tied to the NMHC+NO_x, and are thus not easy to directly compare to. One would expect the brake specific NMHC (bsNMHC) emissions to be less than 1.0 g/hp-hr and they are typically less than 0.1 g/hp-h. Since CH_4 is typically not measured with a PEMS, NMHC is calculated as 0.98* THC, as per 40 CFR Part 1065. The THC emissions ranged from 0.01 to 63 g/hr, 0.18 to 3.5 g/kgfuel, and 0.04 to 0.68 g/hp-h. Two units (#1 and #5, both 410 Deere backhoes) showed relatively high THC emissions of greater than 0.63 g/hp-hr, which is almost two times more than the other units tested. The average percent loads for unit #1 and #5 were greater than 32%. This suggests the high THC is not necessarily due to light load operation. A similar Deere backhoe model 310 used over a very similar duty cycle, for example, showed about half the emissions as those for the 410 backhoe. It is unclear what caused the higher THC emissions for the 410 backhoe compared to the 310 backhoe. The Tier 4i THC emissions were considerably lower than those for most of the other older units.

The overall CO emissions results for each of the units tested are provided in Table 3–2. The top figure shows the time-specific results, the middle figure shows the fuel-specific results, and bottom figure shows the brake-specific results. The CO emission standard doesn't change between Tier levels, but changes from 3.7 g/hp-hr for engine hp less than 175 to 2.6 g/hp-hr for engine hp greater than 175.

The CO emissions ranged from 518 to -15.6 g/hr, 19.1 to -0.7 g/kgfuel, and 3.39 to -0.15 g/hp-h. Three units in the 175 to 600 hp had average CO emissions above 2.6 g/hp-h certification level, including units #9, #3, and #6. Unit #9 was a scraper and units #3 and #6 were wheel loaders. Two units (#14 and #16) in lower power categories (50 hp to 175 hp) also had average CO emissions in the same range, but they were below the 3.7 g/hp-h standard for the smaller engine category. One unit was a wheel loader and the other was a grader. The CO emissions for the Tier 4i units were essentially at the limits of detection of the PEMS, as indicated by the negative CO emissions values for some of the units. There is a strong trend in CO emissions as a function of % load, with lower % loads leading to the higher bsCO and fsCO emissions, with the exception of unit #9, the 2006 rebuilt scraper engine. This unit showed a relatively high % load, but also a high fsCO and bsCO emission of 19.1 g/kgfuel and 3.06 g/hp-h, respectively.

3.3.6 Discussions

The key finding from this study is that in-use emissions for off-road equipment can vary significantly depending on application. NO_x and PM emissions in particular, depending on the actual in-use engine load factor, can vary as much as 100% for the same type of off-road equipment. NO_x and PM emissions showed decreasing trends with engine model year, but a few Tier 3 units were observed to have much greater in-use emissions than the older Tier 2 units. The overall in-use brake power average load was between 20 and 60% for nearly all units, with only 7 units having average loads >50%, and only one unit having an average load of >70%.

The NO_x emissions showed generally lower emissions for the Tier 4i units on a g/kg fuel and g/hp-hr basis. The NO_x emissions for the Tier 2 and 3 units do not show strong trends as a function of certification model year for any of the units of comparison. Engine load appeared to be an important factor for NO_x emissions, with equipment with low average percentage engine loads showing generally higher NO_x emissions on a g/hp-hr basis and lower emissions on a g/hr basis.

The bsPM emissions for twenty of the 26 units with measured brake specific emissions showed bsPM emissions lower than the certification levels. The Tier 4 units with DPFs all showed significant reductions in PM in comparison with those units without aftertreatment. The six units that showed higher bsPM emissions may be a result of operation at lower power and high engine hours. One of the units (#17 a 2010 grader) was equipped with an aftermarket DPF. The bsPM emissions from this unit averaged 0.029 g/hp-h overall and ranged from 0.101 to 0.002 g/hp-h depending on the activity mode.

The THC emissions ranged from 0.01 to 63 g/hr, 0.18 to 3.5 g/kgfuel, and 0.04 to 0.68 g/hp-h. Two units (#1 and #5 both 410 Deere backhoes) showed relatively high THC emissions of greater than 0.63 g/hp-h, which is almost two times more than the other units tested. The Tier 4i THC emissions were considerably lower than those for most of the other older units. CO emissions did not show a trend of increases with older MY engines. The CO emissions ranged from 518 to -15.6 g/hr, 19.1 to -0.7 g/kgfuel, and 3.39 to -0.15 g/hp-h. Three units in the 175 to 600 hp range had average emissions that were higher than the 2.6 g/hp-h standard. Two units in lower power categories (50 hp to 175 hp) also had average CO emissions in the same range, but they were below the 3.7 g/hp-h standard for the smaller engine category. One unit was a wheel loader and the other was a grader. The CO emissions for the Tier 4i units were essentially at the limits of detection of the PEMS, as indicated by the negative CO emissions values for some of the units.

3.4 References

1. The 2011 National Emissions Inventory, U.S. Environmental Protection Agency; 2013; available at http://www.epa.gov/ttn/chief/net/2011inventory.html (accessed May 2014)
2. Control of Emissions of Air Pollution From Nonroad Diesel Engines and Fuel, *Final Rule*, Federal Register, June 29, 2004, vol. 69, No. 124.
3. Control of Emissions of Air Pollution From New Motor Vehicles: In-use Testing for Heavy-duty Diesel Engines and Vehicles, Federal Register, June 14, 2005, vol. 70 No. 113.
4. Abolhasani, S., Frey, H. C., Kim, K., Rasdorf. W., Lewis, P., and Pang, S., (2008) Real-World In-Use Activity, Fuel Use, and Emissions for Nonroad Construction Vehicles: A Case Study for Excavators, Journal of the Air & Waste Management Association, 58:8, 1033-1046
5. Abolhasani, S. and Frey, H. (2013). "Engine and Duty Cycle Variability in Diesel Construction Equipment Emissions." J. Environ. Eng., 139(2), 261–268.
6. Durbin, T. D., Johnson, K., Cocker, D. R., Miller, J. W., Maldonado, H., Shah, A., Ensfield, C., Weaver, C., Akard, M., Harvey, N., Symon, J., Lanni, T., Bachalo, W. D., Payne, G., Smallwood, G. and Linke, M. (2007) Evaluation and Comparison of Portable Emissions Measurement Systems and Federal Reference Methods for Emissions from a Back-Up Generator and a Diesel Truck Operated on a Chassis Dynamometer, Environ. Sci. Technol. 41, 6199- 6204.
7. Durbin, T. D., Jung, H., Cocker, D. R., and Johnson, K., (2009) PM PEM's On-Road Investigation – With and Without DPF Equipped Engines, Report prepared for Engine Manufacturers Association.

8. Durbin, T. D., Jung, H., Cocker, D. R., and Johnson, K., (2009) PM PEM's Pre-Measurement Allowance - On-Road Evaluation and Investigation, Report prepared for The Measurement Allowance Steering Committee.

9. Fiest, M.D., Sharp, C.A., Mason, R.L., Buckingham, J.P., (2008) Determination of PEMS Measurement Allowance for Gaseous Emissions Regulated under the Heavy-duty Diesel Engine In-use Testing Program. Final Report prepared by Southwest Research Institute, San Antonio, TX, EPA. Contract No. EP-C-05-018, February. <http://www.epa.gov/otaq/regs/hd-hwy/inuse/420r08005.pdf>.

10. Johnson, K. C., Durbin, T. D., Cocker, D. R., and Miller, J. W., (2008) On-Road Evaluation of a PEMS for Measuring Gaseous In-Use Emissions from a Heavy-Duty Diesel Vehicle, SAE 2008-01-1300.

11. Johnson, K. C., Durbin, T. D., Cocker, D. R., Miller, J. W., Bishnu, D. K., Maldonado, H., Moynahan, N., Ensfield, C., and Laroo, C. A., (2009) On-Road Comparison of a Portable Emission Measurement System with a Mobile Reference Laboratory for a Heavy-Duty Diesel Vehicle, Atmospheric Environment, 43, 2877-2883.

12. Johnson, K., Durbin, T. D., Jung, H., Cocker, D. R., and Kahn, M. Y., (2010) Validation Testing for the PM-PEM's Measurement Allowance Program, Prepared for Dipak Bishnu, California Air Resources Board, Contract No. 07-620.

13. Johnson, K. C., Durbin, T. D., Jung, H., Cocker, D. R., Bishnu, D., and Giannelli, R., (2011a) Quantifying In-Use PM Measurements for Heavy-Duty Diesel Vehicles, Environmental Science & Technology, 45, 6073-6079.

14. Johnson, K., Durbin, T. D., Jung, H., Cocker, D. R., and Kahn, M. Y., (2011b) Supplemental Testing of PPMD at CE-CERT to Resolve Issues with the PPMD Observed During the HDIUT PM MA Program, Prepared for Mr. Andrew Redding, Sensors Inc.

15. Johnson, K.C., Burnette, A., Cao, Tanfeng (Sam), Russell, R.L., Scora, G., (2013) AQIP Hybrid Off-Road Pilot Project. Draft Final Report submitted by the University of California to the California Air Resources Board, April.

16. Khalek, I.A., Bougher, T.L., Mason, R.L., Buckingham, J.P., (2010) PM-PEMS Measurement Allowance Determination, Final Report by Southwest Research Institute for the Heavy Duty In-Use Testing Steering Committee. SwRI Project 03.14956.12, June.

17. Khan, M. Y., Johnson, K. C., Durbin, T. D., Jung, H., Cocker, D. R., Bishnu, D., and Giannelli, R., (2012) Characterization of PM-PEMS for in-use measurements conducted during validation testing for the PM-PEMS measurement allowance program, Atmospheric Environment, 55, 311-318.

18. Miller, J.W., Durbin, T.D., Johnson, K.J., Cocker, D.R., III, (2006) Evaluation of Portable Emissions Measurement Systems (PEMS) for Inventory Purposes and the Not-to-Exceed Heavy-Duty Diesel Engine Regulations; final Report for the California Air Resources Board, July.

19. Gautam, M., Carder, D.K., Clark, N.N., and Lyons, D.W. (2002) Testing of Exhaust Emissions of Diesel Powered Off-Road Engines. Final Report under CARB contract No. 98-317, May.

20. Scora, G., Durbin, T., McClanahan, M., Miller, W., and Barth, M. (2007) Evaluating the Emissions from Heavy-Duty Diesel Construction Equipment. Proceedings of the 17th CRC On-Road Vehicle Emissions Workshop, San Diego, CA, March.

21. Barth, M., Durbin, T. D., Miller, J. W., and Scora, G. (2008) Final Report, Evaluating the Emissions from Heavy-Duty Construction Equipment, Prepared for: California Department of Transportation (Caltrans) Division of Research and Innovation RTA 65A0197.

22. Barth, M., Thomas D. Durbin, J. Wayne Miller, Kent Johnson, Robert L. Russell, George Scora, (2012) Measuring and Modeling PM Emissions from Heavy-Duty Construction Equipment, Final Report for the California Department of Transportation (Caltrans) by the University of California at Riverside, January.

23. Kishan, S., Fincher, S., Sabisch, M., (2011) Populations, Activity and Emissions of Diesel Nonroad Equipment in EPA Region 7, Final Report for the US EPA and the CRC E-70 program by Eastern Research Group, EPA Contract No. EP-C-06-080.

24. Giannelli, R., Fulper, C., Hart, C., Hawkins, D. et al., (2010) In-Use Emissions from Non-road Equipment for EPA Emissions Inventory Modeling (MOVES), SAE Int. J. Commer. Veh. 3(1):181-194, SAE Technical Paper No. 2010-01-1952.

25. Warila, J.E., Glover, E., DeFries, T.H., Kishan, S., (2013) Load Factors, Emission Factors, Duty Cycles, and Activity of Diesel Nonroad Vehicles. Proceedings of the 23rd CRC Real World Emissions Workshop, San Diego, CA, April.

26. Frey, H. and Bammi, S. (2003) Probabilistic Nonroad Mobile Source Emission Factors, J. Environ. Eng., Vol. 129, 162–168.

27. Frey, C. (2008) Real-World Duty Cycles and Utilization for Construction Equipment in North Carolina. Technical Report for Research Project Number FHWA/NC/ 2006 – 55.

28. Frey, H.C., Rasdorf, W., Kim, K., Pang, H-S, Lewis, P., (2010) Comparison of Real-World Emissions of B20 Biodiesel Versus Petroleum Diesel for Selected Nonroad Vehicles and Engine Tiers, Transportation Research Record, Issue 2058, pp. 33-42.

29. Frey, H.C., Kangwook, K., Pang, H-S, Rasdorf, W., Lewis, P., (2008a) Characterization of Real-World Activity, Fuel Use, and Emissions for Selected Motor Graders Fueled with Petroleum Diesel and B20 Biodiesel. J. Air Waste Manage. Assoc., Vol. 58, pp. 1274-1284.

30. Frey, H.C., Pang, H-S, Rasdorf, W. (2008b) Vehicle Emissions Modeling for 34 Off-Road Construction Vehicles Based upon Real-World On-Board Measurements. Proceedings of the 18th CRC On-Road Vehicle Emissions Workshop, San Diego, CA, April.

31. Frey, H.C., Rasdorf, W., Lewis, P., (2010) Comprehensive Field Study of Fuel Use and Emissions of Nonroad Diesel Construction Equipment, Transportation Research Record, Issue 2158, pp. 69-76.

32. Pang, S.H., Frey, H.C., Rasdorf, W., (2009) Life Cycle Inventory Energy Consumption and Emissions for Biodiesel versus Petroleum Diesel Fueled Construction Vehicles, Enviro. Sci. Technol., Vol. 43, 6398-6405

33. Rasdorf, W., Frey, C., Lewis, P., Kim, K., Pang, S., and Abolhassani, S., (2010) Field Procedures for Real-World Measurements of Emissions from Diesel Construction Vehicles, Journal of Infrastructure Systems, 16: 216-225.

34. Lewis, P., Rasdorf, W., Frey, H.C., (2009a) Development and Use of Emissions Inventories for Construction Vehicles, Transportation Research Record, Issue 2123, pp. 46-53.

35. Lewis, P., Rasdorf, W., Frey, H.C., Pang, S.H., Kim, K., (2009b) Requirements and Incentives for Reducing Construction Vehicle Emissions and Comparison of Nonroad Diesel Engine Emissions Data Sources, J. Constr. Eng. Manage., Vol. 135, 341–351.

36. Lewis, P., Leming, M., Frey, H.C., Rasdorf, W., (2011) Assessing Effects of Operational Efficiency on Pollutant Emissions of Nonroad Diesel Construction Equipment, Transportation Research Record, Issue 2233, pp. 11-18.

37. Lewis, P., Rasdorf, W., Frey, H.C., Leming, M., (2012) Effects of Engine Idling on National Ambient Air Quality Standards Criteria Pollutant Emissions from Nonroad Diesel Construction Equipment, Transportation Research Record, Issue 2270, pp. 67-75.

38. Huai, T., S.D. Shah, T.D. Durbin, J.M. Norbeck. (2005) Measurement of Operational Activity for Nonroad Diesel Construction Equipment. *International Journal of Automotive Technology*, vol. 6, p. 333-340.

39. California Air Resources Board [CARB] (2011) Appendix D: OSM and Summary of Off-Road Emissions Inventory Update.

40. Schindler, W., Haisch, Ch., Beck, H.A., Niessner, R., Jacob, E. and Rothe, D.(2004) A Photoacoustic Sensor System for the Time resolved Quantification of Diesel Soot Emissions, SAE Technical Paper Series 2004-01-0969

Chapter Four: A Generalized Approach for Characterizing Emissions Benefits of Hybrid Off-Road Equipment via Physical Activity and Engine Work: A Case Study for Bulldozers

4.1 Introduction

Hybrid engine technologies are growing in popularity as government agencies and manufactures strive to reduce petroleum consumption and reduce greenhouse gas (GHG) emissions. Worldwide, agencies around the globe are promoting regulations to reduce greenhouse gas (GHG) emissions, an effort to reduce to impacts of climate change. Recently, the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) have jointly issued GHG emissions standards increasing fuel efficiency requirements for heavy duty vehicles (MY 2014) and light duty vehicles (MY 2017) (Federal Register 2010, 2011). The U.S. Energy Information Administration projects that hybrid technology light duty vehicles (LDVs) will play a critical role in meeting increasing stringent fuel economy regulations, with the market share of hybrid LDVs increasing from 4% in 2012 to 40% by 2040 (AEO 2014).

