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16. ABSTRACT

Prior to the development of the Phase 1 prototype (previously developed through a contract with the University of California, Riverside), there was no mutually accepted method by Caltrans and regulatory agencies to estimate construction emissions or to develop the appropriate regulations. The objective of this task is to upgrade the prototype which will be used to quantify off-road fleet emissions to the higher standard known as “Tier 4”: these emissions standards apply to new engines that power equipment commonly found in most construction applications.

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Updating Off-Road Equipment Prototype to Include Tier 4 Final Heavy-Duty Construction Equipment as Related to Job Site Activities

Prepared for:

Mr. Rodney Tavitas
Mr. Lucas Sanchez

Caltrans
1227 O Street - 5th Floor MS 83
Sacramento, CA 95814

November 2019

Submitted by:

Dr. Robert L. Russell
Dr. George Scora

University of California, Riverside
CE-CERT
1084 Columbia Ave.
Riverside, CA 92507
951-781-5723

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Randy White a retired dozer operator for Riverside County who operated the Caterpillar D8T crawler dozer.

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Acronyms and Abbreviations

40 CFR 1065 or 1065........................Part 1065 of Title 40 of the Code of Federal Regulations
BL ....Backhoe Loader
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
COV ....Coefficient of Variation
CVS ....constant volume sampling
DOC ....diesel oxidation catalyst
DPF ....diesel particulate filter
ECM..engine control module
EPA ....United States Environmental Protection Agency
Exc ....Excavator
FID ....flame ionization detector
GFM..gravimetric filter module
GR ....Grade Roller
g/hp-h ....grams per brake horsepower hour
MEL ....CE-CERT's Mobile Emissions Laboratory
MG ....Motor Grader
NMHC...non-methane hydrocarbons
NDIR...Non-Dispersive InfraRed
NDUV ....Non-Dispersive Ultraviolet Analyzer
NTE...Not-to-exceed
NO_x ....nitrogen oxides
OEM..original equipment manufacturer
PEMS ....portable emissions measurement systems
PM...particulate matter
RPM ....revolutions per minute
RTF ....Rough Terrain Forklift
RTL...Rubber Tired Loader
scfm..standard cubic feet per minute
SCR ....Selective Catalytic Reduction
SwRI ....Southwest Research Institute
Tier 2, 3, or 4.....................................federal emissions standards levels for off-road diesel engines
THC...total hydrocarbons
UCR ....University of California at Riverside

Executive Summary

The primary goal of this program was to update the prototype model[1] to include estimate of emissions from Tier 4 Final off-road construction equipment as a function of fuel use. A secondary goal is to determine emissions following cold starts, hot starts, and during Diesel Particulate Filter (DPF) regeneration and incorporate them into the model.

The prototype model was developed from second-by-second emission data from 27 pieces of off-road construction equipment. The equipment included 4 backhoes, 6-wheel loaders, 4 excavators, 2 scrapers (one with 2 engines), 6 Crawler Tractors, and 4 graders. The engines ranged in model year from 2003 to 2012, in rated horsepower from 92 to 540 hp, and from 24 to 17,149 hours of operation. The 27 pieces of equipment include 7 pieces of Tier 2 equipment, 15 pieces of Tier 3 equipment, and 5 pieces of Tier 4i equipment. Analysis of the data indicated that the emissions in g/kg-fuel burned are primarily a function of the emission Tier of the engine and two modes of engine operation defined as idle and non-idle.

The current program involved 10 pieces of Tier 4 final equipment. The engines ranged from model year 2014 to 2017, in rated horsepower from 115 to 397, and in hours of operation from 91 to 3652. The equipment included 3 Excavators, 3 Wheel Loaders; 2 Backhoe/Loaders, and 2 Crawler Tractors. Analysis of the data indicated that the emissions in g/kg-fuel burned are primarily a function of the emission Tier of the engine and two modes of engine operation defined as idle and non-idle. NO_x, CO, and PM emissions can be higher following cold and hot starts and during DPF regenerations.

As in the previous program, the data for each piece of equipment is partitioned into idle and non-idle based on the engine speed. The standard idle speed is determined for each vehicle from the dataset and the data is partitioned into mini events where mini events are defined as sections of continuous and uniform activity modes that end when the activity mode changes. The objective of this analysis is to create a tool that can be used to estimate emissions from off-road construction equipment based upon data readily available to the equipment owners. The developed prototype model, Off-Road Equipment Emission Estimator (ORE2) model is a stand-alone Excel spreadsheet with a graphical user interface and the ability to load parameter files to facilitate running the model. The inputs to the model are the equipment type (i. e. the emission tier of the engine), fuel consumption, and general equipment activity (i. e. whether the engine is idling or operating at a higher speed because the equipment is performing physical work).

Users of the model only need to input the total fuel burned by each piece of equipment and an estimate of the percent of time each piece of equipment was idling. With this input the model calculates the kilogram of fuel burned during idling and non-idling events and multiplies these values by an Emission Factor (EF) for each pollutant. For each pollutant an EF in terms of grams of pollutant per kg fuel burned during idling and non-idling modes was determined from analysis of the experimental measurements. The prototype mode included place holders for EF's for cold starts and Diesel Particulate Filter Regeneration (DPFR) events, but they were all set to zero as there had been no measurements of cold starts or DPFR events. The current program was designed to include emission measurements during cold starts, hot starts, and DPFR (if they occurred). This permitted calculation

[1] Developing a Model to Quantify Emissions from Heavy-Duty Construction Equipment as Related to Job Site Activity Data, report submitted to Caltrans, January 2015

of an EF for each of these events for the experimental data. However, after an extended discussion with George Scora, who created the prototype model, we agreed that there is no way for the prototype model to determine from the inputs to the model whether any cold starts, hot starts, or DPFR events occurred.

1 Introduction

Off-road equipment has been considered one of the most significant sources of nitrogen oxides (NO_x) and particulate matter (PM), both nationally and within California. The California Air Resources Board (CARB) has a web program to estimate statewide emissions from all sources for any chosen year. (https://www.arb.ca.gov/app/emsinv/fcemssumcat/cepam_emssumcat_cat_query_v5.php). Based on this program, for 2019 the statewide NO_x emissions for off-road equipment are estimated to be the 2nd largest source of NO_x emissions representing 3.7% of the total. The 2019 statewide PM emissions for off-road equipment are estimated to be the 17th largest source of PM emissions representing 0.17% of the total. (If only combustion sources are considered, then 2019 statewide PM emissions for off-road equipment are estimated to be the 9th largest source of PM emissions representing 0.38% of the total.) Although increasingly more stringent engine standards are being implemented for off-road engines, there is a still some lag between the implementation of the standards compared to similar standards for on-road vehicles. Off-road engines also have relatively long lifespans, due to their inherent durability, and can sometimes 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 for 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 do not represent real-world activity. Vehicles, on the other hand, are operated on chassis dynamometers over test cycles designed to represent different types of driving conditions. Although a number of studies have measured emissions from in-use off-road equipment, 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, there is still very limited data available on activity patterns for in-use off-road equipment to understand the conditions under which the equipment is typically operated and what types of operation lead to the greatest sources of 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 greatly enhanced the potential for characterizing in-use emissions for off-road equipment. A number of studies of construction equipment have been carried out over the years with different generations of PEMS technology. (Gautam et al., 2002) measured the CO_2 emissions from a street sweeper, a rubber-tired front-end loader, an excavator, and a track type tractor in the field to develop cycles for subsequent testing of the engines on a dynamometer. They also measured all the gas phase emissions from the track type tractor in the field. (Scora, et al., 2007) and (Barth, et al., 2008, 2012) measured the gas phase and PM emissions from a number of pieces of heavy-duty construction equipment. The EPA and its collaborators have also conducted an extensive study of construction emissions in EPA region 7 (Kishan et al. 2011, Giannelli et al., 2010, Warila et al., 2013). Frey and coworkers have conducted a number of studies looking at the emissions of construction equipment and how to model their emissions impact (Abolhasani, et al., [2008, 2013], Frey et al., [2003, 2008, 2008a, 2008b, 2010, 2010a], Lewis et al., [2009a, 2009b, 2011, 2012], Pang et al., [2009], Rasdorf et al. [2010]), Huai et al. [2005]) have also measured the activity for different fleets of off-road diesel construction equipment.

Over the past few years, there has been a considerable effort to standardize PEMS systems to meet regulatory requirements for making in-use compliance measurements for on-road vehicles and off-road equipment. Much of this work was done as part of the Measurement Allowance program, which included extensive laboratory testing at Southwest Research Institute (SwRI) and in-use testing using CE-CERT's Mobile Emission Laboratory (MEL), which conforms to Code of Federal Regulations (CFR) requirements for emission measurements (Cocker, et al., 2004), (Durbin, et al. (2007, 2009, 2009a), Fiest et al. (2008), Johnson, et al. (2008, 2009, 2010, 2011, 2011a), Khalek et al. (2010), Khan, et al. (2012), and Miller, et al. (2006, 2007, 2008)). Under this program, the accuracy of various PEMS systems was extensively evaluated to characterize the accuracy of the PEMS relative to more conventional laboratory regulatory measurements. This program was done in two separate phases to characterize gas-phase and PM-PEMS. The PEMS systems meeting the US EPA Part 40 CFR 1065 developed through the Measurement Allowance program represent the latest generation of PEMS, and the first such PEMS whose performance is traceable back to regulatory requirements. The results of these studies showed a high linear correlation between the MEL and the PEMS for brake specific NO_x ($bsNO_x$) and CO_2 ($bsCO_2$), with the PEMS measurements biased slightly high. The bsTHC and bsCO emissions were so low, near ambient for CO, that no correlation was observed. The best PM-PEMS unit also showed a high linear correlation between the MEL and the PM PEMS with the PM-PEMS biased slightly high.

The goal of this study is to determine if Tier 4F equipment emissions follow the same pattern as the Tier 2 through Tier 4I equipment and therefore can be added to the prototype model developed in the prior program. The equipment chosen to be tested in this program were rented and operated on rental agencies test lots. This provided an opportunity to design test cycles where the equipment performed the work it is designed to do and include designed breaks to check emissions following the designed breaks. Tier 4F equipment is expected to have higher emissions following cold and hot starts and DPF regenerations because the exhaust aftertreatment systems require high temperatures to reduce emissions. The gas phase and PM exhaust emissions and the engine work (E-Work) were measured on a second-by-second basis as in the previous program and hand logs indicated the type of physical work being performed.

2 Tier 4F Testing

2.1 Equipment Tested

Table 2-1 contains information about the equipment and engines tested and Table 2-2 presents the hours on the engine at the start of each test day. The filename consists of the test number, an underscore, the testing date, an underscore, the equipment manufacturer, an underscore, and the model number of the equipment (i.e. 48_2018-01-31_CAT335F). Depending on the engine, the exhaust aftertreatment system consists of a Diesel Oxidation Catalyst (DOC) - Selective Catalytic Reduction (SCR)-Ammonia Slip Catalysis (ASC) in that order, or a (DOC) - Diesel Particulate Filter DPF-SCR-ASC in that order. The DOC oxidizes hydrocarbons to CO_2 and water, CO to CO_2 and the volatile organic hydrocarbon (VOC) to CO_2 and water. The traditional emission measurement method uses a filter to collect PM which consists of solid soot and VOC. The soot which collects in the DPF has to be removed to prevent buildup of back pressure which will eventually result in engine damage. The DPF regeneration method is either passive or active. Passive regeneration occurs when the exhaust gases provide enough heat to vaporize the soot. Active regeneration requires a burner in front of the DPF to provide enough heat to volatize the soot.

Passive regeneration occurs whenever in the duty cycle the exhaust temperature is hot enough (greater than 250 – 350 °C to burn off the Particulate Matter (PM). It is important to minimize idling since idling temperatures are too low to promote regeneration. Larger engines require active regeneration because of the larger size of the aftertreatment system. Active regeneration requires an external source of energy, such as a fuel burner near the inlet to the DOC-DPF or an electrical heater, and injection of oxygen which will raise the exhaust temperature in front of the DPF to 600 to 900 °C.

All of the Caterpillar equipment was rented from Quinn Caterpillar and operated on their test lot at 800 E La Cadena Dr, Riverside, CA 92507. The John Deere and Hitachi equipment was rented from RDO Equipment Company and operated on their test lot at 20 Iowa Avenue, Riverside, CA 92507. The CAT 335F excavator was operated by a hired inexperienced operator. All of the rest of the equipment, except the CAT D8T crawler dozer, was operated by Don Pacocha. The CAT D8T crawler dozer was operated by a retired Riverside County experienced dozer operator, Randy White.