Hybrid technologies for HDVs are more complex than their LDV counterparts. Several studies have shown that the true benefits for on-highway heavy-duty hybrids can vary significantly and are a function of the real-world application and hybrid system design. Hallmark et al. (2013) reports a GHG emission benefit for in-use hybrid buses; however, but the nitrogen oxide (NO_x) emissions were observed to be higher than the conventional bus. The National Renewable Energy Laboratory (NREL) conducted a 13-month study on a fleet of hybrid and conventional class 8 heavy duty trucks. The NREL study found a 0%-30% fuel economy improvement and a 5%-101.3% NO_x increase due to the higher NO_x certification level of the selected engine in the hybrid bus (Walkowicz 2013). Similar to the NREL study, an evaluation by the University of California, Riverside (UCR) found up to a 60% reduction in GHG emissions but higher CO emissions for hybrid class 8 heavy duty trucks in comparison to a conventional truck with both benefits and dis-benefits for NO_x emissions (Russell 2012).

Recently, hybrid configurations are migrating to on off-road equipment. Hybrid off-road equipment offers the potential to reducing both greenhouse gas (GHG) emissions and criteria emissions by cutting engine fuel consumption using sophisticated designs with multiple power sources. However, little independent in-use emission studies have been conducted to evaluate the true emissions benefits of hybrid equipment relative to conventional equipment. Sokolsky et al. (2011) evaluated the fuel consumption and productivity of a diesel-electric (hybrid) bulldozer against selected conventional bulldozers; however no emissions were measured. Block et al. (2012) measured emissions in-use from a hybrid excavator using a portable emissions measurement system (PEMS); however no data was released and ECM data was not logged. At this early stage of deployment, fuel consumption and emissions evaluations are needed to assess the in-use benefits of off-road equipment hybridizations.

The goal of this study was to develop a methodology to evaluate the real-world emissions and fuel consumption benefits from hybrid off-road construction equipment in comparison to conventional alternatives and to evaluate differences in emissions between different types of in-use operations. Traditionally, off-road engines are certified on engine dynamometers on generalized steady state and transient duty cycles that do not reflect the true usage of any particular type of off-road equipment. As a case study, University of California, Riverside, College of Engineering, Center for Environmental Research and Technology (UCR CE-CERT) studied a total of six hybrid and conventional bulldozers. The bulldozers included three

Caterpillar D7E hybrids, one Caterpillar D8T, one Caterpillar D6T, and a Caterpillar D8R. Activity measurements were made on a subset of three hybrids and one comparable conventional piece of equipment to characterize the typical operation of different units. Activity data were obtained from interview of equipment operator, historical records, and in-use activity measurements, which included time-lapse video, real-time engine control module (ECM) broadcast data, and real-time GPS data. The collected activity data were used to develop duty cycles to allow accurate comparisons between the hybrid and conventional equipment. A subset of five pieces of both hybrid and conventional bulldozers were evaluated for emissions and fuel consumption over the developed duty cycles using a 40 CFR 1065 approved PEMS.

4.2 Methodology

4.2.1 *Test Vehicles and Fleets Selection*

A total of 6 bulldozers were recruited for either activity or emission measurements. A list of these bulldozers, including their engine information, emissions tier level, model year, and fleet owner are provided in Table 4–1. The test matrix was designed to obtain emissions data from conventional equipment most similar to the D7E hybrid. The D7E bulldozer utilizes a diesel engine as a generator to power two electric drive motors directly connected to the D7E’s undercarriage. The electric drive system allows the use of a narrower engine speed (between 1500 rpm and 1800 rpm), producing higher overall engine efficiency. Caterpillar considers the D7E a “diesel-electric” rather than a true hybrid since there is no battery for energy storage; however, the D7E is still generically considered a hybrid as it uses both diesel engine and electric motors.

Finding a direct comparison for the D7E in the Tier 4i emissions category was difficult as Caterpillar no longer produces a conventional D7 certified to the Tier 4i emissions level. Therefore, the intended industry replacement was studied instead. Caterpillar produces both the

D6T and the D8T conventional bulldozers in the Tier 4i level. The D6T is a slightly smaller machine but has the same displacement engine, while the D8T is much larger in dimension, push capacity, and engine size. The overall hybrid bulldozer evaluation is primarily based on comparisons to the conventional D6T as the main point of this study is to evaluate benefits due to the hybrid system. Benefits due to unit size, aftertreatment system, tier level, and unit capacity should not be the significant factors in the comparison. Thus the D8T and D8R evaluations were less robust compared to the evaluation of the D6T due to comparable engine sizes and push capabilities.

Table 4–1: Model, Owner, Model Year, and Engine information of bulldozers studied.

ID	Unit Model	Facility [2]	Eng Model	Disp	Year	Eng Hr[1]	Gross Power[3]		ATS	Activity	Emissions
#	n/a	n/a	n/a	liters	n/a	hr	Hp	RPM	n/a	n/a	n/a
1	D8R T2	WM	3406E	14.6	2003	17149	348	1800	n/a	Yes	Yes
2	D6T T4i	JM	ACERT C9.3	9.3	2012	24	229	1850	DOC/DPF	No	Yes
3	D8T T4i	JM	ACERT C15	15.2	2012	600	348	1850	DOC/DPF	No	Yes
4	D7E T4i	WM	ACERT C9.3	9.3	2011	2528	252	1700	DOC/DPF	Yes	Yes
5	D7E T4i	OC	ACERT C9.3	9.3	2011	573	252	1700	DOC/DPF	Yes	Yes
6	D7E T4i	RC	ACERT C9.3	9.3	2011	235	252	1700	DOC/DPF	Yes	No

[1] Nominal hours during testing (varies by day used)
[2] Owner is the equipment owner. JM is Johnson Machinery (rental), WM is Waste Management, OC is Orange County Water District, and RC is County of Riverside Transportation Department.
[3] Gross power ratings are from published materials.

The activity measurements were made at three facilities: Waste Management (WM), the Orange County Water District (OC), and the County of Riverside Transportation Department (RC). WM represents a landfill operation at the El Sobrante landfill near Corona, California. OC represents a water district which maintains local rivers, water basin, and lakes near Santa Ana, California. RC represents a rock quarry for maintaining public roads operated in multiple sites throughout Riverside County, California. WM is a private fleet and operates around the clock six days a week; OC and RC represent public fleets and operate their equipment at Monday through Thursday from 6:00 AM to 3:00 PM. For this reason, the majority of the data were obtained at the WM facility for both activity and emissions. The D8R at WM was not the most equivalent conventional to the D7E in terms of size; however, it is the facility machine to be replaced by the hybrid D7E.

4.2.2 *Activity Measurement Equipment Description*

Two time-lapse cameras were mounted on each unit, and a GPS and an engine control module (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 identify the type of work being performed in both directions. 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 used (PlotWatcher Pro) are battery operated and programmed to record one frame every one to ten seconds depending on the location. The video data was critical for determining the activity performed. The bulldozer activity ranged from refuse pushing, road building, rock pushing, river bed clearing, to slope repairs.

The ECM tool used in this study was a beta version of the UniCAN Pro and GPS data logging system supplied by CSM Product Inc. This system is a self-contained J1939 ECM interface and data logging tool. It was configured to start logging with key-on and stop logging with key-off. The UniCAN was upgraded to send specific J1939 request messaging so that it worked at 100 percent reliability with the Caterpillar D7E. This new tool greatly improved UCR's data capture success in comparison to other ECM tools existing on the market at the time.

4.2.3 *PEMS Description*

The PEMS equipment utilized in this research was compliant with federal test methods for in-use testing (40 CFR 1065) for the gaseous and PM systems. The gaseous and PM PEMS were the AVL gaseous PEMS and AVL PM PEMS, respectively. An exhaust flow meter designed and manufactured by Sensors, Inc. was used with the PEMS systems. The specific AVL 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). The NO_x value is calculated from NO and NO_2 and reported on a NO_2-equivalent basis. The PM PEMS measurement system selected was AVL's 483 micro soot sensor (MSS) in conjunction with their gravimetric filter module (GFM) option. The combined system is called the AVL 494 PM system. The instrument measures the modulated laser light absorbed by particles with an acoustical microphone. The photo-acoustic measurement principle directly measures elemental carbon (EC) mass (also called soot) and has been found to be robust and to have good agreement with the reference gravimetric method for EC dominated PM (Schindler 2004).

The exhaust flow meter (EFM) used was Sensors Inc.'s High Speed EFM (HS-EFM). The EFM is based on differential pressure principle and is desired with the wide range of exhaust flows and dynamics of transient vehicle testing. An appropriate 5" exhaust flow meter was selected to match all of the displacement of the engine being tested in this study.

4.2.4 *In-use Emissions Testing and Analysis*

The in-use emissions duty cycle is based on a push-pull type of operation. A bulldozer starts a push by putting the blade down and move slowly forward. As the materials accumulate in the blade, the loading on the engine goes up, and bulldozer travel speed goes down. When the material loading reaches a maximum, the bulldozer will start to spin its tracks or come to halt. At this point of time, the operator will lift the blade slightly to regain traction and continue moving forward. When the push finishes, the operator lifts up the blade completely, pulls back to its original starting position and is ready for the next push. Each push-pull combined operation defines a micro-trip during which a type of work is performed by a bulldozer from start to finish.

Each D7E bulldozer in this study had a different blade size and track type due to differences in application. Therefore, in order to provide the most fair comparison between engines, instead of pushing material, UCR proposed a draw bar pull test of container bins of known weight to simulate the same engine loading as a push event, but in a much more repeatable and controllable manner than a normal loaded pushing operation. A load cell is added between the draw bar and the bin to measure the load force on the draw bar. Pull-back tests were done separately with the bulldozer traveling backwards for predetermined distances. The two sets of data were subsequently analyzed together to produce a complete push and pull bulldozer operation.

In addition to the push pull test, in-service operations unique to OC were also evaluated. However, the results were not as consistent the draw bar test, as machine to machine feature differences that contributed to productivity variations as great as 51%. This portion of testing was conducted at a stretch of Santa Ana River bed near Santa Ana, California. Controlled in-service operations such as slope building and earth removal pushes were performed. The rental D6T and OC's D7E had the same C9.3 ACERT engine, but was different in almost every other way. The D6T was equipped with 10.8 foot wide standard blade with a side extension made for more generalized application and was equipped with high track with lifted sprocket for better ground clearance. The OC D7E is an OC owned unit equipped with 15.2 foot wide variable radius blade custom made by Balderson Blade Co. The extra wide blade is specially fit for OC's day to day activity and is about 40% larger than that of the D6T equipped blade. The OC D7E is also a LGP model with extra wide track for work in the river where the D6T has the standard track widths.

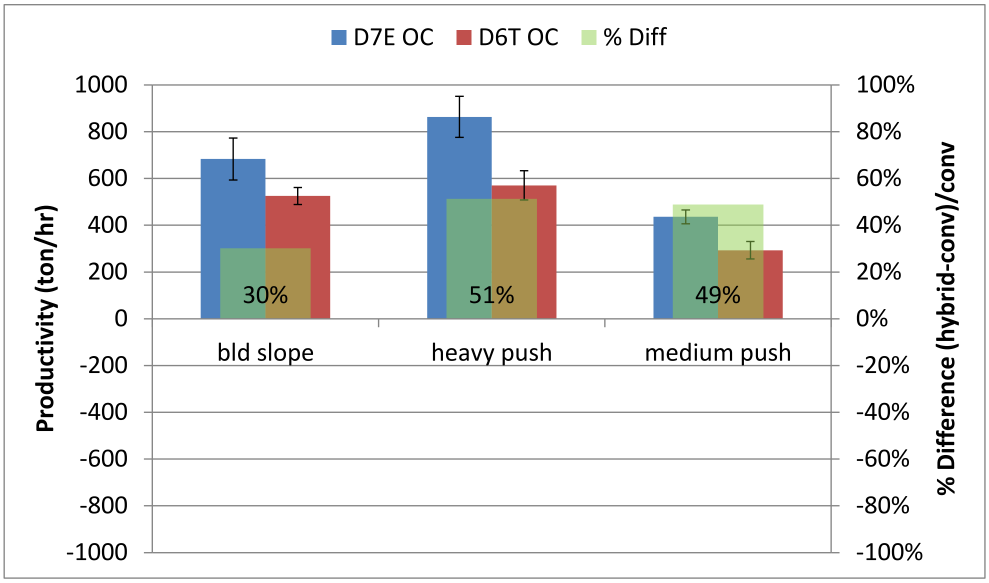

Figure 4-1: Controlled in-use testing performance ton/hr D7E vs D6T

Figure 4-1 shows the performance of the D6T and D7E on a tons/hr basis for three different modes. For each testing mode, comparisons are made between the D7E and D6T bulldozer. The modes include building a slope, and excavating a 50 by 50 foot pad at two different cut depths (heavy and medium). The figure shows that the D7E is about 30% to 50% more productive in term of tons of material moved per hour than the D6T where the two pad excavations showed the highest benefits compared to the slope building. Again, a large D7E benefit is not all due to the hybrid power train but rather a combined contribution from larger machine size, a larger application specific blade (40% larger), and more experienced D7E operator compared to the D6T rented unit. The higher performance of the D7E over the D6T suggests the emissions will also show a benefit. Some of this benefit will be a result of the blade and track details and some of the benefit will be due to the hybrids higher traveling velocity. Thus, these emission differences of the in service testing at OC will be not discussed in detail in this report and the discussion. These observations provide clear evidence of challenges comparing in-use operations of hybrid vs. conventional off-road engines.

4.3 Results

4.3.1 Activity Study and Duty Cycle Development

The development of the bulldozer duty cycle required developing micro-trips, or segments of unique behavior, or a combination of both. It was quickly discovered that the bulldozer behavior is repetitive with its forward and backward movements. Figure 4-2 shows the GPS location of the bulldozer overlaid on a Google map satellite image. The figure shows the bulldozer movement for the 48,000 seconds that it operated on this particular test day.