Table 2-1: Tier 4F Equipment Tested

File Names	Equipment Type	Equipment Manufacturer	CARB #	Engine Mfg	Engine Serial No.	Eng Model Year	Displ Liters	Rated Power (bhp)	Rated Speed (RPM)	HP Category
48, 49, 50 51 _2018-xx-yy_CAT_335F	Excavator	Caterpillar	CH8E88	Perkins	D8T05549	2015	7.01	203.7	1800	175-300
52, 53 _2018-xx-yy_CAT_930M	Wheel Loader	Caterpillar	DB4Y47	Perkins	D8T05679	2015	7.01	187.7	1800	175-300
54, 55 _2018-xx-yy_CAT_430F2	Backhoe/loader	Caterpillar	FB7J34	Perkins	W7N05800	2015	4.4	115.1	2200	100-175
56, 57, 58 _2018-xx-yy2_CAT_336FL	Excavator	Caterpillar	FM9X65	Caterpillar	SYE13070	2016	9.3	317.0	1600	300-450
59, 60 _2018-xx-yy_JD_744KII	Wheel Loader	John Deere	FB6C69	John Deere	RG6090U042695	2017	9	364.6	2100	300-450
61, 62 _2018-xx-yy_JD_310SL	Backhoe/loader	John Deere	MB9S35	John Deere	PE4045U049562	2017	4.53	126	2200	100-175
63, 64 _2018-xx-yy_JD_1050K	Crawler Dozer	John Deere	WR7P47	John Deere	RG6135U002084	2014	13.5	396.8	2000	300-450
65, 66 _2018-xx-yy_Hitachi_210GLC	Excavator	Hitachi	HX6H68	Isuzu	4HK1XDRAB-01	2017	5.19	172.2	2000	100-175
67, 68 _2018-xx-yy_JD_824KII	Wheel Loader	John Deere	VM6L43	John Deere	RG6135U002202	2014	13.5	396.8	2000	300-450
69, 70 _2018-xx-yy_CAT_D8T	Crawler Dozer	Caterpillar	RY9R49	Caterpillar	ENG01073	2015	15.2	316.3	1700	300-450

Table 2-1 Continued

File Names	Equipment Type	Equipment Manufacturer	CARB #	Engine Mfg	Engine Serial No.	Eng Model Year	Displ Liters	Rated Power (bhp)	Rated Speed (RPM)	HP Category
48, 49, 50 51 _2018-xx-yy_CAT_335F	Excavator	Caterpillar	CH8E88	Perkins	D8T05549	2015	7.01	203.7	1800	175-300
52, 53 _2018-xx-yy_CAT_930M	Wheel Loader	Caterpillar	DB4Y47	Perkins	D8T05679	2015	7.01	187.7	1800	175-300
54, 55 _2018-xx-yy_CAT_430F2	Backhoe/loader	Caterpillar	FB7J34	Perkins	W7N05800	2015	4.4	115.1	2200	100-175
56, 57, 58 _2018-xx-yy2_CAT_336FL	Excavator	Caterpillar	FM9X65	Caterpillar	SYE13070	2016	9.3	317.0	1600	300-450
59, 60 _2018-xx-yy_JD_744KII	Wheel Loader	John Deere	FB6C69	John Deere	RG6090U042695	2017	9.03	364.6	2100	300-450
61, 62 _2018-xx-yy_JD_310SL	Backhoe/loader	John Deere	MB9S35	John Deere	PE4045U049562	2017	4.53	126	2200	100-175
63, 64 _2018-xx-yy_JD_1050K	Crawler Dozer	John Deere	WR7P47	John Deere	RG6135U002084	2014	13.5	396.8	2000	300-450
65, 66 _2018-xx-yy_Hitachi_210GLC	Excavator	Hitachi	HX6H68	Isuzu	4HK1XDRAB-01	2017	5.19	172.2	2000	100-175
67, 68 _2018-xx-yy_JD_824KII	Wheel Loader	John Deere	VM6L43	John Deere	RG6135U002202	2014	13.5	396.8	2000	300-450
69, 70 _2018-xx-yy_CAT_D8T	Crawler Dozer	Caterpillar	RY9R49	Caterpillar	ENG01073	2015	15.2	316.3	1700	300-450

Table 2-2: Engine hours at start of test day

File Name	Engine Hours
48_2018-01-31_CAT_335F	2051.1
49_2018-02-01_CAT_335F	2056.2
50_2018-02-01_CAT_335F	2060.0
51_2018-02-02_CAT_335F	2062.7
52_2018-05-30_CAT_930M	2054.4
53_2018-05-31_CAT_930M	2057.0
54_2018-06-28_CAT_430F2	1594.0
55_2018-06-29_CAT_430F2	1600.7
56_2018-07-12_CAT_336F	1611.0
57_2018-07-12_CAT_336F	1612.4
58_2018-07-13_CAT_336F	1615.4
59_2018-07-17_JD_744KII	353.0
60_2018-07-18_JD_744KII	358.7
61_2018-07-26_JD_310SL	694.8
62_2018-07-27_JD_310SL	697.9
63_2018-08-01_JD_1050K	1991.5
64_2018-08-02_JD_1050K	1996.0
65_2018-08-09_Hitachi_210GLC	348.6
66_2018-08-10_Hitachi_210GLC	349.6
67_2018-08-14_JD_824KII	91.8
68_2018-08-15_JD_824KII	96.8
69_2018-12-17_CAT_D8T	3652.2
70_2018-12-18_CAT_D8T	3654.3

2.2 Portable Emission Measurement System (PEMS)

Gaseous emissions were measured with a Semtech-DS emission analyzer[2] (see Figure 2-1). This system measures NO_x using a UV analyzer, total hydrocarbons (THC) using a heated flame ionization detector (HFID), and carbon monoxide (CO) and carbon dioxide (CO_2) using a non-dispersive infrared (NDIR) analyzer. THC emissions are collected through a line heated to 190°C consistent with the conditions for regulatory measurements. The analyzers provide measurements of the concentration levels in the raw

[2] Semtech DS analyzer http://www.sensors-inc.com/

exhaust. The hydrocarbon analyzer did not function properly during this test program so the hydrocarbon emissions are not reported. The Semtech-DS also records information broadcast by the ECM which is needed to calculate emissions in g/bhp-hr.

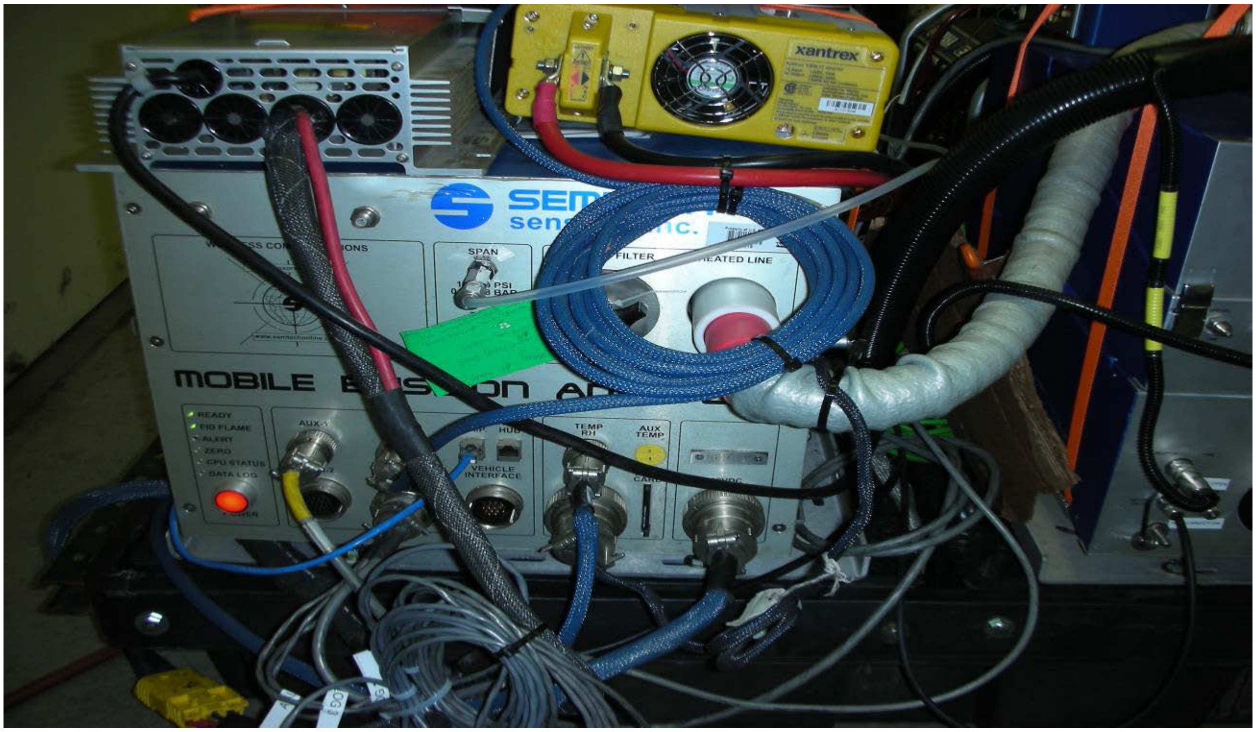

Figure 2-1: Semtech DS PEMS

The particulate matter (PM) analyzer is a prototype AVL Micro Soot Sensor (MSS) with a gravimetric filter box**.** The MSS measures the soot concentration (solid particles) on a second-by-second basis by a photo-acoustic principle. The gravimetric filter box extends the soot measurement to a combination of time resolved soot and integrated volatile organic compounds (VOC) based upon a simple gravimetric span method. The accumulated soot signal from the MSS is compared with the total mass on the filter. The ratio of the difference is multiplied by the soot signal to estimate the total PM. There are a total of 23 test runs, but only 15 filters, as in some cases the filter was not changed between successive runs with the same equipment. In one test run the MSS unit did not function at all so there are no MSS measurements. For the 14 cases with MSS and filter data the ratio of filter weight to total MSS weight ranged from 0.26 to 57.15 with an average of 6.79 and one standard deviation of 15.04. In the past we typically had averages closer to 2.0. If the four values greater than 3.0 are eliminated then the average is 1.10 with one standard deviation of 0.88. For each test we estimated the grams of MSS not detected because of instrument problems and added this weight to the total measured and recalculated the MSS/Gravimetric ratio. For the 14 cases the ratio ranged from 0.16 to 50.00 with an average of 6.01 and one standard deviation of 13.19. Removing the four values greater than 3.0, the average is 0.95 with one standard deviation of 0.91. We decided to assume that the MSS is measuring all of the PM for this Tier 4F equipment, which implies that the DOC is oxidizing all of the VOC.

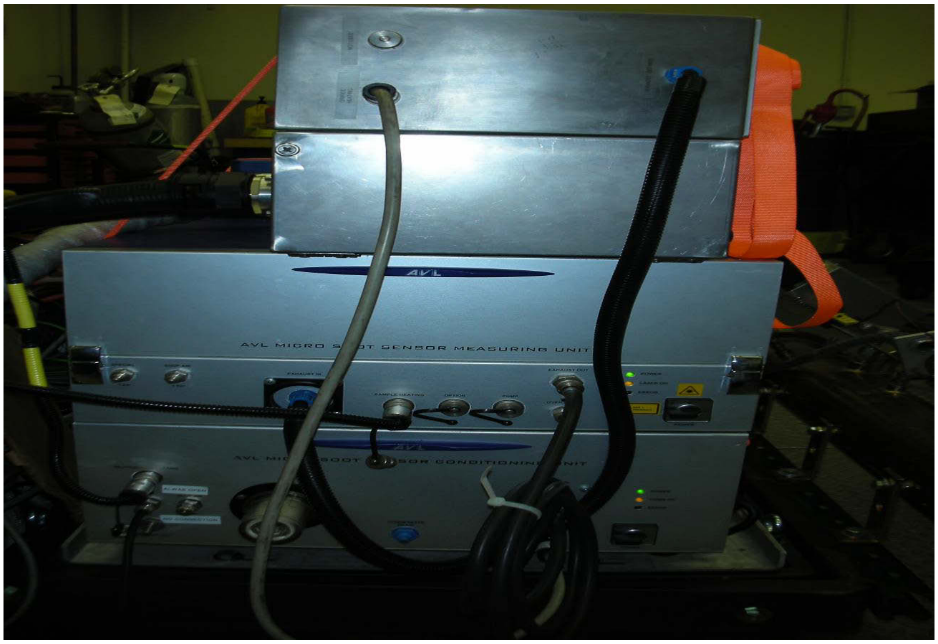

Figure 2-2: AVL Micro Soot Sensor with Gravimetric Filter Box on Top

The exhaust pollutants were extracted from a Sensors flow rate meter attached to the equipment exhaust with a flexible pipe. The flow meter, Figure 2-3, uses a pitot tube to measure exhaust flow rates. The flow meter is housed in a 5” diameter pipe that is placed in line with the engine tailpipe exhaust for the equipment being tested. The exhaust flow rates are multiplied by the concentration levels for the various emission components to provide emission rates in grams per second.

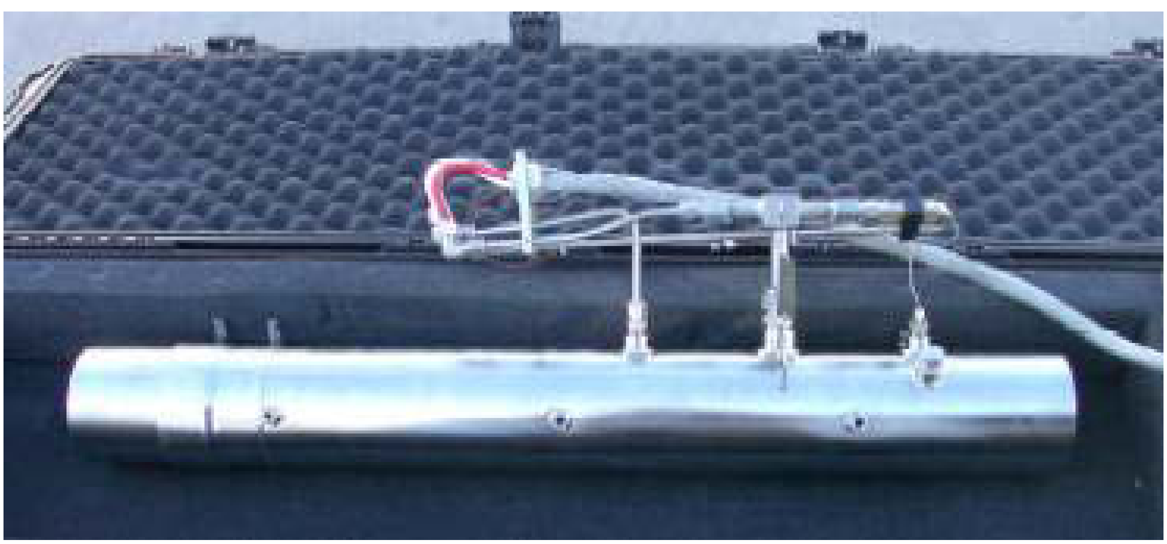

Figure 2-3: Semtech DS Exhaust Flow Meter

2.3 HEM Logger

For this program we also employed a Y connector to the ECM output plug so that a HEM Logger (Figure 2-4) also logged public information broadcast from the ECM. The HEM logger can log all of the information that the engine manufacturer allows to be publicly broadcast. Employing the HEM logger in addition to the ECM logger in the Semtech-DS proved to be very valuable in a couple of cases where the Semtech-DS did not log some critical information required for some final emission calculations, while the HEM logger did record information which allowed calculation of the emissions not calculable by the Semtech-DS.

Figure 2-4: HEM Data Mini Logger

2.4 Test Set-up

The test setup includes the emissions analyzers, associated exhaust flow meter, HEM Data Mini Logger and a gasoline powered Yamaha EF2800 generator (Figure 2-5) to power the AC emission analyzers. The generator has a built-in inverter to power DC equipment, such as the PC, for logging data.

The emission measurement equipment is mounted on a platform which can be lifted by a forklift or a crane (Figure 2-6), placed on the roof of the equipment to be tested and fastened down with straps.

Figures 2-7 through 2-16 show the equipment as mounted upon each of the pieces of equipment which we tested.

Figure 2-5: Yamaha EF2800 generator for powering equipment

Figure 2-6: Emission Measurement Equipment being lifted by forklift

Figure 2-7: Emission Equipment on CAT 335F Excavator

Figure 2-8: Emission Equipment on CAT 950M Wheel Loader

Figure 2-9: Emission Equipment on CAT 430F2 Backhoe/Loader

Figure 2-10: Emission Equipment on CAT 336FL Excavator

Figure 2-11: Emission Equipment on JD 744KII Wheel Loader

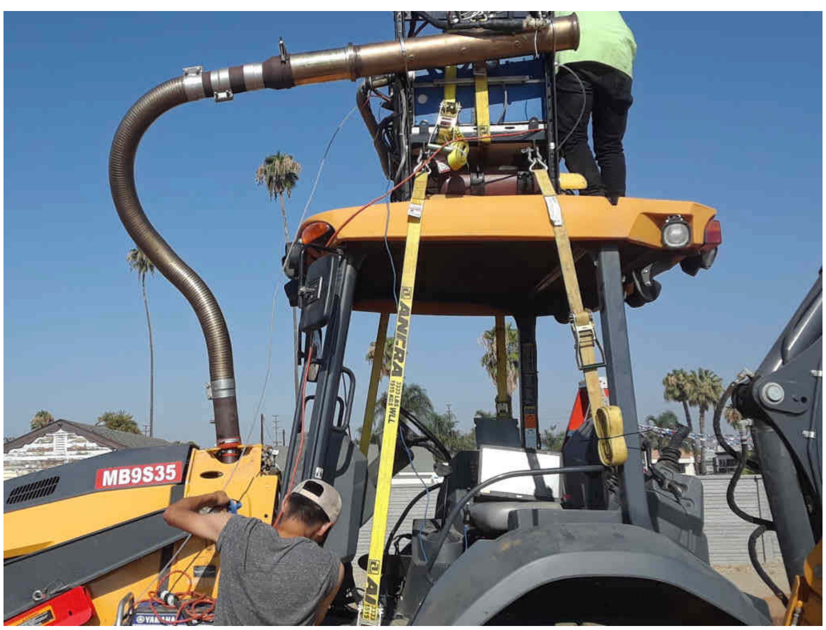

Figure 2-12: Emission Equipment on JD 310SL Backhoe/Loader

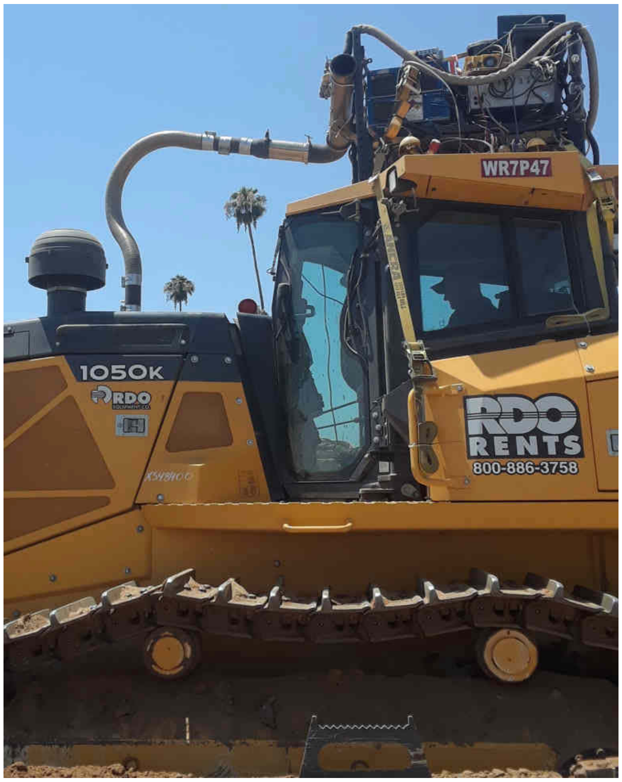

Figure 2-13: Emission Equipment on JD 1050K Crawler Tractor

Figure 2-14: Emission Equipment on Hitachi 210GLC Excavator

Figure 2-15: Emission Equipment on JD 824KII Wheel Loader

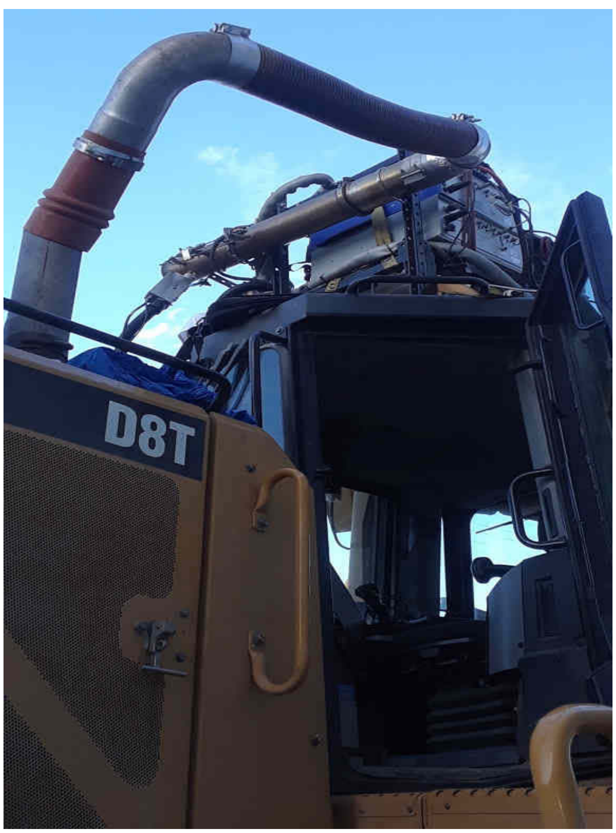

Figure 2-16: Emission Equipment on CAT D8T Crawler Tractor

3 Emissions Data Analysis

3.1 Time Alignment

The gaseous emissions, Semtech-DS ECM output, and Semtech-DS GPS coordinates are recorded in one file on a computer, the AVLMSS Soot in a second file, the dilution ratio of the AVLMSS soot in a third file, and the HEM logged data and GPS coordinates in a fourth file. The Semtech-DS recorded information is post-processed by the Sensor Tech PC program which automatically time aligns all of the gas phase emission data with the exhaust gas flow rate and calculates emissions in g/sec, g/kg-fuel, and g/bhp-hr, provided that all the necessary information for the calculations is available, and produces a CSV file, named PP_*, with all of the recorded data and calculations on a second-by-second basis.

All of the files have a column with a time stamp for each row of data. Appropriate data from the three files are copied and pasted into appropriate blank columns in the PP_* file based upon the time stamps. Subsequently the AVLMSS data is time aligned with the exhaust gas flow rate to permit calculation of MSS soot and PM in g/sec, g/kg-fuel, and g/bhp-hr. The HEM data is also time aligned with the exhaust gas flow rate.

3.2 Calculation of MSS soot in g/sec, g/kg-fuel, g/bhp-hr

The Sensor Tech-PC program normally calculates emissions of CO_2, CO, NO_x, and THC, in g/sec, g/kg-fuel, and g/bhp-hr. The post-processed file contains blank columns with headings of: AVLMSS wet, AVLMSS concentration dry, dilution ratio, AVLMSS adjusted concentration, Instantaneous Fuel Specific AVLMSS, Cumulative Brake Specific AVLMSS, Instantaneous Mass AVLMSS and Cumulative Mass AVLMSS. The AVLMSS concentration dry and dilution ratio are the time aligned values copied and pasted into these columns. All the other columns are calculated based on these two columns and appropriate values in other Sensors_DS post-processed columns.

3.3 Discussion of Specific Tests

3.3.1 All Tests

Table 3-1 presents the total hours of valid data for CO_2, CO, NO_x, PM emissions and Power and Fuel, and comments for each test. When hours for a specific emission, power, or fuel are less than the total hours it is because the data is at or below the detection level or the data was “lost” because of instrument problems. While lost data will mean that there will not be a valid value for the total grams of that pollutant over the whole test period it will have no effect on the g/kg-fuel as this number is calculated for each second and is the important value in the prototype model.