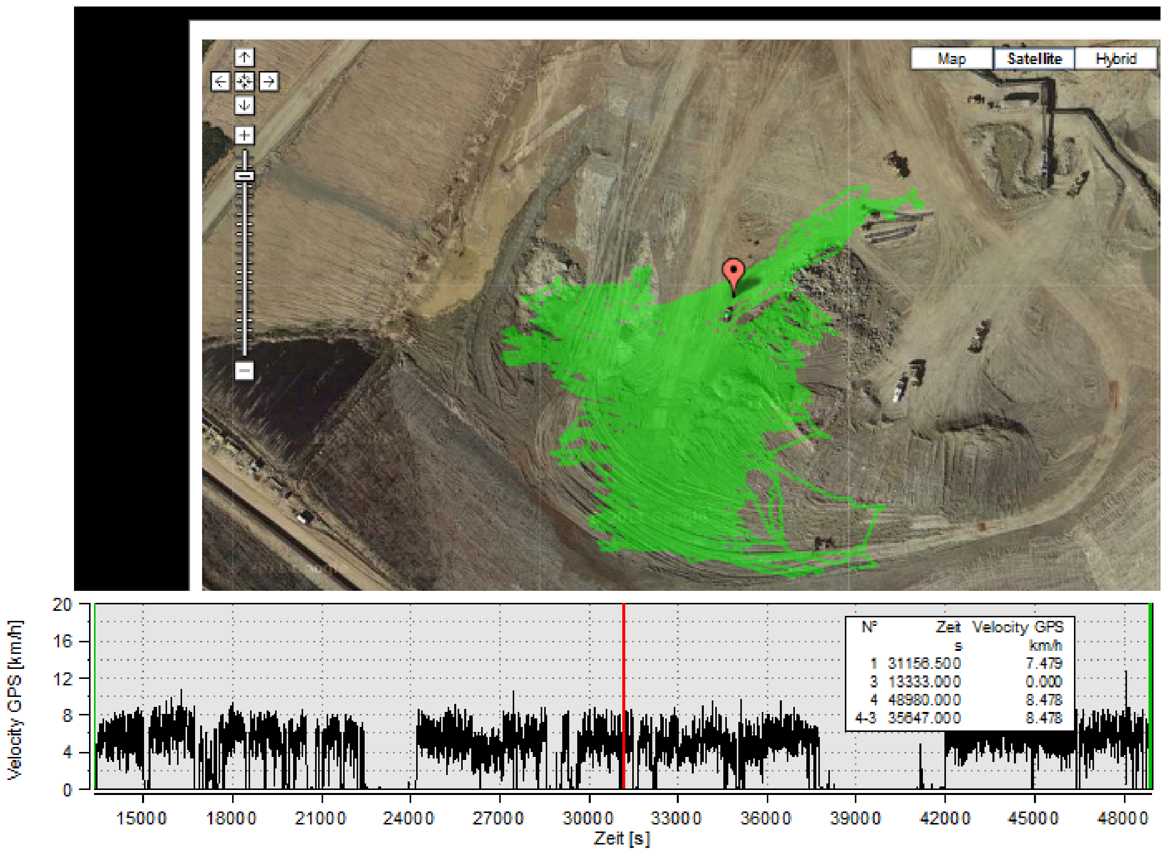

Figure 4-2: GPS overlay onto Google Maps to show physical in-service activity

GPS data was used to provide a real-time heading where a change in direction from forwards to backwards was very easy to calculate and was a reliable metric to determine bulldozer micro-trips. Figure 4-3 shows the bulldozer's GPS signal for heading in degrees. Going from 1º to 359 º is actually only 2º of difference for a 360º circle, but going from 1º to 181º is reverse in direction. In order to calculate a micro-trip, the difference in degrees was calculated (Figure 4-3). Every spike in degree represents a change in heading. This is true as long as the heading difference is greater than 100º but less than 300º. In general, all the micro-trips presented in this report are based on changes in heading direction.

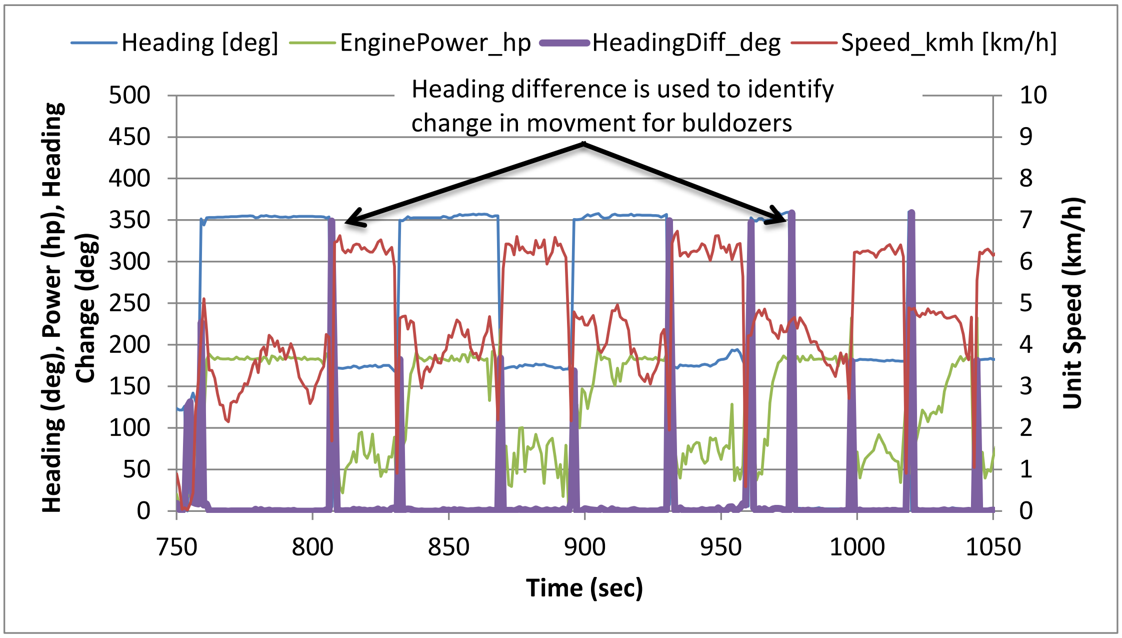

Figure 4-3: Bulldozer micro-trip identification using GPS heading change.

The video was also useful to determine the time spent in each work mode. The video captured approximately 320, 80, and 60 hours of valid activity at WM, OC, and RC, respectively. A record of the time spent in each mode was documented by watching the video. Hours where the equipment was not moving and obviously parked were not counted. Since the ECM logger was independently developed for this program, there was only one unit available during this program, where there were two sets of cameras available. Thus, the cameras were installed on the equipment for a longer period of time (one month), and the ECM logger was installed for about one week at each site. The number of hours and the percentage of time spent in each mode were calculated for the video and ECM results (Table 4–2).

Table 4–2: Video and ECM activity mode percent time fractions for the D7E and D8R

Participant	*Equipment*	*Activity/Mode Number*		*ECM Hours*	*ECM %*	*Video Hours*	*Video %*
WM	D7E T4i	Trash [1]	1	16.9	31.7%	231	72.0%
WM	D7E T4i	Dirt [1]	2	24.3	45.4%	69.9	21.8%
WM	D7E T4i	Ops Layer [2]	3	0.8	1.5%	7.3	2.3%
WM	D7E T4i	Floor [3]	4	10.6	19.9%	11.0	3.4%
WM	D7E T4i	Roads [2]	5	0.8	1.5%	1.5	0.5%
WM	D8R T3	Trash [1]	1	21.3	100.0%	186	100.0%
RC	D7E T4i	Prep [3]	6	15.8	41.4%	42.7	51.8%
RC	D7E T4i	Rocks [1]	7	22.4	58.6%	39.7	48.2%
OC	D7E T4i	Wet River [1]	8	2.2	4.1%	3.8	5.1%
OC	D7E T4i	Water basin [1]	9	42.5	77.7%	59.1	79.8%
OC	D7E T4i	Dry pond [1]	10	2.5	4.6%	3.0	4.0%
OC	D7E T4i	Sides [2]	11	7.4	13.6%	8.2	11.0%

[1] Pushing trash, fill dirt, dry river dirt and weeds, wet river dirt and weeds, and rocks
[2] Building operational layer, roads, and pond sides
[3] Preparing area for material and building roads for trucks

For OC, mode 9 (water basin work) represented ~80% of the activity. For the RC site modes 6 (site preparation) and 7 (pushing rocks) represented 40-50% and 50-60% of the activity, depending on whether the video or ECM data was used. For the WM site, there are more significant differences between the video and ECM percent times. For the video, mode 1 was found to represent ~70% of the activity, and for the ECM data, mode 2 represented the highest percentage time at 45%. The reason for the differences for WM could be due to issues in sampling for short durations with the real-time tools. The ECM data was captured for fewer days than the video, with approximately 53 hours of valid ECM data compared to over 400 hours of recorded video. According to the WM survey information, pushing trash is the dominate operation at the land fill and is estimated at the 60 to 80% range for the D7E and higher for the D8R. The video and survey information suggests that the ECM fractions are less representative of the true operational behavior. This doesn't suggest the ECM data is invalid, but it does suggest that the periods of time captured by the ECM logger at WM are less representative of the overall behavior modes of WM. Thus, the time spent in each mode was weighted on video records.

An idle mode was created to account for idle time separately, as equipment idling cannot be readily identified by video. Any engine speed data of more than 5 seconds of continuous idle was flagged as an idle mode. This idle approach was necessary to quantify the micro-trip statistics properly and to develop the proposed duty cycles as the idle time is very significant part of the operational time for off-road equipment. Percent time at idle is shown in Table 4–3 for each of the participants and all the units tested. Percent idle time ranged from 12% for WM D7E to 20% for OC D7E. WM survey records showed 15% of their bulldozers operation is idling, which agrees well with our activity measurements. Due to the high level of idle for each of the participants, an extended idle time was proposed as one of the test cycle modes.

Table 4–3: Idle time as measured during activity assessment for each of the participants

	WM_D7E		*WM _ D8R*		*OC*		*RC*	
Description	hr.	%	hr.	%	hr.	%	hr.	%
Total Idle	7.6	14%	0.7	12%	4.8	20%	5.5	15%
Idle < 900 rpm	3.4	6%	n/a	n/a	3.8	16%	4.9	14%
900 rpm < Idle < 1350 rpm	1.0	2%	n/a	n/a	0.3	1%	0.2	1%
Idle > 1350 rpm	3.2	6%	n/a	n/a	0.7	3%	0.3	1%
Total ECM Log Time	54.4		6.2		23.8		36.5	

Pushes and pulls are the primary function of the bulldozers. The push/pull distance traversed can vary from a short 1-2 meter push to as large as a few hundred meters. The micro-trip statistics presented below represents all the valid ECM and GPS data for the D7Es and D8R for each of the participants. The data was considered as a whole by participant, by mode, and as a composite from all participants. All the micro-trips were pooled into large files with the appropriate flags and processed with a Matlab program. It was quickly noticed that normal averaged results would not work on the micro-trip statistics due to the skewed data set, as discussed below. As such, statistical percentiles were used from a Matlab program. The program calculated and reported the 10^{th}, 50^{th}, and 90^{th} percentile statistics. From these statistics the proposed duty cycle was prepared.

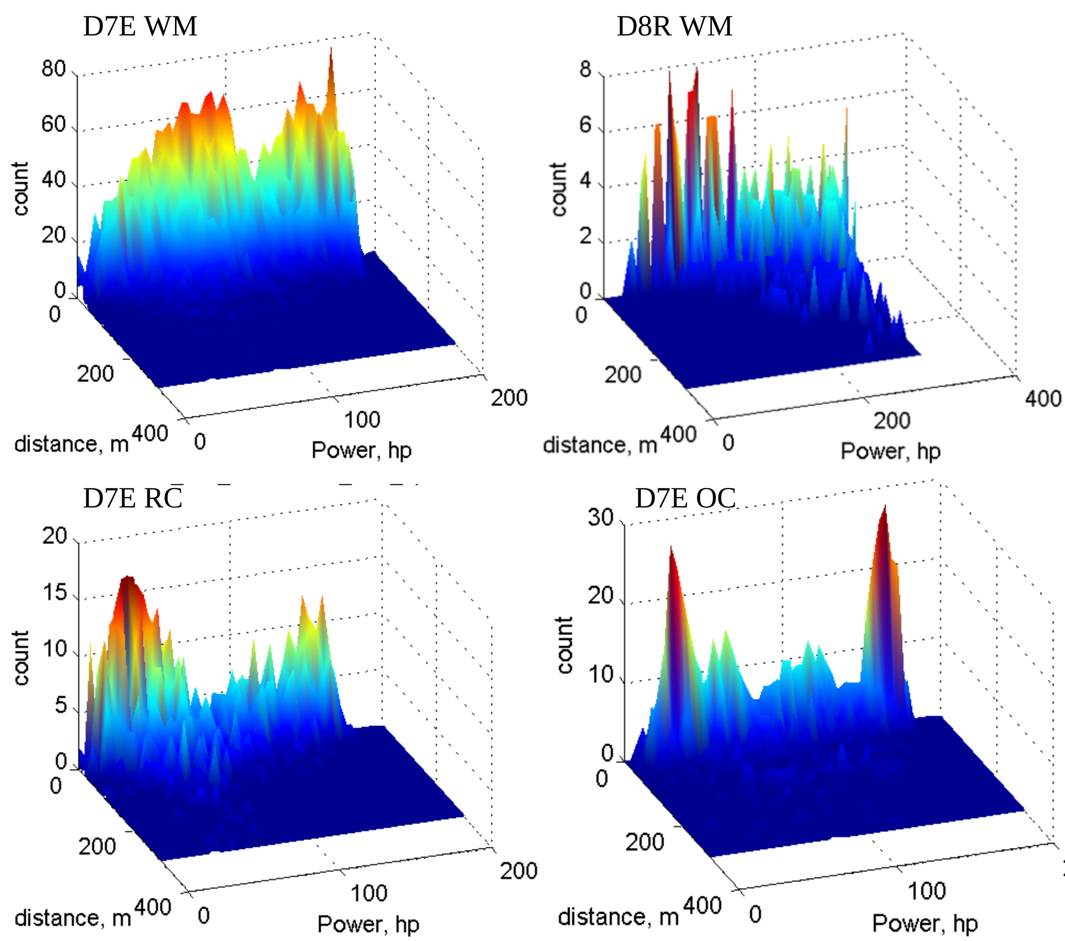

Figure 4-4: Contour plots of micro-trips for distance, power, and frequency for WM D7E, WM D8R, RC D7E, and OC D7E.

The important parameters for a push and pull event are the length of the push and the average load during the push. Figure 4-4 shows the combined statistical distribution of push distance and engine power for the D7Es at all three sites and the D8R at WM. In summary, the statistics showed that the bulldozer micro-trip distance and power vary by operational mode and by facility.

Table 4–4 summarizes the 10th, 50th, and 90th percentile statistics of push distances and engine power of the D7E bulldozers for different operational modes and weighting fractions determined by video. WM shows predominantly short 50th percentile micro-trips for modes 1 – 5, where mode 1 is the longest at 32 m. Mode 1 also represents the bulk of their operation. RC shows micro-trip distances from 37m to 26 m, which represent half of their operation at each mode. OC shows a 29 m micro-trip distance for the dominant operating mode. Thus, a 50th percentile micro-trip distance of 30 m appropriately represents all the facilities. Additionally, the 10th percentile micro-trip is close for all facilities at 10 m; however, the 90th percentile distance is very broad with micro-trip distance ranging from 60 m at WM to 120 m at OC.

Table 4–4: Distance and power micro-trip summary statistics weighted by operational mode

Facility	*Work Mode*	*10th*	*50th*	*90th*	*Use Fraction*
WM	1	8.8 m/65 hp	32.2 m/105 hp	61.7 m/173 hp	72%
WM	2	8.7 m/57 hp	20.9 m/110 hp	45.7 m/174 hp	21.8
WM	3	7.2 m/10 hp	14.7 m/91 hp	21.0 m/ 171 hp	2.3%
WM	4	5.9 m/31 hp	12.1 m/97 hp	32.9 m/166 hp	3.4%
WM	5	7.3 m/43 hp	19.4 m/61 hp	40.1 m/ 89 hp	0.5%
WM Weighted Ave.	n/a	8.6 m/61 hp	28.6 m/105 hp	57.2 m/172 hp	n/a
RC	6	11.5 m/31 hp	37.8 m/53 hp	106.0 m/ 89 hp	51.8%
RC	7	11.0 m/22 hp	26.0 m/78 hp	55.4 m/152 hp	48.2%
RC Weighted Ave.	n/a	11.3 m/26 hp	32.1 m/65 hp	81.6 m/119 hp	n/a
OC	8	8.3 m/42 hp	20.9 m/85 hp	138.8 m/144 hp	5.1%
OC	9	13.1 m/47 hp	29.1 m/84 hp	124.4 m/ 135 hp	79.8%
OC	10	12.9 m/68 hp	27.0 m/100 hp	48.8 m/137 hp	4.0%
OC	11	17.5 m/25 hp	30.9 m/81 hp	37.6 m/168 hp	11.0%
OC Weighted Ave.	n/a	13.3 m/45 hp	29.2 m/84 hp	112.4 m/139 hp	n/a
Overall Weighted Ave.	n/a	11.1 m/44 hp	30.0 m/85 hp	83.4m/143 hp	n/a

WM is observed to load the bulldozer more heavily compared to RC and OC. Table 4–4 shows a list of 10th, 50th, and 90th micro-trip summary statistics for power weighted by operational mode and use fraction. The WM data shows more power at all percentiles compared to OC and RC, suggesting the type of pushes (heavy versus light) vary between facilities. These observations makes sense given WM's business is to move as much material as fast as possible, where OC and RC are trying to accomplish a specific task that requires moving specific material for a given job. As such, both heavy and light pushing were including in the test cycles.