	Hours of Valid Data							
File Name	Total	CO2	CO	NOx	PM	Power	Fuel	Comments
48_2018-01-31_CAT_335F	5.01	5.01	0.35	4.97	0.54	5.01	5.01	MSS data loss caused by power problems. Physical work consists of travel, trenching 45, trenching 90, trenching 180, backfilling 180, backfilling 90, backfilling 45, dressing/dirt leveling.
49_2018-02-01_CAT_335F	3.50	3.50	0.30	3.49	2.22	3.50	3.50	MSS data loss caused by power problems. Initial 3 minutes of emission data missed. Physical work same as on 1/31/18. MSS stopped operating so stopped all testing to fix problem.
50_2018-02-01_CAT_335F	2.34	2.34	0.00	2.34	1.69	2.34	2.34	Data recording restarted, saving data to a new file after fixing MSS problem.
51_2018-02-02_CAT_335F	4.93	4.93	4.93	4.93	3.94	4.93	4.93	Generator and inverter issues throughout the day. Physical work same as previous two days.
52_2018-05-30_CAT_930M	2.06	2.06	2.06	2.06	0.43	2.06	2.06	MSS data loss caused by power problems. SemTech_DS stopped recording critical information needed to calculate emissions at 1:15 PM, ~1 hour of data lost. Physical work consisted of travel, digging trench with light work - (nearly empty bucket), medium work (~1/2 full bucket), heavy work (full bucket), followed by refilling trench.
53_2018-05-31_CAT_930M	3.11	3.11	3.00	3.11	1.56	3.11	3.11	Physical work same as on 5/30/18 but work done on smaller test lot at Quinn Caterpillar.
54_2018-06-28_CAT_430F2	1.47	1.47	1.47	1.47	0.00	1.47	1.47	MSS stopped functioning when testing started. Physical work consists of travel, light, medium, and heavy work with backhoe, light, medium and heavy work with front end bucket. g/bhp-hr emissions manually determined using lug curve.
55_2018-06-29_CAT_430F2	3.15	3.15	3.15	3.15	2.82	3.15	3.15	No MSS data during first hour of operation. Physical work same as on 6/28/18. g/bhp-hr emissions manually determined using lug curve.
56_2018-07-12_CAT_336FL	1.23	1.23	1.21	1.23	1.09	1.23	1.23	Generator stopped running at 12:35. Exhaust Flow Meter not functioning. Calculated exhaust flow rate in scfm from measured wet CO_2, and instantaneous mass of CO_2 in g/s. Physical work same as for CAT 335F excavator.
57_2018-07-12_CAT_336FL	1.23	1.23	1.21	1.23	1.09	1.23	1.23	Restart after restarting generator. Physical work same as for CAT 335F excavator.
58_2018-07-13_CAT_336FL	4.12	4.12	4.04	4.12	3.76	4.12	4.12	Physical work same as for CAT 335F excavator.
59_2018-07-17_JD_744KII	1.58	1.58	1.58	1.58	1.08	1.55	1.58	Physical work includes travel, light, medium, and heavy work
60_2018-07-18_JD_744KII	2.89	2.89	2.78	2.89	2.64	2.84	2.89	Physical work includes travel, light, medium, and heavy work
61_2018-07-26_JD_310SL	2.35	2.35	2.35	2.35	2.27	2.32	2.35	Physical work includes travel, digging with the backhoe and refilling the hole with the front end bucket. MSS went to hibernate at 11:06, measurement restored at 11:25.
62_2018-07-27_JD_310SL	2.72	2.72	2.69	2.72	2.68	2.68	2.72	Physical work includes travel, digging with the backhoe and refilling the hole with the front end bucket.11:54:30 UC Gravimetric filter error - flows at -111. 13:00:00 MSS no flow through.
63_2018-08-01_JD_1050K	4.35	4.35	4.35	4.35	4.35	4.35	4.35	WiFi connection lost a couple of times. Grav PM stopped working at 12:52, restored at ?. Physical work consists of travel, ripping, digging a trench, refilling the trench. HEM logger stopped logging at 10:03:06, reason unknown.
64_2018-08-02_JD_1050K	4.93	4.93	4.92	4.93	4.93	4.92	4.92	Physical work consists of travel, ripping, digging a trench, refilling the trench.

Table 3-1: Hours of Valid Data for each test

	Hours of Valid Data							
File Name	Total	CO2	CO	NOx	PM	Power	Fuel	Comments
65_2018-08-09_Hitachi_210GLC	0.86	0.86	0.44	0.86	0.86	0.84	0.86	Physical work consists of travel, digging a trench, refilling the trench.
66_2018-08-10_Hitachi_210GLC	3.22	3.22	0.37	3.22	3.22	3.22	3.22	Physical work consists of travel and digging a trench. Trench was refilled with a wheel loader which didn't have emission measurement equipment installed..
67_2018-08-14_JD_824KII	2.07	2.07	0.49	2.06	2.07	2.07	1.98	MSS stopped logging at 11:01:35, restarted at 11:17:40. Stopped at 11:24:06, restarted at 11:49:17. Stopped at 12:04:21, restarted at 12:04:56. Data from 12:39:32 to 13:47:11 lost due to Semtech-DS malfunction. Processed Semtech-DS data only reported emissions in g/kg-fuel. Exhaust Flow Meter not functioning. Calculated fuel rate in kg-fuel/s from HEM measured fuel rate in l/hr. Calculated instantaneous mass emissions in g/s from fuel specific emissions times Calculated fuel rate. Calculated exhaust flow rate in scfm from measured wet CO2, and instantaneous mass of CO2 in g/s. Calculated g/bhp-hr emissions from cumulative mass emissions/cumulative work. Physical work was travel, digging trench, refilling trench.
68_2018-08-15_JD_824KII	2.89	2.89	0.34	2.87	2.89	2.74	2.89	MSS stopped logging at 8:49:47. restarted at 8:56:35. Vehicle Interface data not recorded. Processed Semtech-DS data reported emissions in g/kg-fuel and g/s. Exhaust Flow Meter not functioning. Calculated exhaust flow rate in scfm from measured wet CO2, and instantaneous mass of CO2 in g/s. Calculated Derived Engine Torque from HEM reported Percent Torque, Percent Fricition Torque, and Reference Engine Torque. Calculated Derived Engine Power from HEM Derived Engine Torque and HEM reported Engine Speed. Calculated g/bhp-hr emissions from cumulative mass emissions/cumulative work. DPF regeneration at 13:13:40. Physical work was travel, digging trench, refilling trench.
69_2018-12-17_CAT_D8T	1.99	1.99	1.99	1.98	0.65	0.82	1.99	Semtech_DS did not log vehicle ECM data and HEM logger did not log data until 1:31:30 therefore only emissions in g/kg-fuel and g/sec are available from 12:05:10 to 1:31:30. Estimated rpm prior to 1:31:30 from correlation between exhaust flow rate and rpm from 1:31:30 to end of test. MSS lost connection at 12:48:00 so there are no MSS data after that time. Engine load estimated as 0.922533*(Engine %Torque reported by HEM logger). Derived Engine Torque based on lug curve using estimated engine load and rpm from HEM logger. Derived Engine Power from Derived Engine Torque and HEM rpm. Could not estimate engine %load prior to 1:31:30 so no g/bhp-hr results during that period. Cumulative g/bhp-hr emissions = cumulative mass emissions/cumulative work. Physical work = travel, ripping,, pushing dirt pile.
70_2018-12-18_CAT_D8T	4.25	4.25	4.25	4.23	4.25	4.25	4.25	Semtech_DS did not log vehicle ECM data. Engine load estimated as 0.922533*(Engine %Torque reported by HEM logger). Derived Engine Torque based on lug curve using estimated engine load and rpm from HEM logger. Derived Engine Power from Derived Engine Torque and HEM rpm. Cumulative g/bhp-hr emissions = cumulative mass emissions/cumulative work. Physical work = travel, ripping,, pushing dirt pile.

Table 3-2 (continued): Hours of Valid Data for each test

3.3.2 Caterpillar 335F Excavator

This unit was tested on 1/31/2018, 2/1/2018, and 2/2/2018. The AVLMSS and gravimetric filter box stopped functioning multiple times on all 3 days because of loss of power to these instruments. On each day the excavator traveled around the test lot three times and then began digging a trench about 10-foot-long depositing the dirt after a 45^{o} swing. Then it would back up and dig a trench about 10-foot-long depositing the dirt after a 90^{o} swing. Then it would back up and dig a trench about 10-foot-long depositing the dirt after a 180^{o} swing. The trenches would then be backfilled in the reverse order with equivalent swings. Then the dirt would be leveled out by swinging the bucket back and forth (dressing/dirt leveling). Idles or engine off were interspersed between various operations. On 2/1/2018 testing was interrupted to fix problems with the MSS and gravimetric filter box and when testing was resumed the data was saved to a new file which is why there are "two" tests on that day.

3.3.3 Caterpillar 930M Wheel Loader

This unit was tested on 5/30/2018 and 5/31/2018. On 5/30/2018 the unit was operated on the Quinn large test lot and on 5/31/2018 it was operated on the smaller test lot. The reason for the move was because the soil on the large lot was hard and compacted while there was a large pile of loose soil on the smaller lot. The bucket on the 930M was not designed for digging hard compacted soil. Physical work consisted of travel, light work ("digging" very shallow, ~empty bucket), medium work (digging until bucket ~half full), heavy work (digging until bucket totally filled). Periods of idle or engine off interspersed between various operations. On 5/30/2018 the MSS stopped functioning when the testing started so there are no measurements of PM emissions. The Semtech-DS stopped recording critical information needed to calculate emissions at 1:15 PM thus losing about 1 hour of emission data.

3.3.4 Caterpillar 430F2 Backhoe/Loader

This unit was tested on 6/28/2018 and 6/29/2018. On 6/28/18 the MSS unit stopped functioning when the testing started so there are no measurements of PM emissions. Physical work consisted of light, medium, and heavy work with the backhoe and with the front-end loader. Emissions were also measured during the travel to and from the test lot. Periods of idle or engine off interspersed between various operations. On 6/29/18 the MSS unit didn't function properly for the first hour so there are no PM measurements during that time. Relative to other units there were some unusually high spikes in the MSS data (6 which were 5 to 50 times higher than the approximate average of the others). These spikes may be due to dust being drawn into the exhaust stream by the venturi (see Figure 3-1)[3]. With the exception of the excavators, all the other units tested also had a venturi associated with the exhaust stack. However, we were able to unbolt the outer exhaust stack and attach the connection to our exhaust flow meter directly to the inner exhaust stack thus eliminating the venturi. We attempted to do the same for the 430F2, but could not gain access so attached our connection to the top of the exhaust stack (see Figure 2-9). While the introduction of ambient air into the exhaust will reduce the concentration of the gaseous species it will not affect the calculation of the emissions since they depend on concentration and total exhaust flow. The PM emissions will be affected by any solid particles in the ambient air drawn into the exhaust stack. However the spikes were only about 5 seconds wide so they were not eliminated as they do not have much effect on the PM emissions in g/kg-fuel.

[3] Photo provided by Matthew Stefanick of Caterpillar

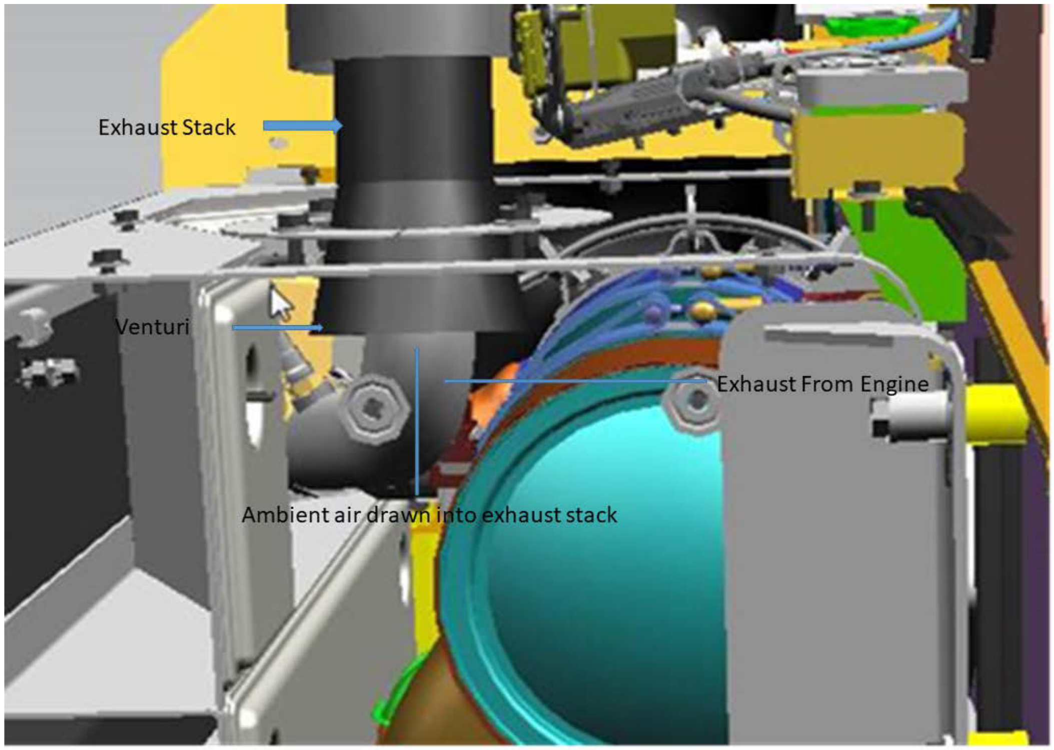

Figure 3-1: Exhaust Stack Venturi on CAT 430F2

3.3.5 Caterpillar 336FL Excavator

This unit was tested on 7/12/2018 and 7/13/2018. On 7/12/2018 the exhaust flow meter was not functioning for the first half of the day and the generator stopped running at 12:35. After correcting the problem with the exhaust flow meter and restarting the generator the data was stored in a new file which is why there are two tests on 7/12/2018. The physical work for this test was the same as for the Caterpillar 335F excavator.

3.3.6 John Deere 744KII Wheel Loader

This unit was tested on 7/17/2018 and 7/18/2018. All of the John Deere and Hitachi equipment was tested on the RDO Equipment Co. test lot, which was considerably smaller than the Quinn test lots. Physical work includes travel from the repair building to the test lot, light, medium, and heavy work similar to the Caterpillar 930M, and traveling back to the repair building. Idle or engine off times are interspersed at various times. No major problems during these tests. The data analysis revealed many more idle events than were scheduled. It is assumed that this may be related to the limited working area which required very short travel distance between filling the bucket, reversing the equipment, emptying the bucket, reversing the equipment, and then going forward to refill the bucket. Having more idle events than scheduled is generally true for all of the equipment tested on the RDO test lot.

3.3.7 John Deere 310SL Backhoe/Loader

This unit was tested on 7/26/2018 and 7/27/2018. Physical work includes travel from the repair building to the test lot, multiple digging with the backhoe, multiple refilling the hole with the front-end bucket, and traveling back to the repair building. Idle or engine off times are interspersed at various times. No major problems during these tests.

3.3.8 John Deere 1050K Crawler Tractor

This unit was tested on8/01/2018 and 8/02/2018. Physical work includes travel from the repair building to the test lot, ripping the length of the test lot a few times followed by multiple bulldozing and then refilling a trench, and traveling back to the repair building. Idle or engine off times are interspersed at various times. No major problems during these tests.

3.3.9 Hitachi 210GLC Excavator

This unit was tested on 8/09/2018 and 8/10/2018. Physical work on 8/9/2018 includes travel from the repair building to the test lot, multiple digging and refilling a trench, and traveling back to the repair building. Physical work on 8/10/2018 includes travel from the repair building to the test lot, multiple digging a trench, multiple parking the excavator while refilling the trench with a wheel loader, and traveling back to the repair building. Idle or engine off times are interspersed at various times. No major problems during these tests.

3.3.10John Deere 824KII Wheel Loader

This unit was tested on 8/14/2018 and 8/15/2018. Physical work includes travel from the repair building to the test lot, multiple digging and refilling a trench, and traveling back to the repair building. Idle or engine off times are interspersed at various times. On 8/14/2018 the MSS stopped logging for short intervals. At 12:39:32 the Semtech-DS malfunctioned so no data was recorded from that time to the test end at 14:15:06. The processed Semtech-DS only reported gas phase emissions in g/kg-fuel. The exhaust flow meter malfunctioned and didn't report any flow data. The fuel rate was hand calculated based on the HEM reported fuel rate in l/hr. Instantaneous gas phase emissions were calculated by multiplying the calculated fuel rate times the fuel specific emissions in g/kg-fuel. The exhaust flow rate in scfm was calculated from the measured wet CO_2 and the Instantaneous mass of CO_2 in g/s. The g/bhp-hr emissions were then calculated from the cumulative mass emissions divided by the cumulative work.

On 8/15/2018 the vehicle interface data was not recorded and the exhaust flow meter was not functioning so the Semtech-DS processed data only reported gas phase emission in g/kg-fuel and g/s. The exhaust flow rate in scfm was calculated from the measured wet CO_2 and the Instantaneous mass of CO_2 in g/s. Calculated the Derived Engine Torque from the HEM reported Percent Torque, Percent Friction Torque, and Reference Engine Torque. The g/bhp-hr emissions were then calculated from the cumulative mass emissions divided by the cumulative work. Calculated Derived Engine Power from HEM Derived Engine Torque and HEM reported Engine Speed. Calculated g/bhp-hr emissions from cumulative mass emissions/cumulative work. A DPF regeneration started at 13:13:40.

3.3.11Caterpillar D8T Crawler Tractor

This unit was tested on 12/17/2018 and 12/18/2018. Physical work includes travel from the warehouse building to the small test lot, ripping the width of the test lot a few times followed by multiple bulldozing of the pile of earth, and traveling back to the warehouse building. Idle or engine off times are interspersed at various times. On 12/17/2018 the Semtech-DS did not log vehicle ECM data and the HEM logger did not begin logging until 1:31:30. Therefore only emissions in g/kg-fuel and g/sec are available from 12:05:10 to 1:31:30. MSS lost connection at 12:48:00 so there are no recorded PM emissions after that time. For the data where the HEM logger reported engine rpm the correlation between rpm and exhaust flow rate (EFR) is: rpm = $5x10^{-7}$ $(EFR)^3$ - $0.0025(EFR)^2$ + 3.7211(EFR) -278.6 with an R^2 of 0.84. For this data the calculated rpm's differ from the measured rpm's by an average of 0.24% with maximum differences of -49.3% and +31.8%. 88.4% are within ±10% of the measured values. This equation was used to determine the rpm's between 12:05:10 and 1:31:30. Engine load was not recorded by the HEM logger and no reasonable correlation was found whereby engine load or engine torque from 12:05:10 and 1:31:10 could be estimated. Therefore, brake specific emissions could not be estimated during this time interval. For the other 4 Caterpillar engines we found that engine load (on average) = 0.9225(Engine %torque). Used this equation to estimate engine load and then used this in conjunction with the engine rpm and the engine lug curve to calculate the Derived Engine Torque and the Derived Engine Power. For 1:31:30 to the end of the dataset the g/bhp-hr emissions were calculated as the cumulative mass emissions divided by the cumulative work. A DPF regeneration occurred a few minutes after starting the engine on 12/18/2018. On 12/18/2018 the Semtech-DS did not log vehicle ECM data but the HEM logger did work over the full range of the test data so was able to use the above method (except did not have to estimate any rpm's) to calculate g/bhp-hr emissions.

4 Data Analysis

4.1 Preliminary data processing

The Semtech-DS processor analyzes the raw data and creates a CSV file containing the raw data and calculations of gas phase emissions of CO_2, CO, NO_x, and HC in g/s, g/kg-fuel, and g/bhp-hr, provided that all of the information necessary for the calculations is present in the raw data file. The processor has place holders for the calculation of MSS emissions in the same units, but since the MSS data is not added to the raw file these emissions are not calculated. The CVS file is opened and the MSS raw data is added to the appropriate columns based upon the time stamps of the files. The HEM data is added to the end of the file based upon the time stamps of the files. A sheet is added labeled CTA (Check Time Alignment) and plots are made of critical parameters versus the Exhaust Flow Rate (EFR). The raw data sheet is copied and pasted into another sheet labeled TAD (Time Aligned Data). The MSS data columns are cut and moved within the TAD sheet the number of rows determined in the CTA sheet to bring them into alignment with the EFR within 1 to 3 seconds. The HEM data is moved in the TAD sheet in the same manner. However, the HEM logger stops logging whenever the equipment is shut off and starts logging when the equipment key is turned on and there can be differences in the time stamps which may require moving separate sections of the HEM data individually instead of moving every row at the same time.

Once all the data is time aligned and all calculations of MSS and PM emissions, and gas phase emissions (where problems with the Sensors_DS or missing lug curve data required hand calculations) are completed, portions of the TAD sheet containing the data of most interest for presenting final results and making correlations of emissions versus fuel used are copied and the values pasted into a blank spread sheet. This latter spread sheet is saved with the following nomenclature: XX_YYYY-MM-DD_EQ_EQM where XX is the sequential number of the test, YYYY-MM-DD is the year-month-day of the test, EQ is the Equipment Manufacturer, and EQM is the equipment model number.

4.2 Work

For construction equipment, two different types of work are defined: (1) the physical work which the equipment is performing, i.e., digging, moving, idling, pushing, etc., which we designate as A-work and (2) the work which the engine is performing, which we designate as E-work, which is expressed as horsepower. During the emission measurements, CE-CERT personnel maintained hand logs of the physical work versus clock time. From this information, start and stop times for specific A-work within segments of the continuous emission and engine data are assigned. For these specific segments, the fuel consumption in kg/hr, engine work in hp, the emissions in g/hr, in g/kg-fuel, and in g/hp-h are calculated.

Typically, the construction equipment set overnight in a location where we could install the emission measurement equipment on day 1 without moving the construction equipment. The emission measurement equipment had been in standby mode overnight and therefore was warmed up and ready to start emission measurements as soon as it was securely in place. Following spanning and calibrating the emission measurement equipment, the construction equipment is started and allowed to idle for a few minutes or immediately travel to the work site. At the end of the testing the equipment traveled to a location where electricity was available to keep the emission measurement equipment warmed up and ready for testing the next day. Post-test spanning and calibration of the emission measurement equipment was performed after parking the construction equipment. On day 2 the emission measurement equipment was spanned and calibrated and then the construction equipment started and idled for a few minutes or traveled immediately to the test site. At the end of the second day the construction equipment traveled to a location where the emission measurement equipment could be removed following the post-test spanning and calibration.

4.3Mode of Operation

In the prior program George Scora partitioned test data for an excavator into several operating modes based on video recordings from mounted cameras on the front of the equipment during testing. The results showed that, in general, fuel-specific emissions and fuel consumption rate vary significantly between the idle mode and the non-idle modes, but the variance among the non-idle modes (Travel, Trench 45, Trench 90, Trench 180, Dress, and Backfill) is relatively small. The same conclusion is reached for the Tier 4F equipment tested in this program when the exhaust temperature is high enough that the DOCDPF and SCR systems are functioning at maximum efficiency, as seen in Figure 4-1 thru Figure 4-12. In these figures the temperatures are the average temperature for each "bar", with the exception of the gold bars, which are an indication of the engine being off, not of NOx emissions, and the temperature is the temperature at the time the engine is started. Figure 4-1 thru Figure 4-3 are for a CAT 335F Excavator and Figure 4-4 thru Figure 4-6 are for a CAT 930M Wheel Loader which has the same model engine as the CAT 335F Excavator. The non-idle modes Travel, "digging" with bucket just skimming the surface, digging to fill the bucket half-full, and digging to fill the bucket full, and refilling the hole with full buckets, have approximately the same variance as the non-idle modes for the excavator. Figure 4-7 thru Figure 4-9 are for a John Deere 1050K Crawler Tractor and Figure 4-12 thru Figure 4-14 are for a John Deere 824KII Wheel Loader which has the same model engine as the Crawler Tractor. The non-idle modes of the Crawler Tractor (travel, rip, digging hole, refilling hole) and the wheel loader (travel, digging hole, refilling hole) have approximately the same variance.

In the prior program, George based the prototype model on two modes of operation defined as idle and non-idle (work), and not on specialized activity such as travel, trenching, scraping, backfilling, etc. and therefore partitioned the test data into idle and non-idle (work) with the exclusion of cold-start and DPF regeneration events.