Based on the overall weighted averages, seven test cycles were proposed. This included push distances representative of the 10th, 50th, and 90th percentiles with both a heavy and light load at each distance, along with an idle mode, and several in-service cycles were also used. The test cycles are summarized in Table 4–5.

Table 4–5: In-use test duty cycles developed in this study for hybrid and conventional bulldozer emissions comparison.

Mode	*Cycle Description*
1	Heavy & light push 10 meters (10th percentile distance)
2	Heavy & light push 30 meters (50th percentile distance)
3	Heavy & light push 80 meters (90th percentile distance)
4	Idle for 10-15 minutes
5	In-service pushes (normal operation)
6	In-service with std. grade operation
7	In-service heavy & light push operation

The weighting function of the different modes for the final analysis is critical for identifying the overall benefit. According to local Caterpillar dealers, the most popular bulldozers are the D6 and D8. The D6 is mainly used by the housing industry and the D8 is mostly used by landfills. The larger dozers the D9, D10 and D11 are used in large quarries, dams, major road projects, and major industrial or housing building projects. As such, it is expected that the D7E will replace D6's for commercial projects and D8's for landfills. According to a local dealer, more D7E's have been sold to landfills than to general construction projects. Additionally, landfill operations put over 2000 hours in one year on their D7E unit, where the public fleet operations put 700 hours of use on their D7E (see Table 4–1). This suggests landfills operate their equipment almost 3-times as much.

The overall weighting function used in this study was based on the 50th percentile push distance of 30 meters. The load recommended for the 30 m distance is based on the operation of the land fill where higher loads were found. It is expected higher loads are used (and fuel is burned) by the land fill operation than other operations. Thus, it is expected 90% of emissions come from high loaded tests and 10% come from light loaded tests. Thus, the overall emissions benefit calculation is based on 80% full load tests at 30 meter push distances, 10% light load pushes at 30 meter distances, and 10% idle. The D6T represents the benefit expected for general construction operations and overall implementation of the hybrid system since the D6T is technically the most similar to the D7E. The D8T represents the benefits at landfill operations, which represents a large fraction of the landfill bulldozers in CA. Given that the D6T is the most similar to the D7E, the main analysis is based on the D6T and not the D8T.

4.3.2 *In-Use Emissions Comparison D7E & D6T*

The CO_2 emissions for the controlled pull tests by test mode are presented (Figure 4-5) on a gram per hour and a gram per ton of material moved basis. The results are based on triplicate tests for each unit and then averaged over the number of units tested on each test cycle. For each test cycle or each test mode, as well as the idle modes, comparisons are made between the hybrid and conventional bulldozer. Controlled pull tests are done based on distance pulled (i.e., 10 m, 30 m, and 80 m) and the amount of material in the bin being pulled (a #0.5 bin for light load, a #2 bin for heavy load). The percent difference in CO_2 emissions between hybrid and conventional bulldozers are also presented (right y-axis). The error bars represent 90^{th} percent confidence intervals about the mean measurement for each mode tested.

Overall, the CO_2 emissions show a benefit ranging from approximately 10 to 30% for the hybrid bulldozer. These benefits were statistically significant at 90% confidence level, for all but the high idle. The benefit for the hybrid bulldozer is more significant for the lower weight bins and for the shorter pull distances. Interestingly, the results on a g/ton of material moved basis show similar trends to those on a g/hr basis, but the benefits for the hybrid are not as great on a g/hr basis. Furthermore, since majority fuel combusted by an engine is converted to CO_2

emissions, characterization CO_2 benefit is important for this work since it directly ties into engine fuel consumption.

Figure 4-5: CO_2 emissions on a g/hr and g/ton basis for the different controlled push tests.

The NO_x emissions for the controlled pull are also presented in Figure 4-6 on a g/hr and a g/ton basis. The NO_x results show higher emissions for the hybrid under nearly all test conditions. The NO_x increases ranged up to 17% on a g/hr basis and up to 31% on a g/ton basis. The increases in NO_x for the hybrid equipment may be due to the calibration of the engine in terms of different duty cycles.

The NO_x dis-benefits are higher for the heavier bin than the lighter bin. For the lighter bin, the NO_x increases were statistically significant for the 80 meter distance and for the 30 meter distance on a g/ton basis, but the results were not statistically significant for the 10 meter distance and the 30 meter distance on a g/hr basis. The idle results showed mixed results, with a NO_x increase for the hybrid bulldozer for the high idle and NO_x decrease for the hybrid bulldozer for the low idle. The hybrid high idle is at a higher engine speed compared to the conventional, thus the hybrid is under slightly higher load, and thus higher emission rates are expected on a g/hr basis.

Figure 4-6: NO_x emissions on a g/hr and g/ton basis for the different controlled push tests

4.3.3 *In-Use Emissions Comparison D7E & D8T*

Overall, the in-use results show a benefit for CO_2 emissions ranging from approximately 25 to 60% for the hybrid bulldozer for nearly all of the controlled tests (Figure 4-7). The benefit for the hybrid bulldozer is more significant for the lower weight bins and for the shorter pull distances. The differences between the low idle emissions for the hybrid and conventional bulldozers were comparable within the experimental variability.

The NO_x results for the controlled pull are presented in Figure 4-8 on a g/hr and a g/ton basis. The NO_x results show lower emissions for the hybrid under nearly all test conditions. The NO_x decrease ranged up to 54% on a g/hr basis and up to 47% on a g/ton basis. The decrease in NO_x for the hybrid equipment compared to the D8T was different than for the D6T. The lower hybrid NO_x emissions may be due to the low duty cycle used for the comparison such as testing of the D8T as compared to the D6T.

The NO_x decreases are lower for the heavier bin than the lighter bin. For the lighter bin, NO_x decreases were found for the 10, 30, and 80 meter distances on a g/hr and g/ton basis, but the percentage decreases were generally within the experimental variability on a g/hr basis. The idle results showed mixed results, with a NO_x increase for the hybrid bulldozer for the high idle and NO_x decrease for the hybrid bulldozer for the low idle, but these differences were not statistically significant.

Figure 4-7: CO_2 emissions on a g/hr and g/ton basis for the controlled pull tests D8T

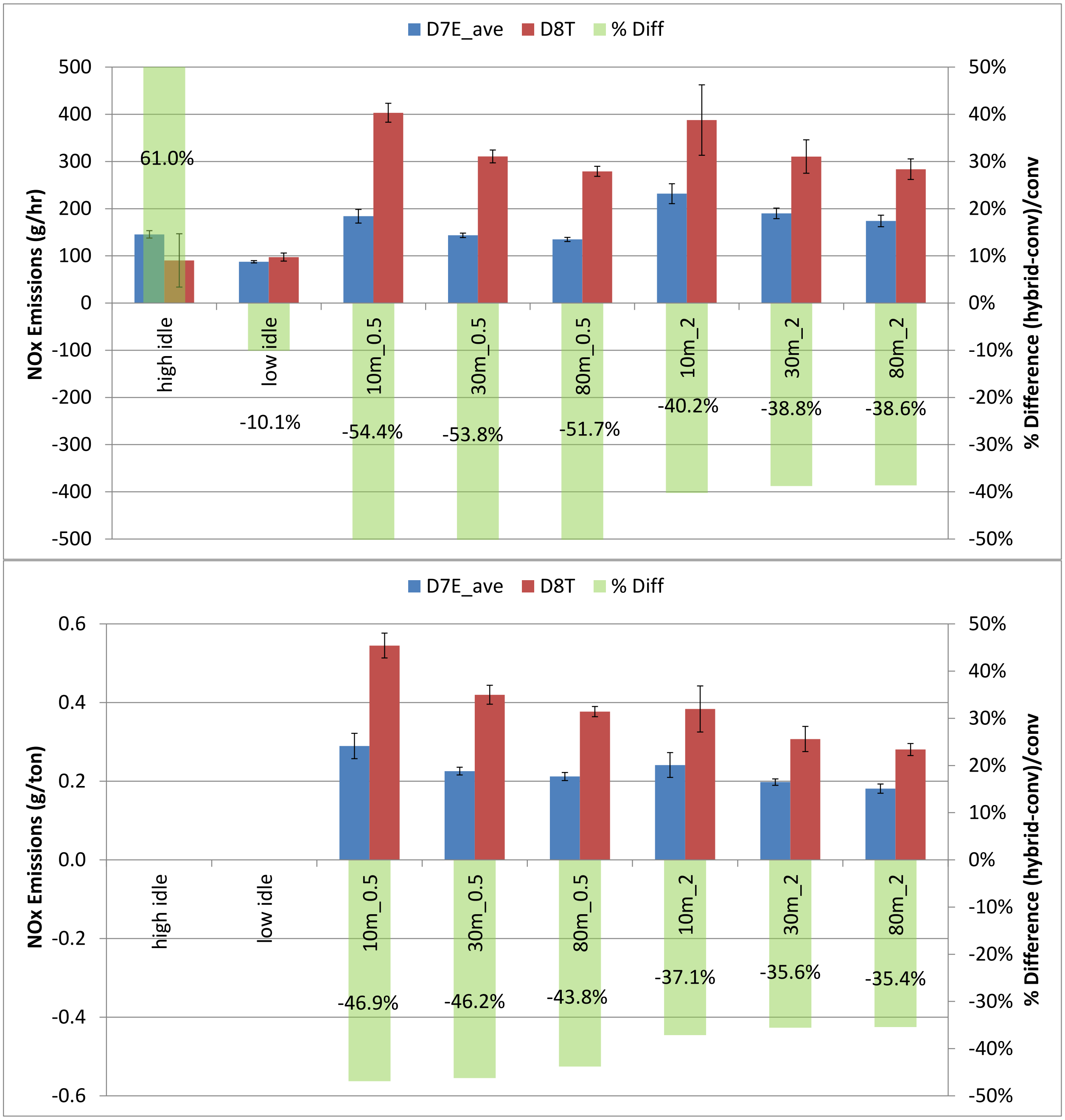

Figure 4-8: NO_x emissions on a g/hr and g/ton basis for the controlled pull tests D8T

4.3.4 *Overall Discussion*

The overall benefit of the D7E analysis is based on two conventional units, the D6T and the D8T. The overall weighting function was developed in the activity study results section. In general, the overall emissions benefit calculation is based on 80% full load tests at 30 meter push distances, 10% light load pushes at 30 meter distances, and 10% idle. In summary, the final weighted differences between the D7E and the D6T were -12% for CO_2 and +13% for NO_x. For the D7E comparison to the D8T, the weighted differences were -23% and -28% for CO_2 and NO_x, respectively. The final finding was not surprising for the D7E vs. D8T comparison was not surprising given the much larger engine an capacity of the D8T. While the D7E is larger than the D6T, the D7E showed fuel economy savings; however, the NO_x emissions was observed to be increased. The cause for the observed difference between the D7E and D6T is somewhat complex and may be due to engine operation. Figure 4-9 shows the D6T and D7E engine power versus engine speed on a second by second basis for a day of controlled in-use testing. The engine power data suggests the D6T and D7E operate over a very different portion of the engine map. The D6T covers a wider range with high-use at full load and part load whereas the D7E operates over a very narrow range in the middle of the engine map. The specific narrow range of the D7E in-use operation may be operating in a higher weighted NO_x region of the engine map not captured during the certification process. Although the differences cannot be quantified, this observation provides some insight into for why there may be a NO_x dis-benefit for the hybrid compared to the conventional D6T.

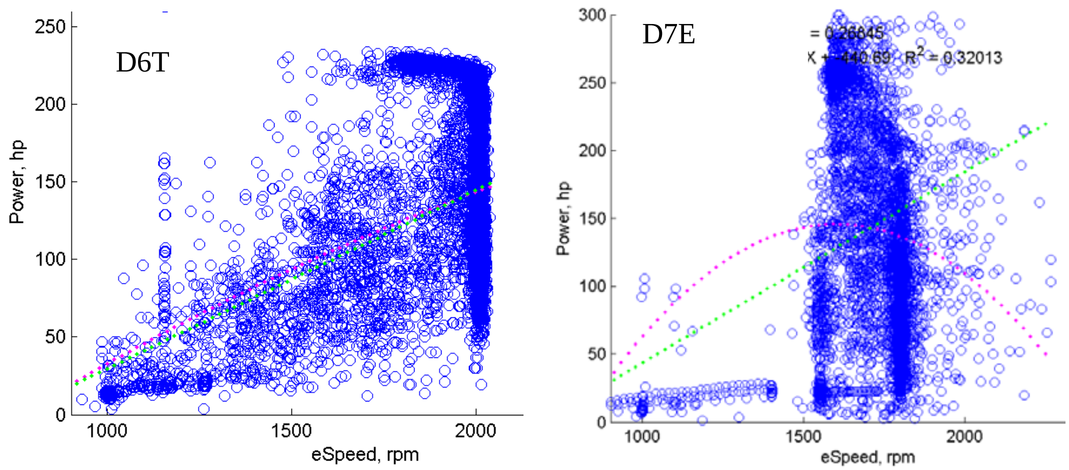

Figure 4-9: Engine load as a function of engine speed for the D6T and D7E

Discussion with Caterpillar yielded additional insight into the D7E and D6T comparison. Majority of the discussions was focused on the difference in engine ratings of the two bulldozers. Unlike on-road engines, where engine ratings within a family are relatively few (~3).Off-road engine have many more tailored applications (eg. dozer vs. excavator vs. wheel loader) leading to many more (>10) unique engine ratings each tailored to their specific off-road application. For instance, there are 26 different engine ratings within the D7E engine family, as shown in Table 4–6. The current regulation only requires certification of one parent engine per family (usually the highest power rating/fuel rate), all other engine ratings called child ratings should have emissions less than the parent engine. At the same time, depending on the overall emissions, engine manufacture can set a Family Emission Limit (FEL) equal to less than the current emissions standard. Thus, for this study, since both the D6T and D7E were child ratings of their respective engine families, it is unknown how comparable the emissions of these engines.

Table 4–6: D7E and D6T Engine NO_x Emissions Certification based on ARB EO in g/kWhr

Unit	Standard g/kWhr	FEL g/kWhr	Certification g/kWhr	MY	Engine Rating	Family	Parent Hp	EO Date Issued
D7E	2	2.0	1.1	2011	1 of 26	BCPXL09.3HPA	361	Nov 4 2010
D6T	2	1.8	1.6	2012	1 of 18	CCPXL09.3HPB	409	Oct 1 2011

[1] Nov 24 2010 there was an updated parent EO submitted to ARB, but it was not posted on the website.

Additionally, Caterpillar made a change to the C9.3 Family FEL between MY 2011 and MY 2012. The MY 2012 D6T bulldozer's FEL is 10% lower than the MY 2011 D7E bulldozer even though the standard remained the same for both model years (MY). Caterpillar lowered the FEL as part of the Banking and Trading Program as the C9.3 engine family is able to achieve a lower FEL than the standard. Also, the number of engine ratings has reduced from 26 in MY 2011 to 18 in MY 2012 to reduce cost.

According the Executive Orders (EO) from Air Resources Board (ARB) database, for engine certifications, two other major differences have been made to the MY 2012 EO compared to MY 2011 EO (Table 4–6). The MY 2012 EO's certification NO_x value increased from 1.1 g/kWhr in 2011 to 1.6 g/kWhr, a net 45% increase. Further information was also provided to UCR that the 2012 EO parent engine rating has changed from 361 hp to 409 hp. The fuel rate data for the two ratings are the same in both the 2011 and 2012 EO. Therefore, Caterpillar did not change calibrations for 2012. Based on this information, it can be concluded that between two known engine ratings within the same engine family, the NO_x emission can vary as much as 45%.