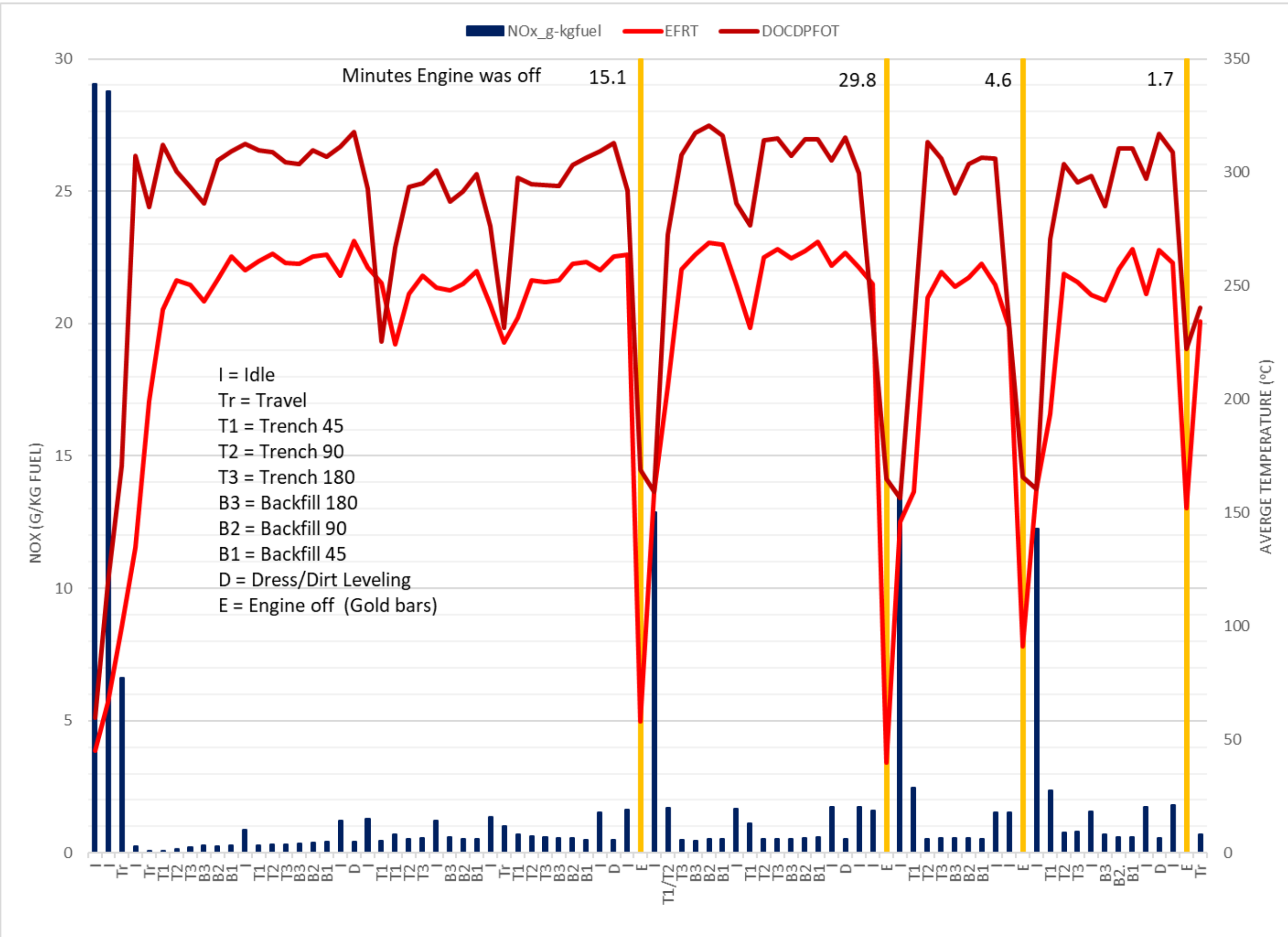

Figure 4-1: Fuel based NOx emissions by mode of operation for 2015 tier 4F CAT335F Excavator

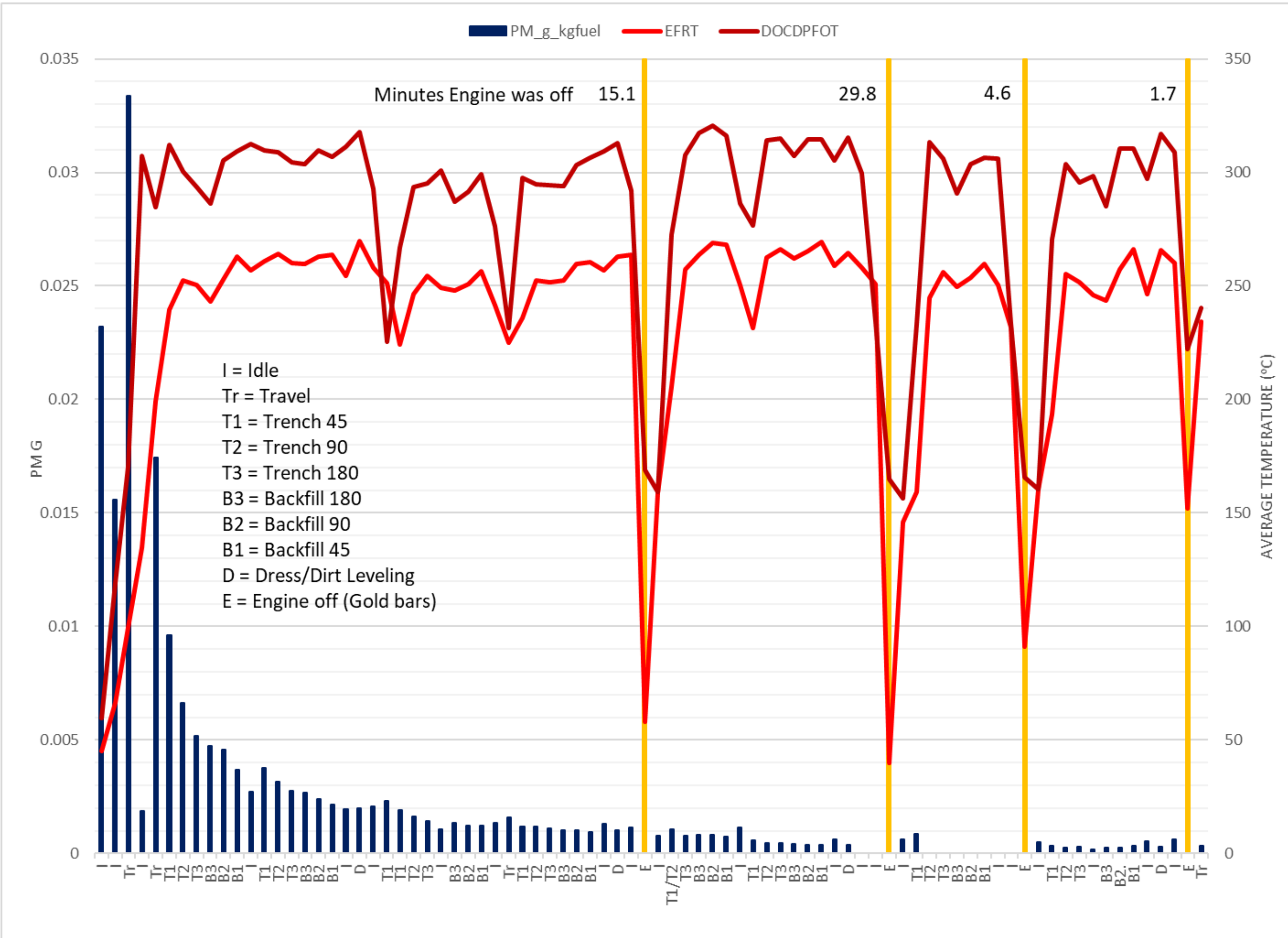

Figure 4-2: Fuel based PM emissions by mode of operation for 2015 tier 4F CAT335F Excavator

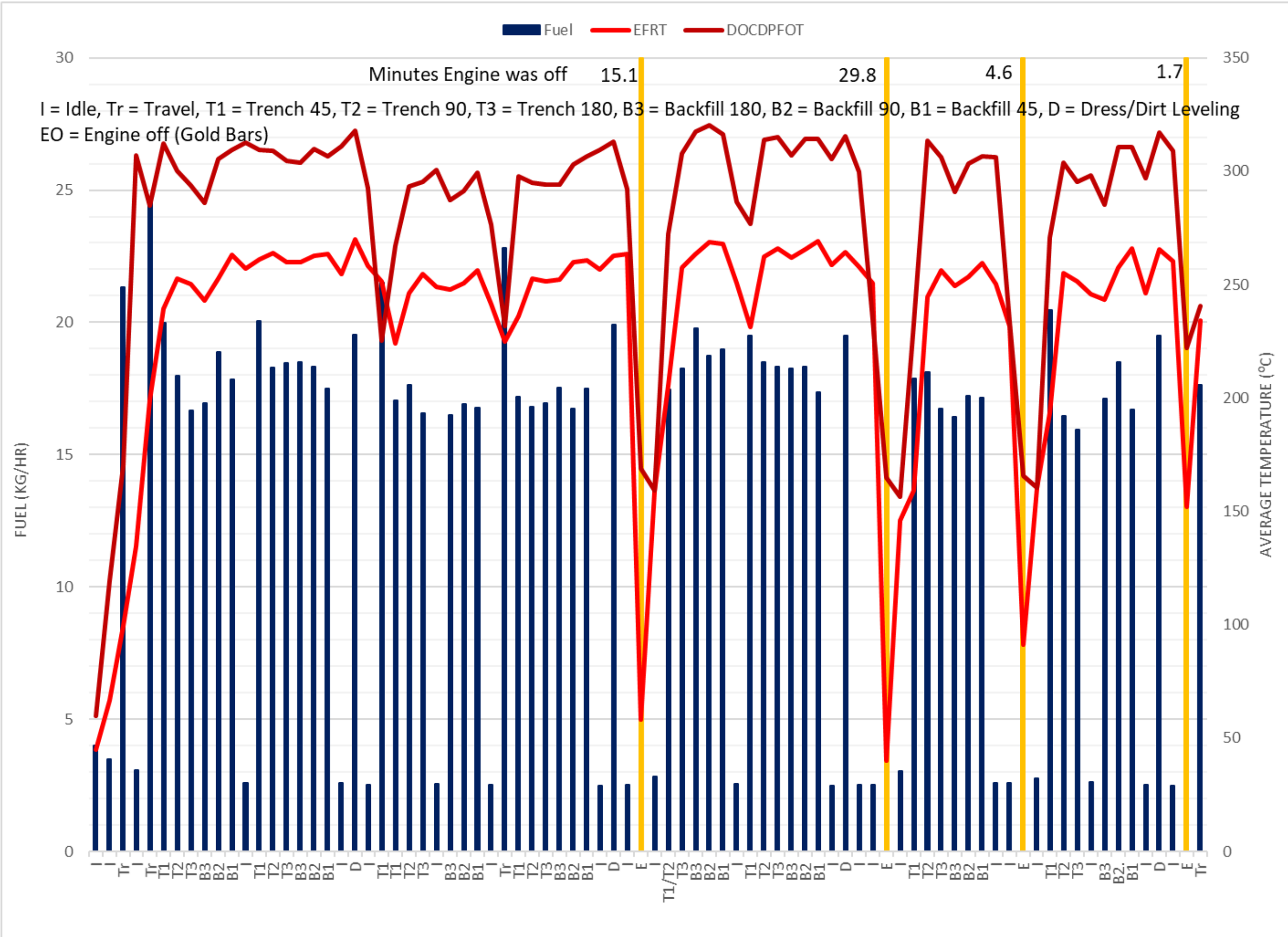

Figure 4-3: Fuel consumption rates by mode of operation for 2015 tier 4F CAT 335F Excavator

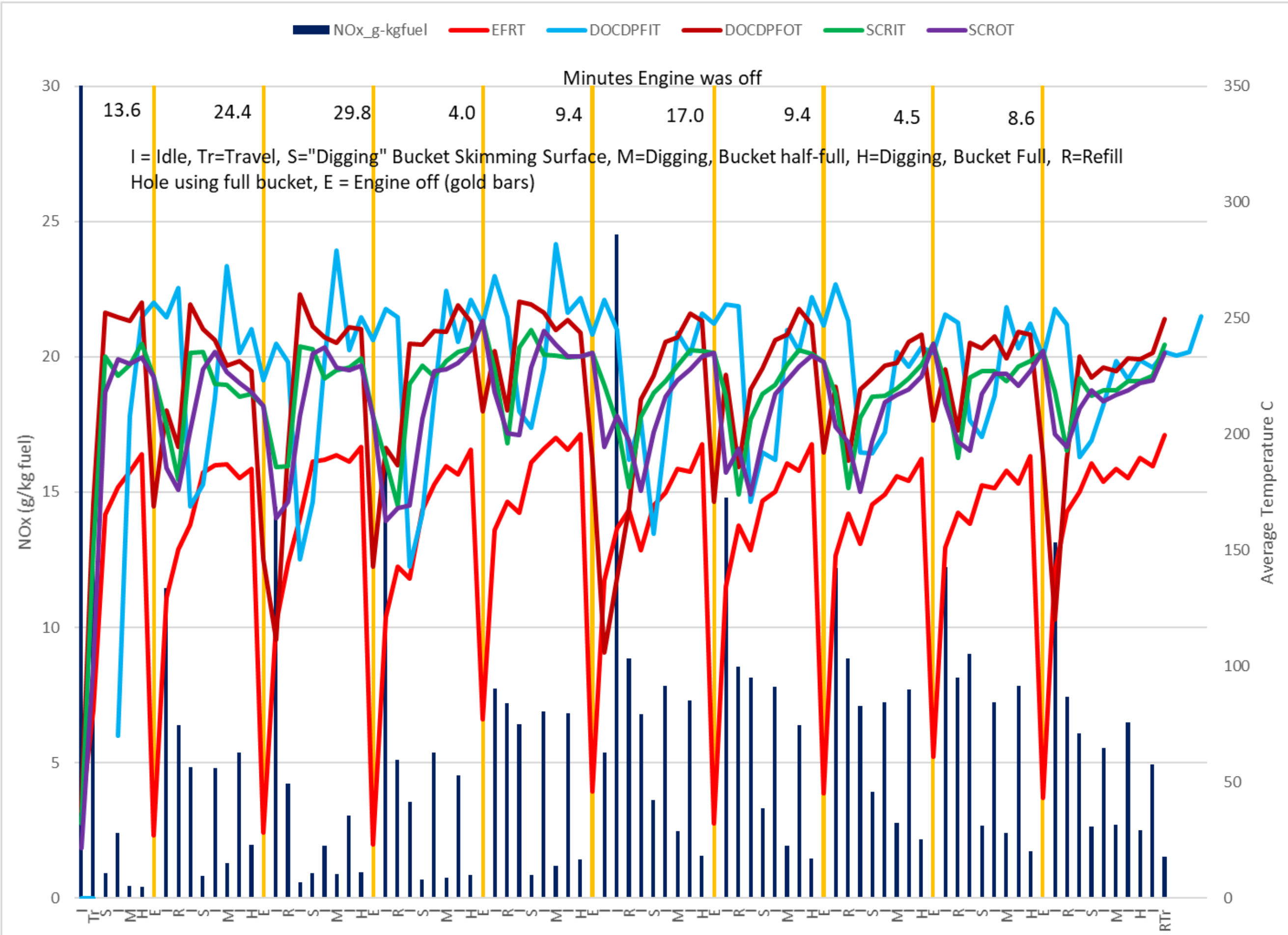

Figure 4-4: Fuel based NOx emissions by mode of operation for 2015 tier 4F CAT930M Wheel Loader

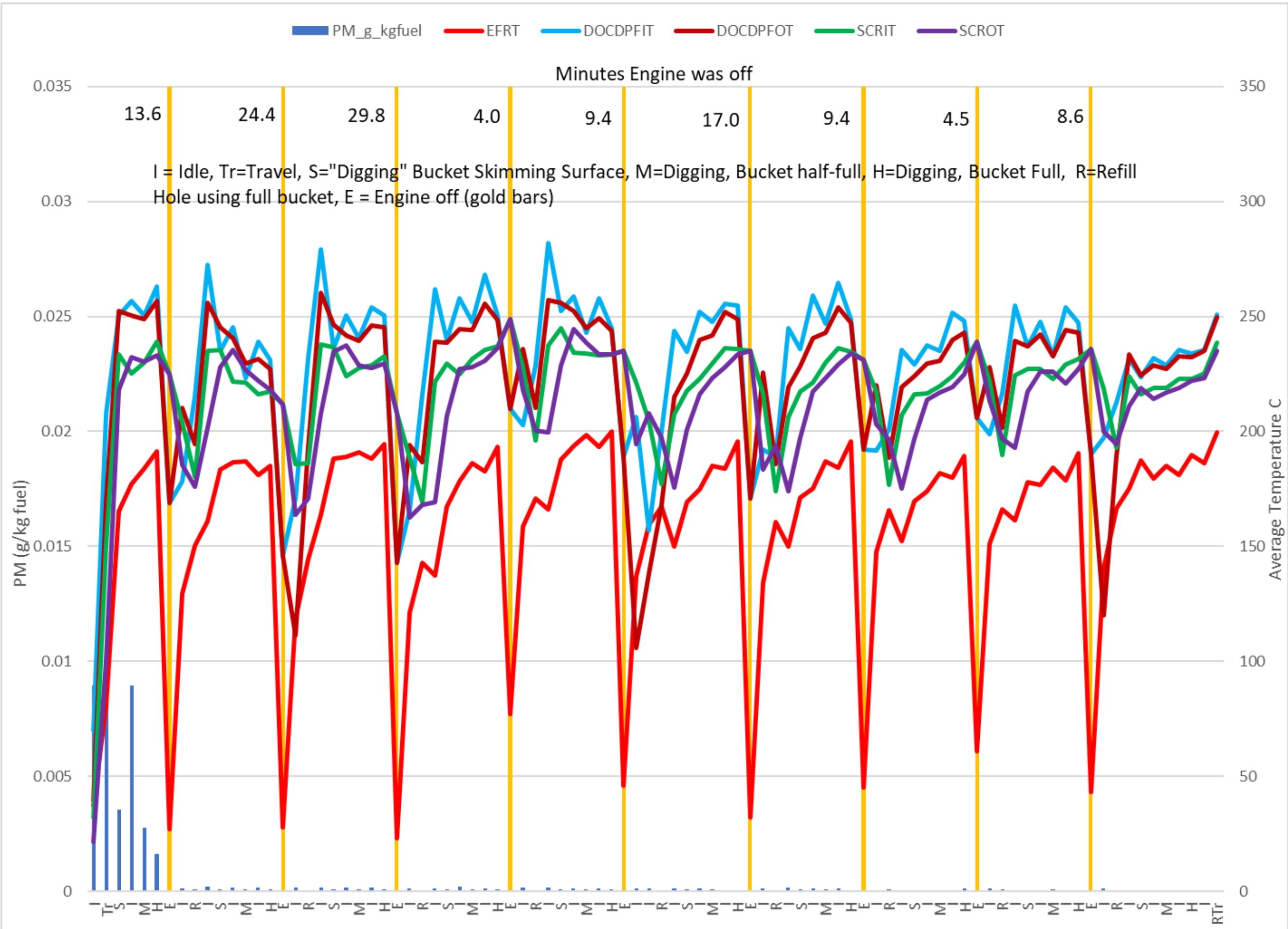

Figure 4-5: Fuel based PM emissions by mode of operation for 2015 tier 4F CAT930M Wheel Loader

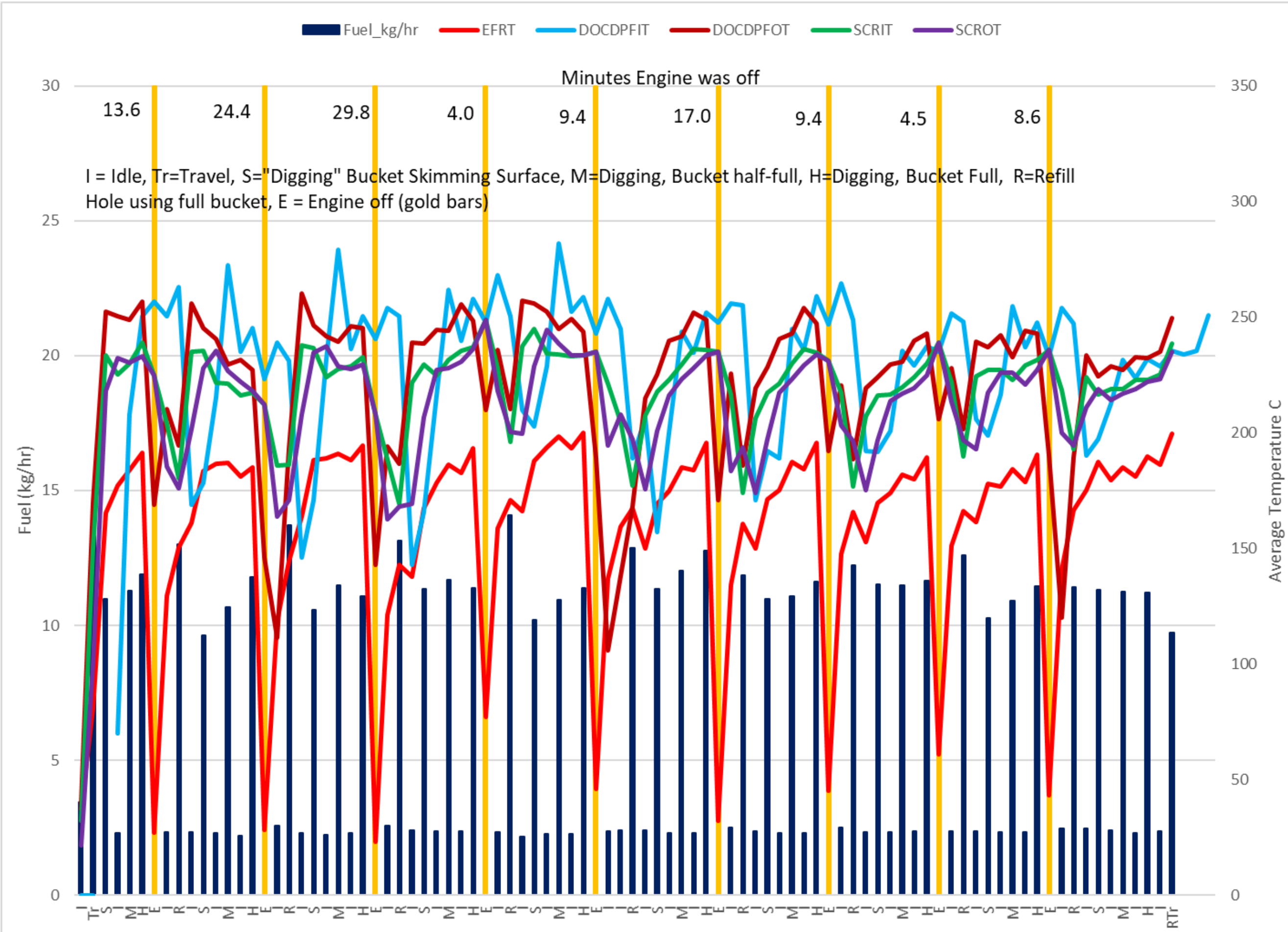

Figure 4-6: Fuel consumption rate by mode of operation for 2015 tier 4F CAT930M Wheel Loader

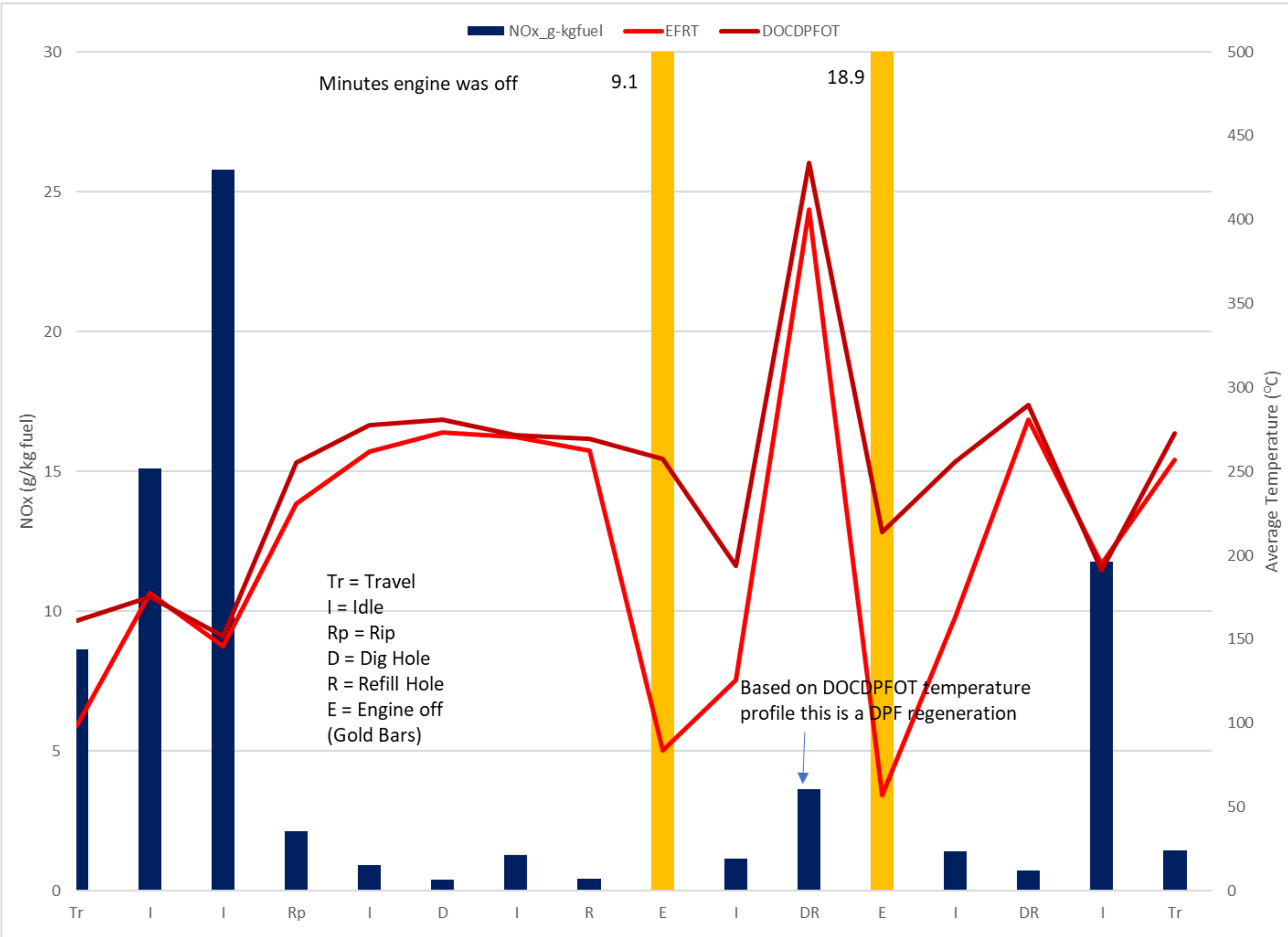

Figure 4-7: Fuel based NOx emissions by mode of operation for 2014 tier 4F John Deere 1050K Crawler Tractor