This study found the final weighted NO_x difference between the D7E and D6T to be around 13%. If the NO_x variations between two different engine ratings can vary as much as 45%, it is possible that the 13% NO_x difference could be due to engine ratings differences between the D7E and the D6T. It might be expected that, if an engine reduces fuel consumption by 20%, a corresponding reduction in criteria emissions might be seen as there is 20% less fuel burned. However, the dynamics of engine control with multiple systems, combinations of an internal combustion engine with electric motors are 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 condition will likely provide addition insights into potential hybrid benefits and perhaps provide a better understand of how such systems can be optimized.

4.4 References

1. Light-Duty Vehicle Greenhouse Gas Emissions Standards and Corporate Average Fuel Economy Standards; Final Rule, Federal Register, May 7, 2010, vol. 75, No. 88.
2. Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles; Final Rule, Federal Register, September 14, 2011, vol. 76, No. 179.
3. Annual Energy Outlook 2014, US Department of Energy, Energy Information Administration, www.DOE.EIA.gov
4. Hallmark, L. S., Wang, B., Sperry. R., (2013) Comparisons of On-road Emissions for Hybrid and Regular Transit Buses, J. Air & Waste Mange. Assoc., Volume 63, Issue 10, 2013, DOI: 10.1080/10962247.2013.813874
5. Walkowicz, K., Lammert, M. Curran, P., (2012) Coca-Cola Refreshments Class 8 Diesel Electric Hybrid Tractor Evaluation: 13-Month Final Report, final report prepared by National Renewable Energy Laboratory. Contract No. DE-AC36-08GO28308.

   < http://www.nrel.gov/docs/fy12osti/53502.pdf>
6. Russell, R., Johnson, K., Durbin, T. D., (2012) Assessment of the Emissions and Fuel Economy of a Class 8 Conventional and Class 8 Hybrid Truck Chassis Dynamometer Testing. Final report prepared for CALSTART, July.
7. Control of Emissions of Air Pollution From Nonroad Diesel Engines and Fuel, Final Rule, Federal Register, June 29, 2004, vol. 69, No. 124.
8. Sokolsky, S., Presentation by CALSTART, "Joint Military Evaluation of the Benefits of an Electric-Drive Bulldozer", Presented to Ventura County Naval Base, Port Hueneme, CA, November 2011.

9. Block, M., Abolhasani, S., Toscano, F., Persson, E., Presentation by EMISSTAR LLC. "PEMS Testing – Applications and Lessons Learned", Presented to V2012 PEMS Conference and Workshop, Riverside, CA, March 2012.

10. Schindler, W., Haisch, Ch., Beck, H.A., Niessner, R., Jacob, E. and Rothe, D.(2004) A Photoacoustic Sensor System for the Time resolved Quantification of Diesel Soot Emissions, SAE Technical Paper Series 2004-01-0969

Chapter Five: A Generalized Approach for Characterizing Emissions Benefits of Hybrid Off-Road Equipment via Physical Activity and Engine Work: A Case Study for Excavators

5.1 Introduction

Hybrid engine technologies are growing in popularity as government agencies and manufactures strive to reduce petroleum consumption and reduce greenhouse gas (GHG) emissions. Worldwide, agencies around the globe are promoting regulations to reduce greenhouse gas (GHG) emissions, an effort to reduce to impacts of climate change. Recently, the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) have jointly issued GHG emissions standards increasing fuel efficiency requirements for heavy duty vehicles (MY 2014) and light duty vehicles (MY 2017) (Federal Register 2010, 2011). The U.S. Energy Information Administration projects that hybrid technology light duty vehicles (LDVs) will play a critical role in meeting increasing stringent fuel economy regulations, with the market share of hybrid LDVs increasing from 4% in 2012 to 40% by 2040 (AEO 2014).

Hybrid technologies for HDVs are more complex than their LDV counterparts. Several studies have shown that the true benefits for on-highway heavy-duty hybrids can vary significantly and are a function of the real-world application and hybrid system design. Hallmark et al. (2013) reports a GHG emission benefit for in-use hybrid buses; however, but the nitrogen oxide (NO_x) emissions were observed to be higher than the conventional bus. The National Renewable Energy Laboratory (NREL) conducted a 13-month study on a fleet of hybrid and conventional class 8 heavy duty trucks. The NREL study found a 0%-30% fuel economy improvement and a 5%-101.3% NO_x increase due to the higher NO_x certification level of the selected engine in the hybrid bus (Walkowicz 2013). Similar to the NREL study, an evaluation by the University of California, Riverside (UCR) found up to a 60% reduction in GHG emissions but higher CO emissions for hybrid class 8 heavy duty trucks in comparison to a conventional truck with both benefits and dis-benefits for NO_x emissions (Russell 2012).

Recently, hybrid configurations are migrating to on off-road equipment. Hybrid off-road equipment offers the potential to reducing both greenhouse gas (GHG) emissions and criteria emissions by cutting engine fuel consumption using sophisticated designs with multiple power sources. However, little independent in-use emission studies have been conducted to evaluate the true emissions benefits of hybrid equipment relative to conventional equipment. Sokolsky et al. (2011) evaluated the fuel consumption and productivity of a diesel-electric (hybrid) bulldozer against selected conventional bulldozers; however no emissions were measured. Block et al. (2012) measured emissions in-use from a hybrid excavator using a portable emissions measurement system (PEMS); however no data was released and ECM data was not logged. At this early stage of deployment, fuel consumption and emissions evaluations are needed to assess the in-use benefits of off-road equipment hybridizations.

The goal of this study was to develop a methodology to evaluate the real-world emissions and fuel consumption benefits from hybrid off-road construction equipment in comparison to conventional alternatives and to evaluate differences in emissions between different types of in-use operations. Traditionally, off-road engines are certified on engine dynamometers on generalized steady state and transient duty cycles that do not reflect the true usage of any particular type of off-road equipment. As a case study, University of California, Riverside, College of Engineering, Center for Environmental Research and Technology (UCR CE-CERT) studied a total of seven hybrid and conventional excavators. The excavators included three

Komatsu HB215 hybrids, two Komatsu PC200s, and two Komatsu PC220s. 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 interviews, historical records, and in-use activity measurements which included time-lapse video, real-time engine control module (ECM) broadcast data, and real-time GPS data. The collected activity data were used to develop duty cycles to allow accurate comparisons between the hybrid and conventional equipment. A subset of five pieces of both hybrid and conventional excavators were evaluated for emissions and fuel consumption over the developed duty cycles using a 40 CFR 1065 approved PEMS.

5.2 Methodology

5.2.1 *Test Vehicles and Fleets Selection*

A total of 7 excavators were recruited for instrumentation for activity or emissions testing. A list of excavators, including their engine information, model year, and fleet owner is provided in Table 4–1. The test matrix was developed to provide conventional engine data most comparable to the HB215 hybrid excavator. The HB215 utilizes an energy storage system that recovers energy otherwise lost as the upper structure slows its rotation. As effectively, 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 during increasing engine RPM or torque. 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 conventional excavator design uses only the diesel engine for power, whereas the hybrid excavator also utilizes regenerated energy to assist the engine when it is accelerating, enabling the use of the engine in a low RPM zone with high-efficiency combustion. Additionally, the hybrid excavator optimizes engine operation for minimal fuel consumption. The HB215 is the hybrid version of the conventional PC200 and both are certified to the Tier 3 emissions level. Furthermore, the slightly more powerful Tier 3 machine PC220 has the same engine model as the PC200 but with a slightly higher power rating. The PC220 is a much larger machine in terms of exterior dimensions as well.

Table 5–1: Model, Owner, Model Year, and Engine information of bulldozers studied

ID	Unit Model	Facility [2]	Eng Model	Disp	Year	Eng Hr [1]	Gross Power [3]		Activity	Emissions
#	n/a	n/a	n/a	liters	n/a	hr	Hp	RPM	n/a	n/a
1	HB215	RM	SAA4D107E-1	4.5	2011	245	148	2000	Yes	Yes
2	PC200	DD	SAA6D107E-1	6.7	2007	2097	155	2000	Yes	Yes
3	HB215	DD	SAA4D107E-1	4.5	2011	245	148	2000	Yes	Yes
4	PC220	DD	SAA6D107E-1	6.7	2006	2228	180	2000	No	Yes
5	PC220	CE	SAA4D107E-1	6.7	2006	3516	180	2000	No	Yes
6	HB215	CE	SAA4D107E-1	4.5	2011	280	148	2000	Yes	Yes
7	PC200	RM	SAA6D107E-1	6.7	2010	1228	155	2000	No	Yes

[1] Nominal hours during testing (varies by day used)
[2] Owner is the equipment owner. RM is Road Machinery (rental), DD is Diamond D General Engineering, and CE is Clairemont Equipment Company (rental)
[3] Gross power ratings are from published materials

Excavator activity measurements were made at three facilities on a subset of three hybrid units and one conventional unit (Figure 5-1). The first excavator studied was owned by Road Machinery (RM), a private sales and rental fleet based in Phoenix, Arizona. The particular RM hybrid unit studied was rented to a general construction company performing ground work for a hospital building project near Lancaster, California. The second excavator studied was owned by Diamond D General Engineering (DD), a private general construction company based in Northern California. The hybrid unit they owned was performing ground work at a car wash site near Ft. Hunter Liggett, California. The third excavator studied was owned by Clairemont Equipment Company (CE), and also was a rental and sales fleet. The particular hybrid excavator was rented to a general construction company performing demolition work at a housing project near Escondido, California. RM supplied a conventional PC200 to DD at the Ft. Hunter Liggett worksite to provide comparison to the hybrid unit that was also working at the site.

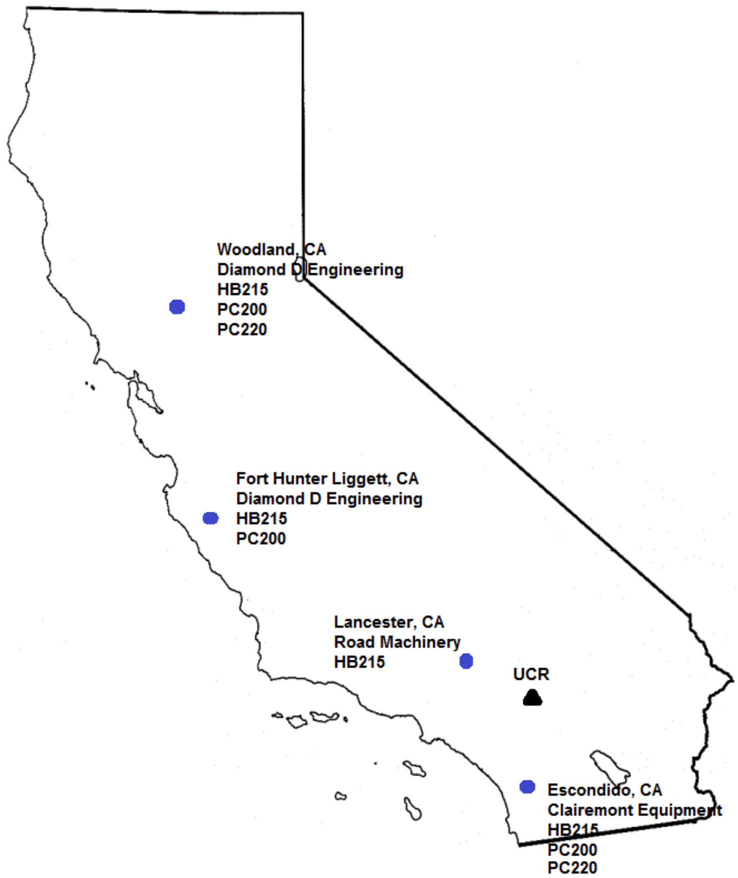

Figure 5-1: Locations and participants information for each of the excavators tested in study

5.2.2 *Activity Measurement Equipment Description*

Two time-lapse cameras were mounted on each unit, and a GPS and an engine control module (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 identify the type of work being performed in both directions. 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 used (PlotWatcher Pro) are battery operated and programmed to record one frame every one to ten seconds depending on the location. The video data was critical for determining the activity performed. The bulldozer activity ranged from refuse pushing, road building, rock pushing, river bed clearing, to slope repairs.

The ECM tool used in this study was a beta version of the UniCAN Pro and GPS data logging system supplied by CSM Product Inc. This system is a self-contained J1939 ECM interface and data logging tool. It was configured to start logging with key-on and stop logging with key-off. The UniCAN was upgraded to send specific J1939 request messaging so that it worked at 100 percent reliability with the excavators in this study. This new tool greatly improved UCR's data capture success in comparison to other ECM tools existing on the market at the time.

5.2.3 *PEMS Description*

The PEMS equipment utilized in this research was compliant with federal test methods for in-use testing (40 CFR 1065) for the gaseous and PM systems. The gaseous and PM PEMS were the AVL gaseous PEMS and AVL PM PEMS, respectively. An exhaust flow meter designed and manufactured by Sensors, Inc. was used with the PEMS systems. The specific AVL 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). The NO_x value is calculated from NO and NO_2 and reported on a NO_2-equivalent basis. The PM PEMS measurement system selected was AVL's 483 micro soot sensor (MSS) in conjunction with their gravimetric filter module (GFM) option. The combined system is called the AVL 494 PM system. The instrument measures the modulated laser light absorbed by particles with an acoustical microphone. The photo-acoustic measurement principle directly measures elemental carbon (EC) mass (also called soot) and has been found to be robust and to have good agreement with the reference gravimetric method for EC dominated PM (Schindler 2004).

The exhaust flow meter (EFM) used was Sensors Inc.'s High Speed EFM (HS-EFM). The EFM is based on differential pressure principle and is desired with the wide range of exhaust flows and dynamics of transient vehicle testing. An appropriate 5" exhaust flow meter was selected to match all of the displacement of the engine being tested in this study.

5.2.4 *Excavator Emissions Testing*

A total of seven different hybrid and conventional excavators were tested at two different locations for emissions over the seven-mode test cycle developed in this work (see results section for the cycle details). Test sites were carefully selected as ground materials can have an important impact on engine loads. The terrain was evened and prepared prior testing, as the 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. Both the DD and RM testing was conducted at an open agriculture field at a farm owned by DD near Woodland, California. The CE testing was conducted at open area near a hillside in Escondido, California.

A single 24" wide bucket was used for all test modes for testing consistency between three different of excavators. .The test area was prepared by marking out locations for the travel mode and other modes would also occur. The equipment operators conducted one warming up cycle before testing. Each test was conducted in triplicate. The dimensions of the trench dug during each mode were measured to determine the volume of bank material removed. The sketch in Figure 5-2 shows the recorded dimensions. The length of a trench was measured between the half-way points of the slopes on each end. Because the cross-section of a trench is not uniform from bottom to top, the depth and width of the trenches were measured in two stages, as shown. The final volume of the trench was calculated as its length times its average cross-sectional area. Soil samples were collected throughout the site to determine the material density.

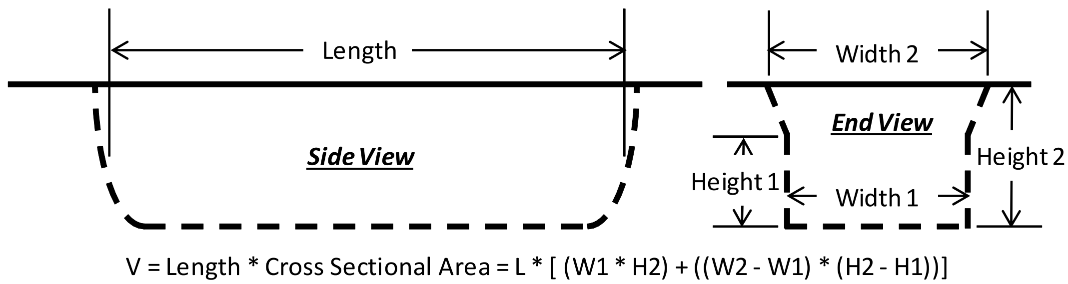

Figure 5-2: Measurements of trench dimensions used for final analysis.

5.3 Results

5.3.1 *Activity Study Results*

Activity information on the excavators was obtained via interviews with expert participants and via direct measurement of video, engine, and GPS data. The expert opinions and feedback helped focus the direct measurements and fill data holes left due to the relatively small sample size of this study. Directly measured activity data was recorded at three project sites: a vehicle wash construction site for DD (both hybrid and conventional), a housing project demolition site for CE, and a hospital construction site for RM.

The development of the excavator duty cycle required the defining of micro-trips, behaviors, or a combination of both. Excavators of this size are used for many more types of work, and these types of work are generally not identifiable in the ECM/GPS data. Thus, the video data played a large role in the duty cycle development. Excavator videos were reviewed frame by frame so that work modes and the date/time could be assigned when the excavators were active. Engine idle was the only mode identified by ECM data, and later parsed into either “stop low idle” or “stop high idle” based upon the corresponding engine speed data. Table 5–2 shows the final developed excavator work modes in this study along with a brief explanation of what each mode represents.

Table 5–2: Video based work mode identification for excavators

Name	Mode No. [1]	Work Mode Description
Stop rpm low	0	Stop doing what was being done and be still for 30 (or so) seconds or more with idle low. Idle determined during post processing.
Stop rpm high	0.5	Stop doing what was being done and be still for 30 (or so) seconds or more with idle high. Idle determined during post processing. Could be still but using PTO.
Btrench	1	Trench or dig with bucket facing backward (toward operator) with big bucket and 45 ° swings.
Strench	2	Trench or dig with bucket facing backward (toward operator) with small bucket. 45 ° swing.
Bscoop	3	Trench or dig with bucket facing forward (away from operator) with big bucket. All swings.
Sscoop	4	Trench or dig with bucket facing forward (away from operator) with small bucket. All swings.
Dig	4.5	Dig with 180° swings.
Bbackfill	5	Move loose dirt back into a hole or trench with big bucket and 45 ° swings.
Bditch	5.5	Dig over the side track with bucket facing backward (toward operator) with big bucket and 90 ° swings.
Sbackfill	6	Move loose dirt back into a hole or trench with small bucket. 45 ° swing.
Sditch	6.5	Dig over the side track with bucket facing backward (toward operator) with small bucket and 90 ° swings.
Compact	7	Use compacting wheel attachment to compact dirt.
Crane	8	Move objects. Hold them in the air. Hold or push them down. Usually without attachment but sometimes with.
Dress	9	Scrape, break-up packed surface with teeth, move loose dirt, smooth the surface. Light demolition (wall, fence), move loose material, clear debris. Up to 45 ° swings.
Maneuver	10	Short moves. Change attachments. Reposition at same work location.
Move	11	Move on tracks longer than 30 (or so) seconds. Change work locations.
Carry	12	Carry items, debris, etc. to pile or hopper
Grab	13	Grab items, debris and put them somewhere nearby. 90 to 180 ° swings.
Unknown	14	Unknown activity due to obscured camera view (rain, bucket low, etc.)

[1] Mode ID Number is based on the filter code added to the data files and is not the duty cycle mode number.+

The first mode of typical day was “Move” with the excavator positioning itself to begin work at a certain location. Next, the excavator stopped and waited for the conditions to begin work to occur. Later the excavator began some type of work activity, and the date and time the activity began was noted. For each day a spreadsheet with three columns (date, time and mode) was developed. There data were aligned with the ECM using a cross-correlation function in MATLAB®. Figure 5-3 shows an example comparison of original data and shifted data to be aligned with the ECM data, and mode data for a conventional excavator being used by DD at the Ft. Hunter Liggett construction site. The various modes (blue line) are represented by their mode number on the primary Y axis and labels to the left side of the graph. The engine RPM is on the secondary Y axis.

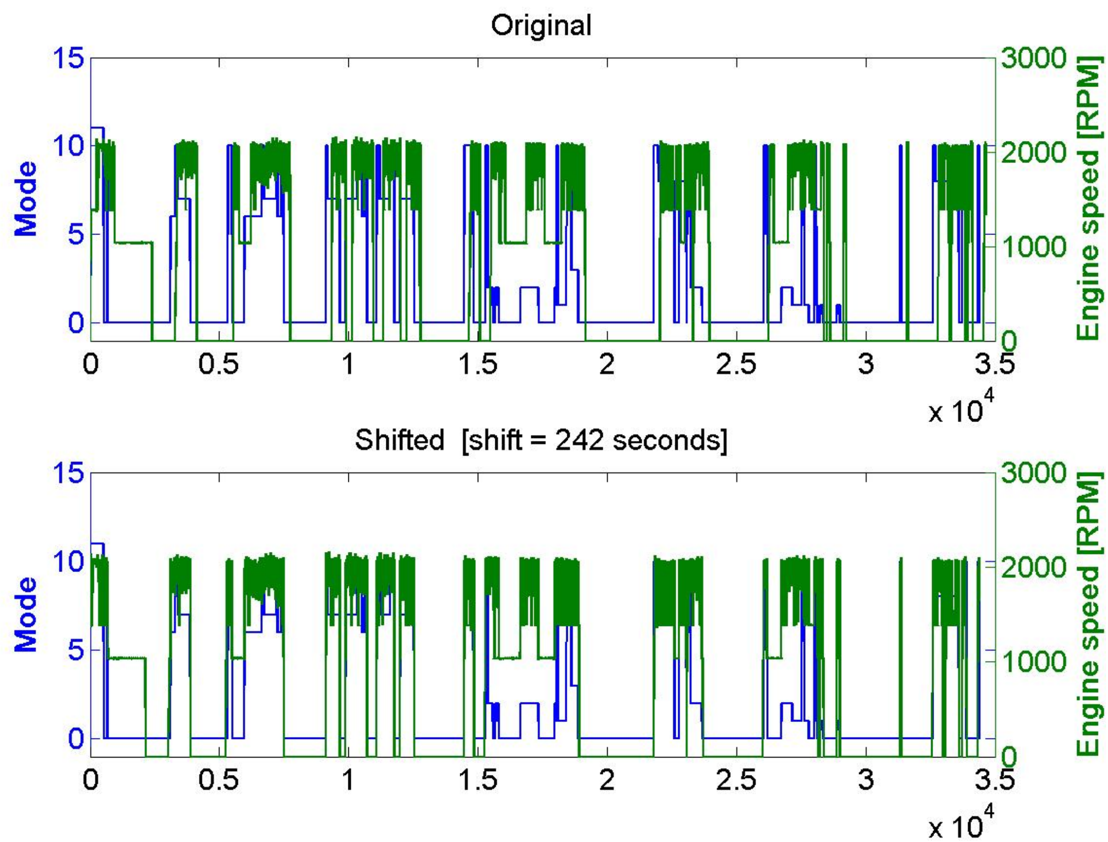

Figure 5-3: Example of an aligned excavator video modal data plot

From different work modes assigned for the ECM data, a high number of different operating modes were identified. Mode reduction from the original operation modes was required in order to construct a reasonable test duty cycle. Mode reduction was performed bu combination 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 combined nature of engine power, engine speed, and distribution shape for each of the modes, additional visual analysis was performed to support the ANOVA analysis. The details of this analysis can be found in the supporting information section. Table 5–3 shows a list of the final combined modes after the ANOVA analysis. The modes were reduced from 19 to 7. The modes grouped are 1) carry, grab, dress; 2) s-trench, b-backfill; 3) crane, maneuver, bscoop; 4) compact, s-backfill; 5) travel, move; 6) b-trench; and 7) idle. 44% of the hybrid excavator activity was performing trench and backfill operations at one location and carry, grab, and dress at another location (Table 5–3). The conventional excavator also showed the highest fraction of usage (26%) in the same trench and backfill operations. This suggests the type of work was similar between the hybrid and conventional operation at this facility. The time fraction spent in each mode is critical for determining the final weighing factor for the modes.

Table 5–3: Video and ECM activity mode percent time fractions for the HB215 and PC200.

Participant	*Equipment*	*Activity* [4]	*ECM Hours* [1]	*ECM %* [3]	*Video Hours* [2]	*Video %*
DD	HB215 T3	carry,grab,dress	0.1	0.2%	0.1	0.2%
DD	HB215 T3	strench, bbackfill	16.2	49.3%	17.2	44.4%
DD	HB215 T3	crane, maneuver, bscoop	3.4	10.4%	6.6	17.0%
DD	HB215 T3	compact, sbackfill	8.1	24.6%	8.9	22.9%
DD	HB215 T3	move, travel	2.3	7.1%	3.0	7.7%
DD	HB215 T3	btrench	2.8	8.4%	3.1	7.9%
	EP 1 Hybrid Total [3]		32.8	100.0%	38.8	100.0%
DD	PC200 T3	carry,grab,dress	1.6	6.2%	1.7	4.9%
DD	PC200 T3	strench, bbackfill	8.2	31.4%	9.8	28.3%
DD	PC200 T3	crane, maneuver, bscoop	4.3	16.4%	9.0	26.0%
DD	PC200 T3	compact, sbackfill	5.1	19.7%	6.7	19.5%
DD	PC200 T3	move, travel	1.7	6.5%	2.2	6.3%
DD	PC200 T3	btrench	5.2	19.8%	5.2	15.1%
	EP 1 Conventional Total [3]		26.1	100.0%	34.6	100.0%
CE	HB215 T3	carry,grab,dress	45.8	82.9%	tbd	tbd
CE	HB215 T3	strench, bbackfill	0.0	0.0%	tbd	tbd
CE	HB215 T3	crane, maneuver, bscoop	5.0	9.1%	tbd	tbd
CE	HB215 T3	compact, sbackfill	0.0	0.0%	tbd	tbd
CE	HB215 T3	move, travel	4.5	8.1%	tbd	tbd
CE	HB215 T3	btrench	0.0	0.0%	tbd	tbd
	BP 3 Hybrid Total [3]		55.3	100.0%	tbd	100.0%
RM	HB215 T3	carry,grab,dress	0.4	4.2%	2.4	10.4%
RM	HB215 T3	strench, bbackfill	5.5	62.8%	7.9	34.4%
RM	HB215 T3	crane, maneuver, bscoop	1.6	17.7%	9.4	41.0%
RM	HB215 T3	compact, sbackfill	0.0	0.0%	0.1	0.6%
RM	HB215 T3	move, travel	1.3	15.3%	3.1	13.6%
RM	HB215 T3	btrench	0.0	0.0%	0.0	0.0%
	EP 3 Hybrid Total [3]		8.8	100.0%	23.0	100.0%

[1] ECM activity hours obtain from filtered data
[2] ECM and video total hours obtained from total filtered data, excludes stops mode
[3] Percentage based on filtered data which exclude stop and other modes
[4] Activity is only moving activity, does not include equipment idle/stops

The idle mode was analyzed separately. An idle event is identified when the engine was operating at idle speeds for over 5 seconds. The idle speed for the conventional and hybrid are significantly different, as suggested by the manufacturer's literature. The hybrid's low-idle is 700 rpm and the conventional low-idle is around 1000 rpm. Table 5–4 shows the percent of time the excavators idled for both high and low-idle. The idle time ranged from 35% for DD's conventional (construction work) to 8.4% of CE's hybrid (demolition work).

Table 5–4: Excavator idle time measured during activity assessment

	DD Hybrid [1]		*DD Conventional* [3]		*CE Hybrid* [1]		*RM Hybrid* [1]	
Description	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	

[1] Hybrid low idle = 680~720 rpm, high idle = 1150~1175 rpm
[2] Conventional low idle = 1000~1050 rpm, high idle = 1350~1400 rpm

5.3.2 *Duty Cycle Development*

For additional input into mode development, an excavator test cycle developed by Komatsu was reviewed (Block 2012). The Komatsu cycle shows what the manufacturer considers to be important features of the various modes of operation for the purposes of emissions testing the hybrid excavator. Prominent modes 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 "dress" mode), 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 site tested, they have been included in the list of modes because they are almost certainly widely used in the industry. Some of these (e.g., digging with a 180 degree swing) were probably not observed during the project due to the limited range of excavator projects sampled.

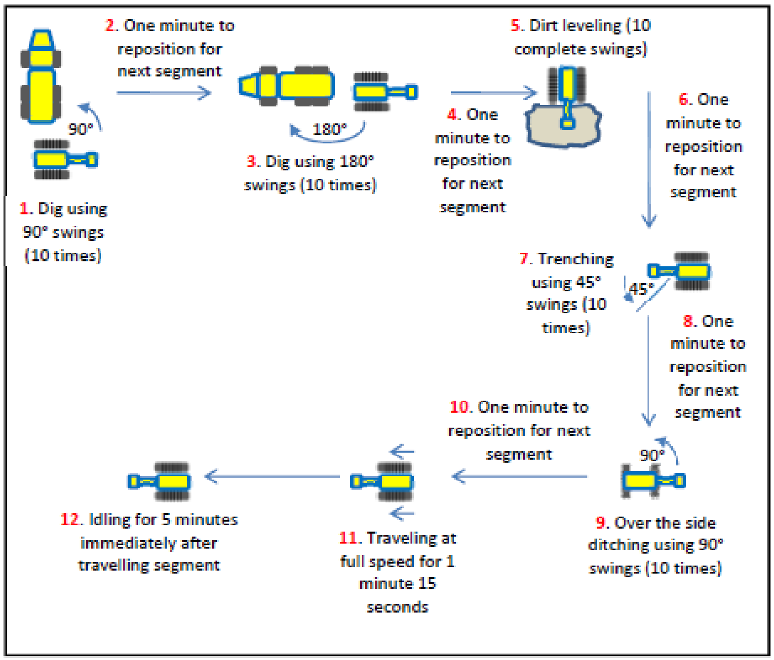

Figure 5-4: Komatsu cycle used to evaluate between excavator technology improvement.

Based on the consolidated modal data, supported with a statistical analysis of the logged activity data and operator opinions from DD, RM, and CE, UCR developed a duty cycle with 7 different work modes was developed to represent the operation of excavators approximately the same size as the Komatsu HB215 and the PC200.Table 5–5 lists the sequence of events of the test cycle as they were conducted during emissions testing.

Table 5–5: Details of the UCR proposed excavator test cycle.

Cycle Mode	Description	Work Modes Represented
1	Travel in a predetermined 100-yd line, back and forth for about 3 laps. *Idle for 30-60 seconds.	Maneuver, Move, Carry
2	Trench (trench with 45° swing) to single bucket width and 4 to 5 ft. depth for 8 minutes. *Idle for 30-60 seconds.	Btrench, Strench, Bscoop, Sscoop
3	Ditch (trench with 90° swing) to same depth with width for 8 minutes. *Idle for 30-60 seconds.	Bditch, Sditch,Bscoop, Sscoop
4	Dig for 8 minutes (trench with 180° swing) a pit of specified width and depth. *Idle for 3 minutes.	Dig, Bscoop, Sscoop
5	Dress the "trench 180" spoils into a level pile about 1 ft high until the entire pile is finished. Idle for 30-60 seconds.	Dress, Bscoop, Sscoop, Compact, Crane, Grab
6	Backfill the spoils from the "trench 45" (mode 2) trench back into the same trench. . Idle for 30-60 seconds.	Bbackfill, Sbackfill, Compact, Carry
7	Idle mode was assembled during post processing from the delay between test modes	stop RPM low, stop RPM high

The weighting functions for the final overall analysis of the excavators testing are critical in determining the overall hybrid benefit. This analysis is based on measured activity data, 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 provide context to specify how the selected excavators are typically used and what fraction of excavators are represented by this power category. An estimate of how this class of excavator is typically used was calculated by combining the observed modal fraction. 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, UCR arrived at an estimate of about 20% of engine time is for demolition type of work and the rest is for construction. The estimates of the fraction of calendar time for these types of operations was closer to 10% demolition, but we observed in the activity data that a much larger fraction of the work day was spent with the engine on for demolition projects than for construction projects. This resulted in our increasing the fraction for engine-on time to 20% demolition as the final value was adjusted to account for more general usages, as this data set is relative small.

Table 5–6: Summary of observed mode fractions and final weighing factors

		Construction (DD)		Demolition (CE)		Final Weighting Factors	
Mode No.	Mode Name	Total Hours	Fraction	Total Hours	Fraction	Wtd. Ave.[1]	Adjusted Wtd. Ave. [2]
1	Travel	4	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	10%	21%	21%
	Total	77.4		31.5			

[1] Weighted average based on 80% constructions and 20% demolition activities
[2] Final weighted average were adjusted based on industry input

5.3.3 *In-Use Emissions Variability*

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 see variability due to the influence of unit to unit, operator to operator, and site to site differences. Table 5–7 summarizes the time specific CO_2 emissions for all the units. CO_2 emissions can further be directly correlated to fuel consumption rate.

Table 5–7: Average and variance in CO_2 emissions for the same types of excavator tested.

Time Specific CO_2 Emissions (g/hr)								
	Operator	**Travel**	**Trench 45**	**Trench 90**	**Trench 180**	**Dress**	**Backfill**	**Working Ave**
PC200 RM	CE1	67737	57467	60128	62881	67479	68181	63945
PC200 DD	DD1	54949	54030	54234	55120	54255	54723	54617
Ave.		61343	55749	57181	59000	60867	61452	59281
COV		15%	4%	7%	9%	15%	15%	11%
HB215 DD	DD1	62683	49018	46911	48360	41112	46905	51024
HB215 CE	CE1	64198	46474	49254	43507	50142	51352	52418
HB215 RM	DD2	59164	53422	53013	48197	39496	53909	52503
Ave.		62015	49638	49726	46688	43583	50722	51982
COV		4%	7%	6%	6%	13%	7%	2%
PC220 DD	DD2	65067	73925	74009	72386	66565	73927	71064
PC220 CE	CE1	71890	64636	64612	63570	67958	68866	66916
Ave.		68479	69281	69311	67978	67262	71397	68990
COV		7%	9%	10%	9%	1%	5%	4%

Two PC-200 excavators were tested, one at the Woodland site and the other at the Escondido site (Table **5**–**7**). It can be seen that the two PC200 units had significantly different rates of fuel consumption, particularly during the “travel” mode and the modes that involved a lot of maneuvering (dress and backfill). 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 DD PC200 is 2007 model where the RM PC200 is a newer 2010 model. Furthermore, the operator noticed that the tread for the DD PC200 unit needed maintenance, which could contribute to the observed differences in the travel mode. Upon reviewing the data, the DD PC200 also traveled significantly slower than the other excavators. Three HB215LC-1 excavators were tested in the project. Two were tested in Woodland (the same material but operated by different persons) and the third was operated by a third operator in Escondido. The three HB215s have very similar fuel consumption rates for the same job except in a few instances, particularly the “dress” mode. This result is interesting since the techniques of the operators and the material they were working within seemed to be more different than these results imply. 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, in-use testing of excavators could prove to be a valuable source of data for inventory and other, such as regulatory purposes. Two PC220 excavators were tested for the project, one at the Woodland site and the other at the Escondido site. They also were operated by different persons as well. The PC220 results did not differ from site to site and operator to operator differences as the two units were the same model year and all have 2000+ engine hours.

Operator to operator differences can also be determined by productivity, as individual techniques and experiences vary. Figure 5-5 shows the average productivity for the two different DD operators at the Woodland site. The data for the Escondido site is not shown in order to eliminate the site to site variability. Although we confirmed through observation that the one of the operator at DD was much smoother and less aggressive than the other one, the emissions and fuel consumption differences between their operation styles were not dramatic for the hybrid excavators. In summary, the excavator emissions comparisons between different operators and sites did not show any significant variability.

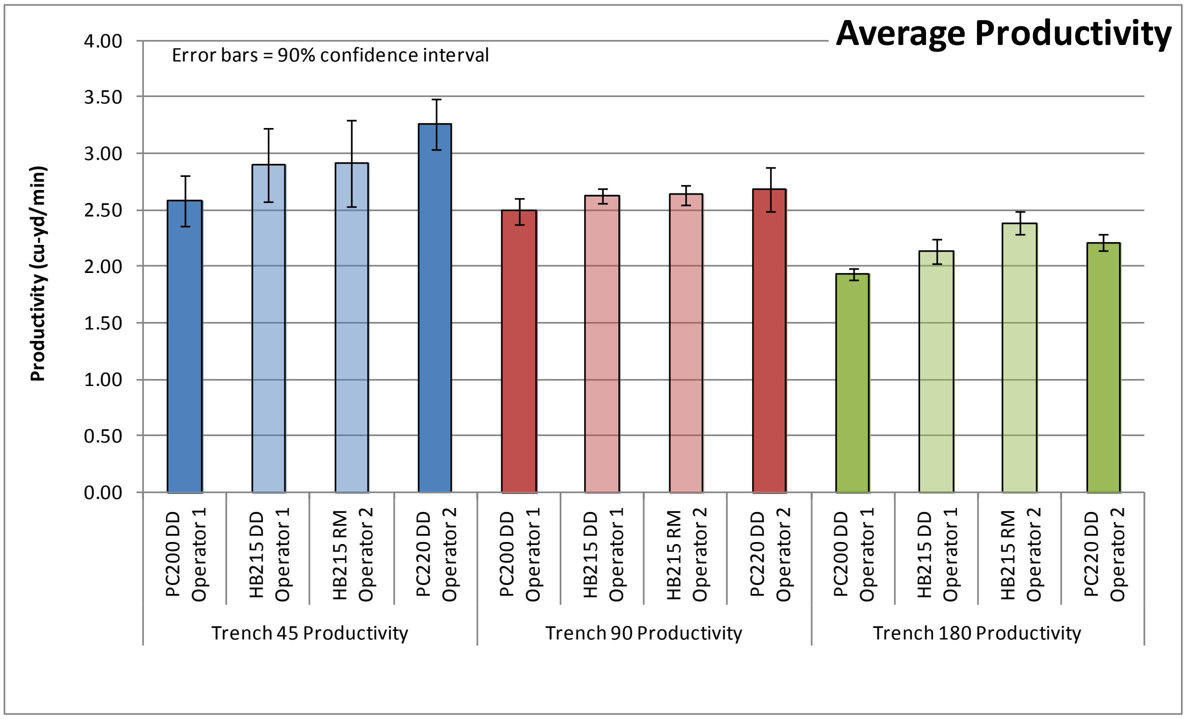

Figure 5-5: Productivity of two different operators at the Woodland Site

Average productivity decreased for all excavator models, as the amount of swing increased, the. This makes sense because with larger swings, more time is spent moving dirt from the trench to the pile and less time is spent digging. Also, for a given operation, the PC200 was less productive than either the HB215or the PC220. But as the amount of swing increased, it seems like the productivity of the hybrid becomes closer to the productivity of the PC220. This supports the anecdotal observations of the operators who suggest the hybrid is more productive for jobs with more swing, and it also argues for the possibility that for certain types of work, the HB215 may be a good replacement for the PC220, in spite of the fact that the PC220 is a slightly larger machine.

5.3.4 *In-Use Emissions Comparisons: HB215 vs PC200 vs PC220*

Comparing the combined, averaged results for each mode of the test shows the potential benefits and dis-benefits of each model of excavator when it comes to fuel consumption and emissions. This comparison focuses on the results for average CO_2, NO_x, and PM emissions for each model. THC and CO emissions were generally low.

CO_2 emissions serve as an analog of fuel consumption as practically all of the carbon in the fuel is converted to CO_2. The unit averaged CO_2 emissions for each mode of the test and each model of excavator are compared in Figure 5-6. The unit averaged emissions of NO_x and PM are similarly compared in Figure 5-7 and Figure 5-8. The three figures compare excavator models side by side for each mode. The left (blue) column represents the PC200 result, the middle (red) column represents the HB215LC-1, and the right (green) column represents the PC220. The error bars in these graphs show the 90% confidence interval for each mean.

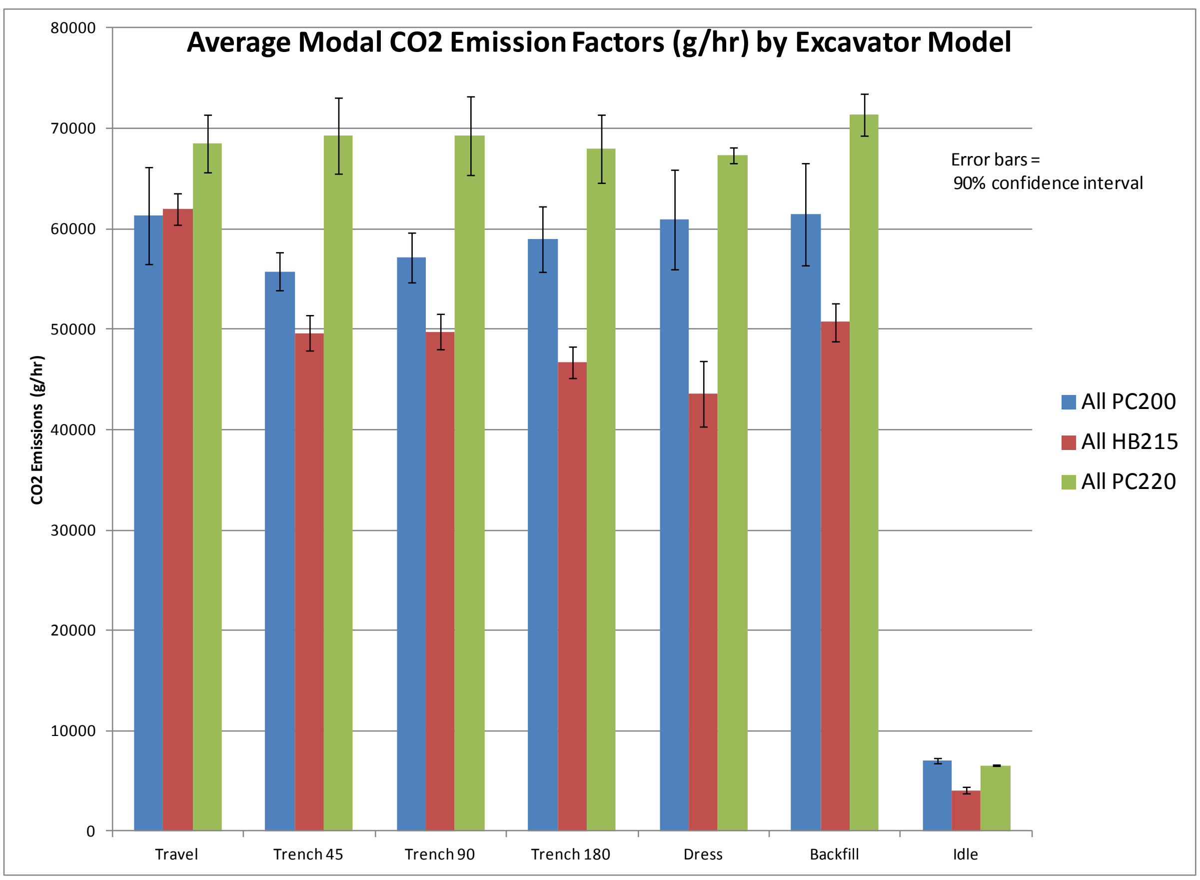

Figure 5-6: Average modal CO_2 (fuel consumption) differences between excavator models

For fuel consumption, the HB215 is consistently more efficient than either of the conventional excavators, except during the travel mode, where it consumes about the same amount of fuel as the 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 time of work. This translates to less fuel per job for the hybrid because these excavators are similarly productive.

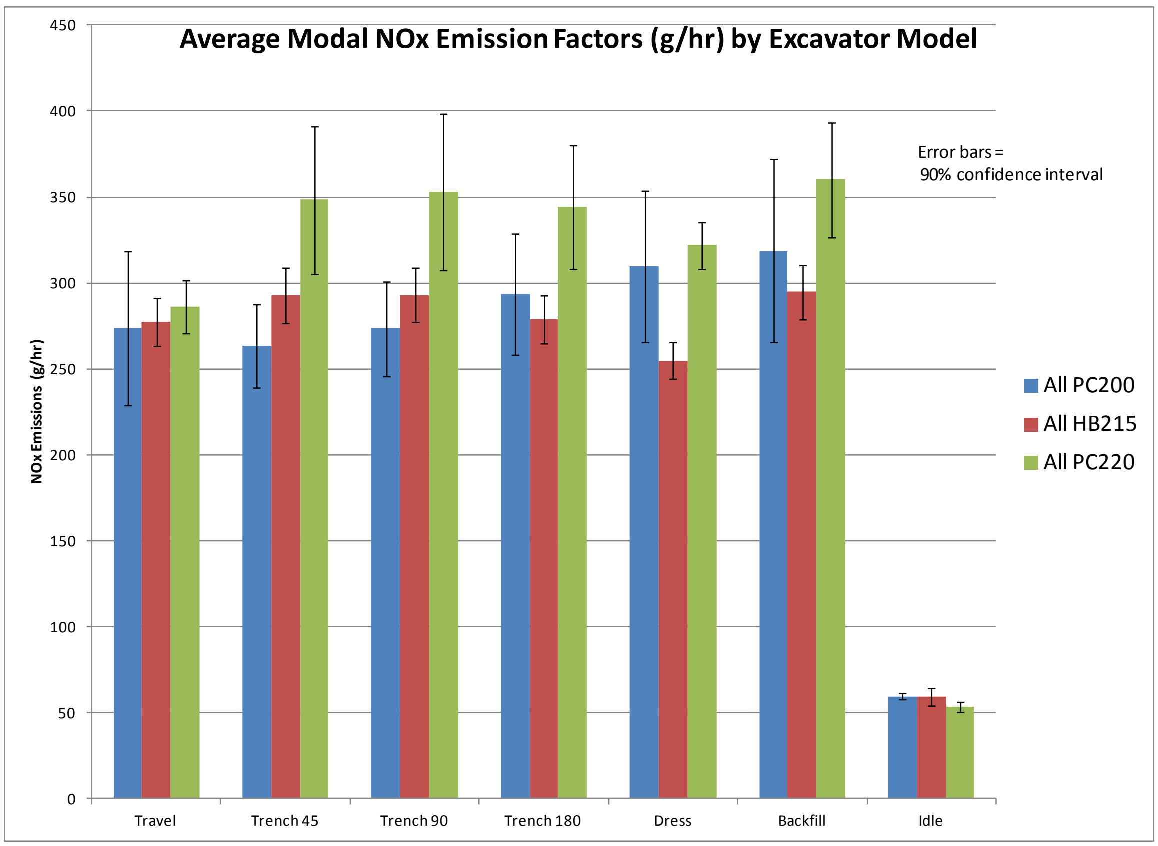

Figure 5-7: Average modal NO_x differences between excavator models

NO_x emissions from the HB215 and the PC200 are similar for the different modes of work, but those from the PC220 are consistently higher than from either the HB215 or the PC200, as the PC220 is a much larger machine than the other two and has the highest fuel consumption rate among the three.

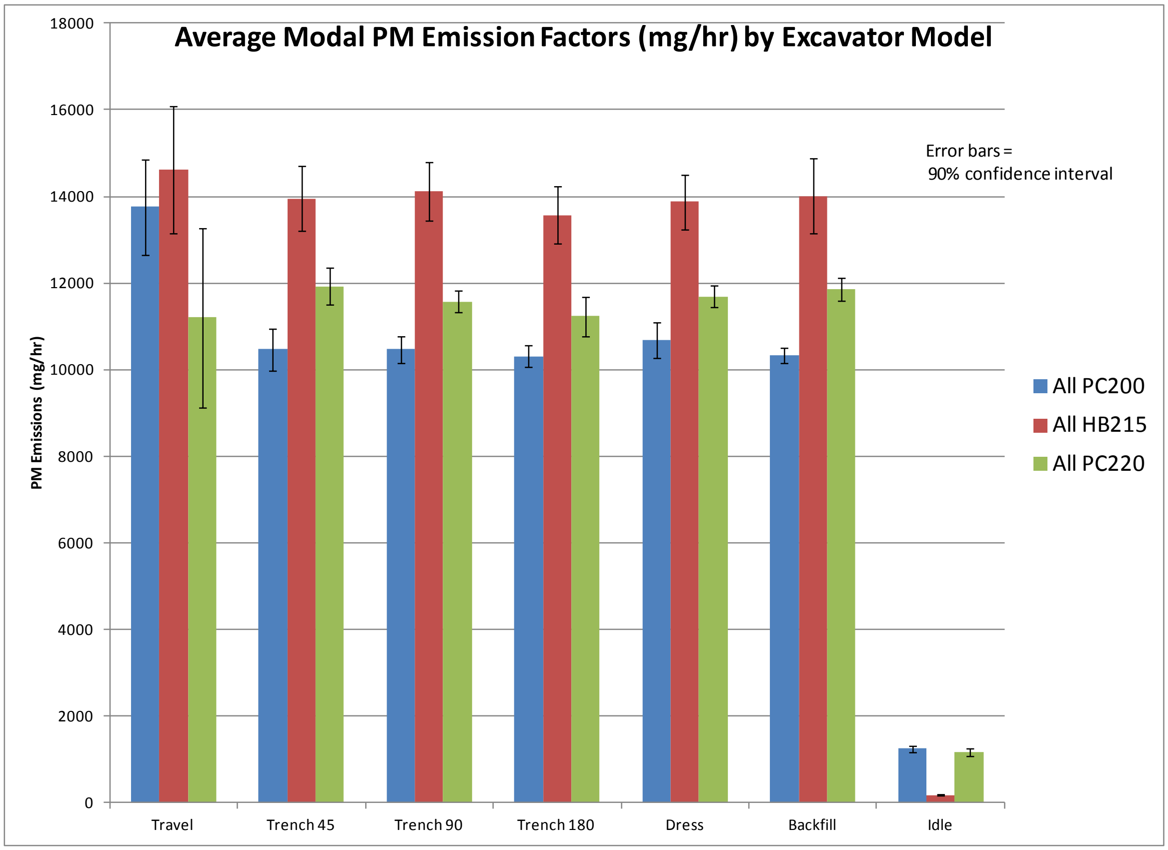

Figure 5-8: Average modal PM differences between excavator models

Particulate emissions from the 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 plume from the exhaust pipes of these units. The HB215 models all had more visible smoke plumes than the two conventional units. A possible explanation for the higher PM emissions from the hybrid is suggested by the comparison of second-by-second engine power versus engine speed for the hybrid HB215 and the conventional PC200 (Figure 5-9). The plot for the hybrid is on the left and that for the conventional is on the right. The power output of the hybrid's engine can be seen to vary significantly over a much wider range of engine speeds than the engine in the conventional excavator. The PC220 had a similar plot as the PC200. Abrupt engine speed changes under load can lead to higher PM and CO emissions from diesel engines. During emissions testing, the hybrid excavator engine speeds changed rapidly as the engine was loaded during various operations. If the engine calibration were changed to decrease the severity of these engine speeds changes under load, the PM emissions from the hybrid could be significantly decreased. Judging from previous work in this area, it is speculated this could be accomplished with little impact on fuel consumption and NO_x emissions.

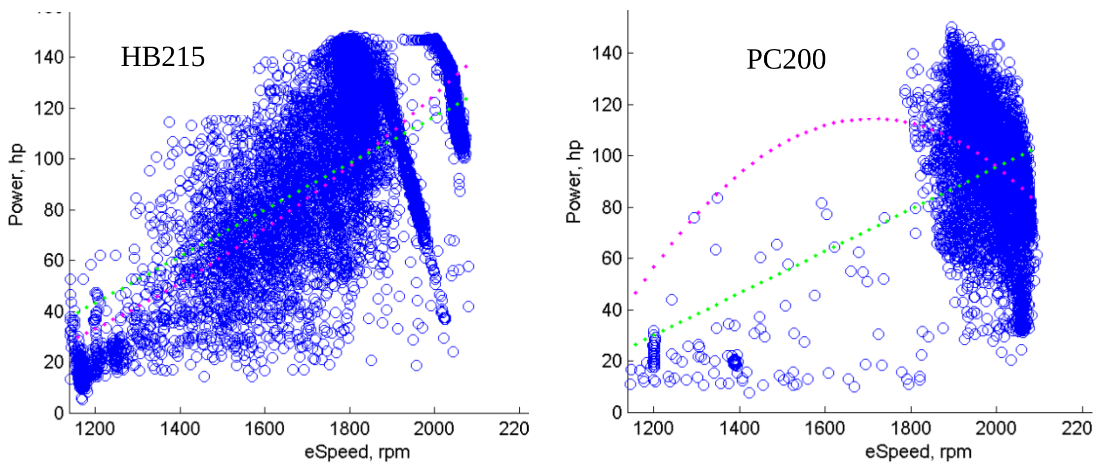

Figure 5-9: Engine load as a function of engine speed for the HB215LC-1 and PC200

5.3.5 Overall Benefit

The HB215 comparison results to PC200 and PC200 are summarized in Table **5–8**. The extremes of the ranges are a weighted average of the modal distribution observed in the general construction activity and those observed in the demolition activity data. And lastly, the overall weighted benefit of the HB215 is based on comparisons with PC200 and assumes 80% construction activity and 20% demolition activity. For example, the HB215 can provide savings from 13% to 23% in fuel (a benefit), but would emit from 26% to 27% more PM (a dis-benefit) in doing so. The expected ranges depend upon whether the excavators would be used more for construction or demolition type of work. As previously stated, Komatsu considers their PC200 to be the unit directly comparable to the HB215. By assuming that an average mix (80%

construction and 20% demolition) of work would be done by the excavators, a 16% fuel consumption benefit is estimated, along with a 27% increase in PM.

Table 5–8: Range of overall benefits of HB215 relative to conventional PC200 and PC200

	CO_2	NOx	PM	THC	CO
Ranges of overall benefits as " construction" only **or** "demolition" only					
PC200 Tier 3 [1]	-23% or -13%	-12% or 4%	26% or 27%	-70% or -68%	7% or 10%
PC220 Tier 3 [1]	-31% or -28%	-18% or -15%	15% or 19%	-74% or -73%	-12% to 0%
Overall weighted comparison (80% construction and 20% demolition)					
Wtd. PC200 Tier 3	-16%	1%	27%	-70%	8%

[1] Negative value means hybrid benefit and positive values mean dis-benefit, weighting factor from Table 5–6

It might be expected that, if an engine reduces fuel consumption by 20%, a corresponding reduction in criteria emissions might be seen as there is 20% less fuel burned. In reality, the dynamics of engine control with multiple systems, combinations of an internal combustion engine with electric mothers in the case of the hybrid 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 understand of how such systems can be optimized. The hybrid manufacturers today are able to achieve significant fuel savings, which is appealing to the end customers and helps reduce GHG emissions; however, an unexpected increase in criteria emissions needs to be accounted for. 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. Additional in-use testing, such as what was done in this study, could provide valuable information for optimizing emissions while maintaining the fuel economy benefits for the hybrid.

5.4 References

1. Light-Duty Vehicle Greenhouse Gas Emissions Standards and Corporate Average Fuel Economy Standards; Final Rule, Federal Register, May 7, 2010, vol. 75, No. 88.
2. Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles; Final Rule, Federal Register, September 14, 2011, vol. 76, No. 179.
3. Annual Energy Outlook 2014, US Department of Energy, Energy Information Administration, www.DOE.EIA.gov
4. Hallmark, L. S., Wang, B., Sperry. R., (2013) Comparisons of On-road Emissions for Hybrid and Regular Transit Buses, J. Air & Waste Mange. Assoc., Volume 63, Issue 10, 2013, DOI: 10.1080/10962247.2013.813874
5. Walkowicz, K., Lammert, M. Curran, P., (2012) Coca-Cola Refreshments Class 8 Diesel Electric Hybrid Tractor Evaluation: 13-Month Final Report, final report prepared by National Renewable Energy Laboratory. Contract No. DE-AC36-08GO28308. < http://www.nrel.gov/docs/fy12osti/53502.pdf>
6. Russell, R., Johnson, K., Durbin, T. D., (2012) Assessment of the Emissions and Fuel Economy of a Class 8 Conventional and Class 8 Hybrid Truck Chassis Dynamometer Testing. Final report prepared for CALSTART, July.
7. Control of Emissions of Air Pollution From Nonroad Diesel Engines and Fuel, Final Rule, Federal Register, June 29, 2004, vol. 69, No. 124.
8. Sokolsky, S., Presentation by CALSTART, “Joint Military Evaluation of the Benefits of an Electric-Drive Bulldozer”, Presented to Ventura County Naval Base, Port Hueneme, CA, November, 2011.

9. Block, M., Abolhasani, S., Toscano, F., Persson, E., Presentation by EMISSTAR LLC. “PEMS Testing – Applications and Lessons Learned”, Presented to V2012 PEMS Conference and Workshop, Riverside, CA, March 2012.

10. Abolhasani, S., Frey, H. C., Kim, K., Rasdorf. W., Lewis, P., and Pang, S., (2008) Real-World In-Use Activity, Fuel Use, and Emissions for Nonroad Construction Vehicles: A Case Study for Excavators, Journal of the Air & Waste Management Association, 58:8, 1033-1046

Chapter Six: Conclusions

The main objective of this research was to develop the analytical frame work to quantify in-use emissions and fuel consumption benefits from hybrid off-road construction equipment. The first phase of this research performed a validation of a new PEMS system for making accurate emissions measurements. This phase was critical since making accurate in-use measurements was challenging in the past. The second phase of the research studied in-use emission variability from high-use, off-road equipment, which is a great platform for gaining additional understanding of the real off-road equipment operations as well as developing in-use emission measurement methodologies. The last phase of this research combined the tools and experiences from first two phases to perform a comprehensive evaluation of the real-world emissions and fuels consumption benefits from hybrid bulldozer and hybrid excavators. From these two case studies, a general approach for making in-use evaluation of hybrid off-road sources was developed.

Chapter 2 studied in-lab and on-road emissions comparisons made between a new gaseous portable emissions measurement system (PEMS) and the UCR Mobile Emissions Laboratory (MEL) that's suitable for performing the gas PEMS comparison and validation studies. These comparisons were made over three different engines providing NO_x emission levels from 0.27 g/kW-hr to 5.4 g/kW-hr. The brake-specific emissions during the Not-To-Exceed (NTE) engine operating zone were compared between the MEL and PEMS to quantify the measurement uncertainty of this new PEMS. Overall, the PEMS showed good correlation to MEL and demonstrated its excellent ability to measure a wide variety range of emission levels. The PEMS brake-specific NO_x ($bsNO_x$) measurement is well behaved and on the order of a +5 to - 10% relative error from 1.0 to 7.0 g/kW-hr. The relative NO_x error ranged from a +15% to -15% from 0.1 to 1 g/kW-hr, and increased sharply from 15% to more than 50% below 0.1 g/kW-hr. The relative error below 0.10 g/kW-hr is high mostly because the emission level is so low that the error may be approaching the detection level of the two measurement methods. The PEMS $bsCO_2$ average bias was slightly higher than the MEL reference laboratory at 2% overall. NMHC and CO emissions were relative low for comparisons due to different configurations of aftertreatment systems (ATS). The main purpose of this study is to determine feasibly of the newly improved PEMS on today's ultra-low emission vehicles.

Chapter 3 investigated gaseous and particle emissions from twenty-seven pieces of construction equipment which included four backhoes, six wheel loaders, four excavators, two scrapers (one with two engines), six bulldozers, and four graders. The engines ranged in model year from 2003 to 2012, in rated horsepower from 92 to 540 hp, and in hours of operation from 24 to 17,149. The key finding from this study is that in-use emissions for off-road equipment can vary significantly depending on particular application. NO_x and PM emissions in particular, depending on the actual in-use engine load factor, can vary as much as 100% for the same type of off-road equipment. NO_x and PM emissions showed decreasing trends with engine model year, but a few Tier 3 units have shown much great in-use emissions than the older Tier 2 units. The overall in-use brake power average load was between 20 and 60% for nearly all units, with only 7 units having average loads >50%, and only one unit having an average load of >70%.

Chapter 4 studied emissions and fuel benefits of hybrid bulldozers. The goal of this study was to develop a methodology to evaluate the real-world emissions and fuel consumption benefit from hybrid off-road construction equipment in comparison to conventional alternatives, and to evaluate differences in emissions between different types of in-use operations. In this chapter, a total of six hybrid and conventional bulldozers were studied. In order to characterize the typical operation of different units, activity measurements were made on a subset of three hybrid and one comparable conventional pieces of construction equipment. Activity data were obtained using interviews, historical records, and in-use activity measurements with the time-lapse video; engine control module (ECM) broadcast data, and GPS data. The activity study found push distance and engine load were the most important metric for bulldozer activity and from this data seven test cycles were developed. A subset of five bulldozers were evaluated for emissions and fuel consumption over the developed duty cycles and in-service using a 40 CFR 1065 approved particulate matter (PM) and gaseous portable emissions measurement system (PEMS). The overall weighted results suggest the D7E hybrid bulldozer had a significant reduction in CO_2 emissions (-12%) but have increased NO_x emissions (+13%) when compared to a D6T conventional bulldozer. It should be noted that this NO_x difference is small enough and could be due to variation in the certifications of the engines within a given engine family and does not necessarily indicate dis-benefit for hybrid technologies as a whole. For the comparison to the much larger D8T, the D7E had a significant benefit for CO_2 (-23%) and NO_x (-28%) emissions, as expected.

Chapter 5 studied a total of seven hybrid and conventional excavators. In order to characterize the typical operation of different units, activity measurements were made on a subset of three hybrid and one comparable conventional pieces of construction equipment. Activity data were obtained using interviews, historical records, and in-use activity measurements with the time-lapse video; engine control module (ECM) broadcast data, and GPS data. From this activity data, a test cycle was developed with seven modes representing different types of excavator work. A subset of five bulldozers were evaluated for emissions and fuel consumption over the developed duty cycles and in-service using a 40 CFR 1065 approved particulate matter (PM) and gaseous portable emissions measurement system (PEMS). The overall weighted results suggest the HB215 hybrid excavator had a significant reduction in CO_2 emissions (-23% to -13%) but have increased PM emissions (+26 % to +27%) when compared to a PC200 conventional excavator. It should be noted that this PM emissions difference is large enough and could be due to more in-use RPM variation of the hybrid engine due to the hybrid system design which in term caused higher PM. For the comparison to the much larger PC220, the HB215 had a significant benefit for CO_2 (-31% to -28%) and dis-benefit for PM (27%) emissions, similar to the comparison to the PC200.

Chapter Seven: Recommendations

The California AB32 outlined some very challenging GHG emissions reduction goals by year 2050. The work from this thesis has demonstrated the GHG reduction potential of hybrid technologies on off-road equipment and the transportation sector as a whole. In summary, up to 50% GHG emissions reduction is possible with existing powertrain technologies within the transportation sector. However, any further reductions beyond 50% by existing powertrain technologies are difficult and not economically feasible, thus carbon neutral fuels and renewable energy sources are required to meet the 80% reduction goal. The existing production of corn derived ethanol in gasoline has not yet becoming beneficial in-terms GHG emission reduction due to the current fuel conversion process, current bio-diesels formulas do show some GHG benefits but the relative cost of the bio-diesel itself are still high. Recently, a few studies have shown that transformation to full electric vehicle (EV) within transportation sector can help reduce GHG emissions significantly but the cost and reliability of EV are still major areas of concern.

On another hand, the latest PEMS system has shown impressive accuracy for making in-use measurements. However, reliability, size, and weight of current PEMS systems are still on-going issues that need to be addressed. PEMS users are seeking for reliable, easy to install, and cost effective sensors that are more user-friendly and less maintenance intensive. Future PEMS research should focus on smaller, modular, light weight PEMS systems; at the same time, better power efficiency as well as the current PEMS systems does require external power generators for extended periods of sampling.

The off-road equipment chapters in this thesis have unfolded the complexity in off-road engine emissions. Future research should be focus on a complete assessment of different type off-road equipment to develop generalized equipment categories based on similar engine operations. The use of hybrid off-road equipment should be preceded with caution as this study has shown the reducing in fuel consumption came in the expense of increase in criteria emissions. Future hybrid off-road system development should better optimization of the engine around the hybrid system to avoid any potential emission increase due to unique hybrid engine operations.