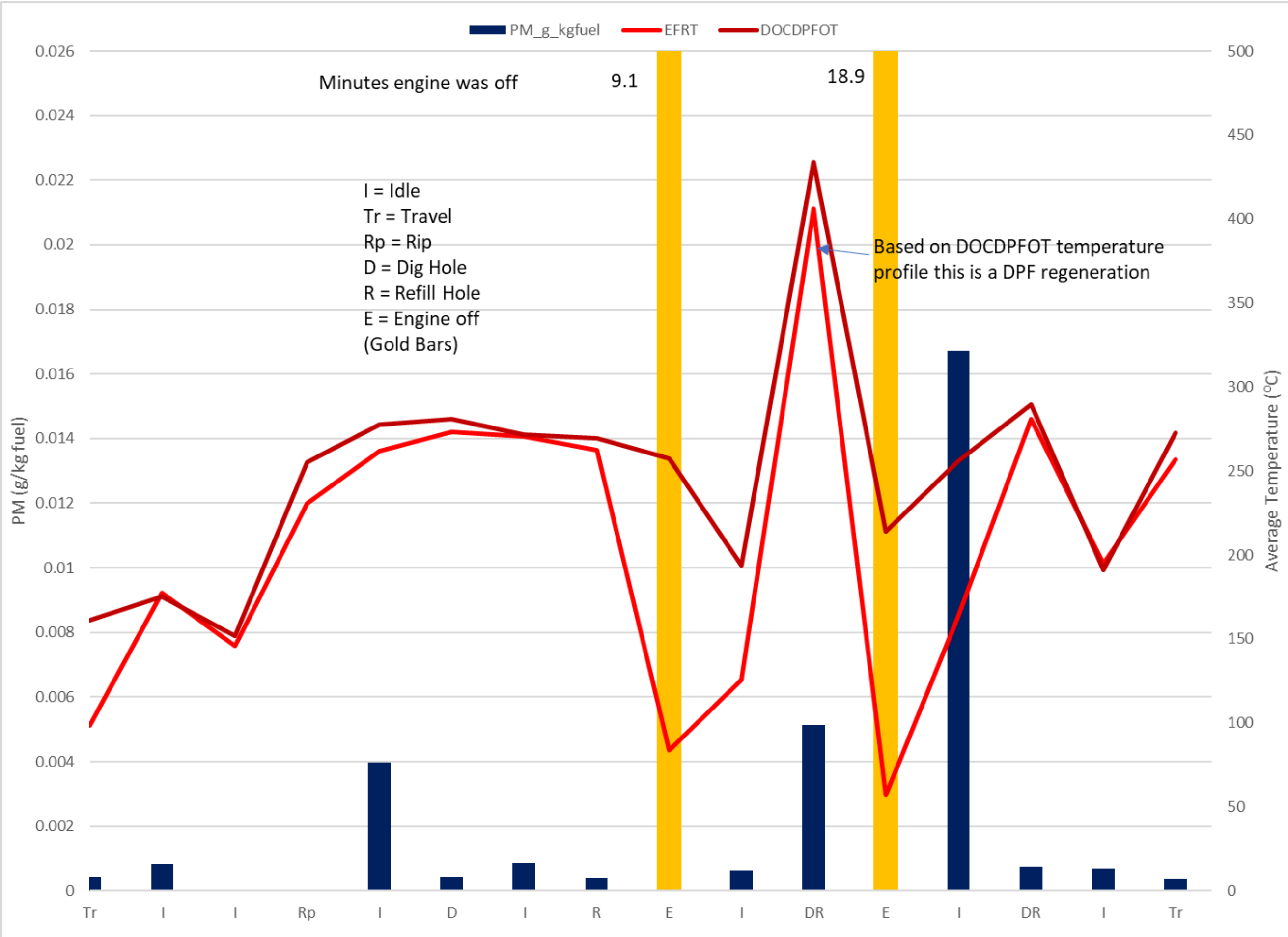

Figure 4-8: Fuel based PM emissions by mode of operation for 2014 tier 4F John Deere 1050K Crawler Tractor

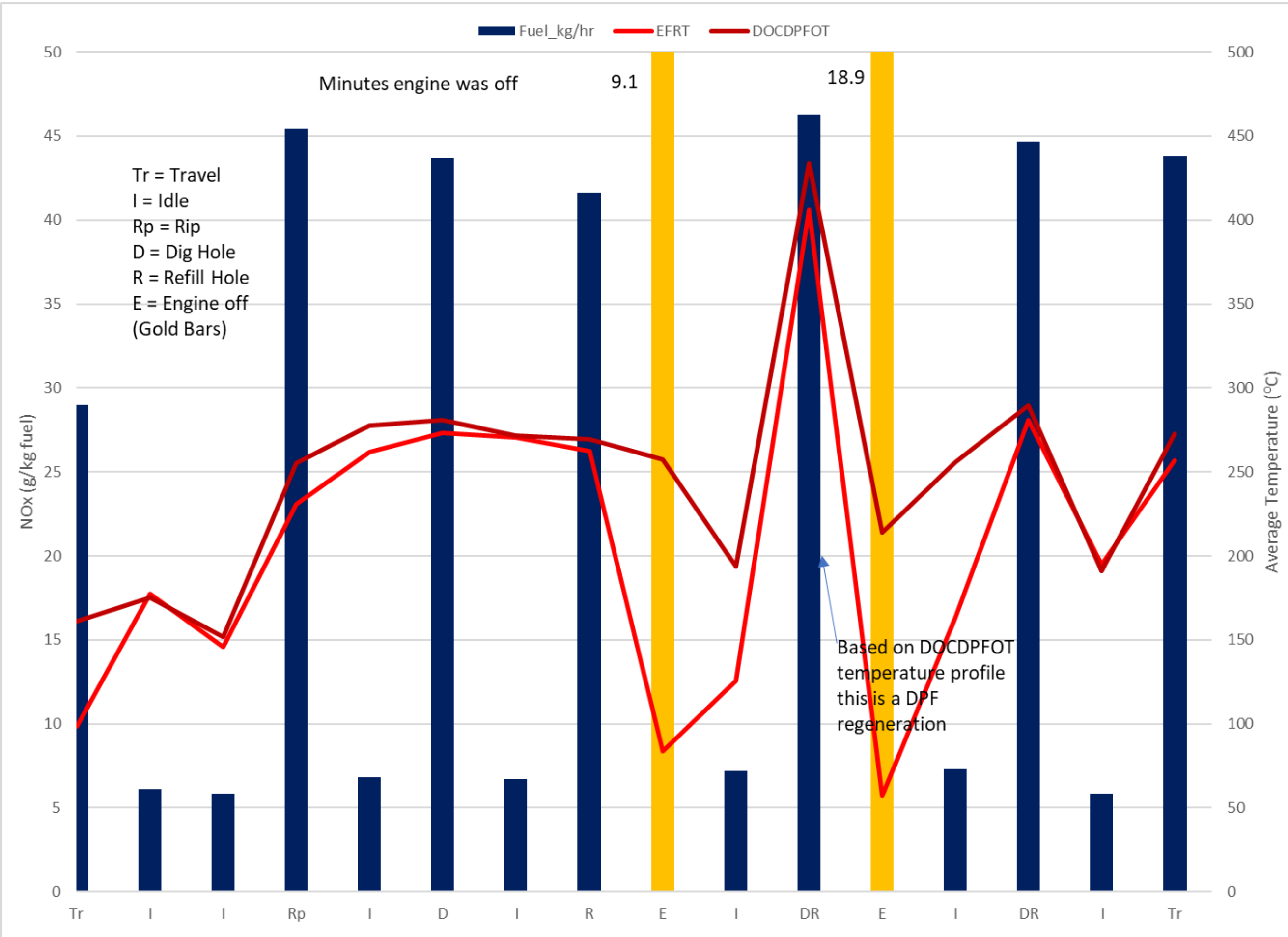

Figure 4-9: Fuel consumption rate by mode of operation for 2014 tier 4F John Deere 1050K Crawler Tractor

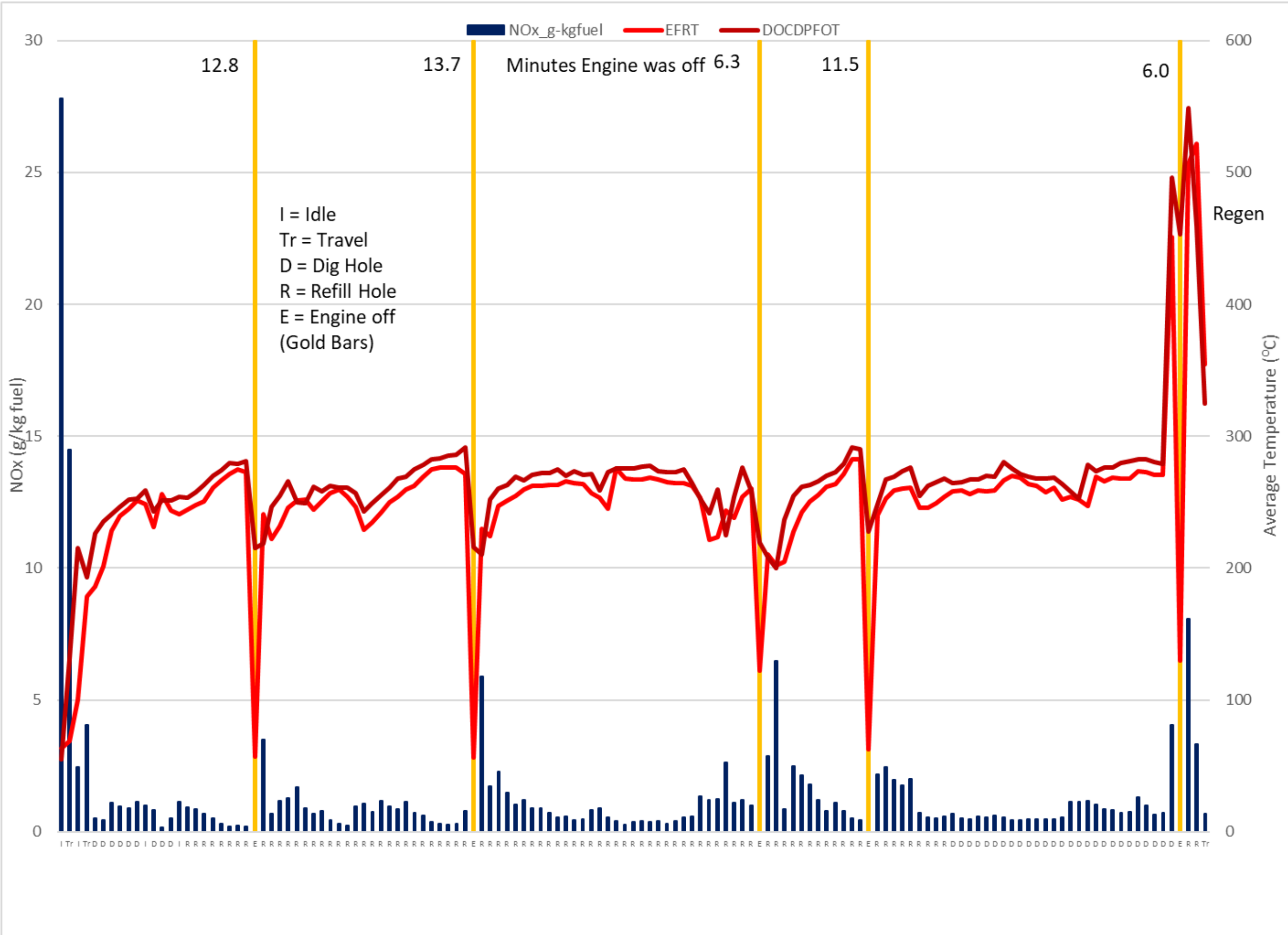

Figure 4-10: Fuel based NOx emissions by mode of operation for 2014 tier 4F John Deere 824KII Wheel Loader

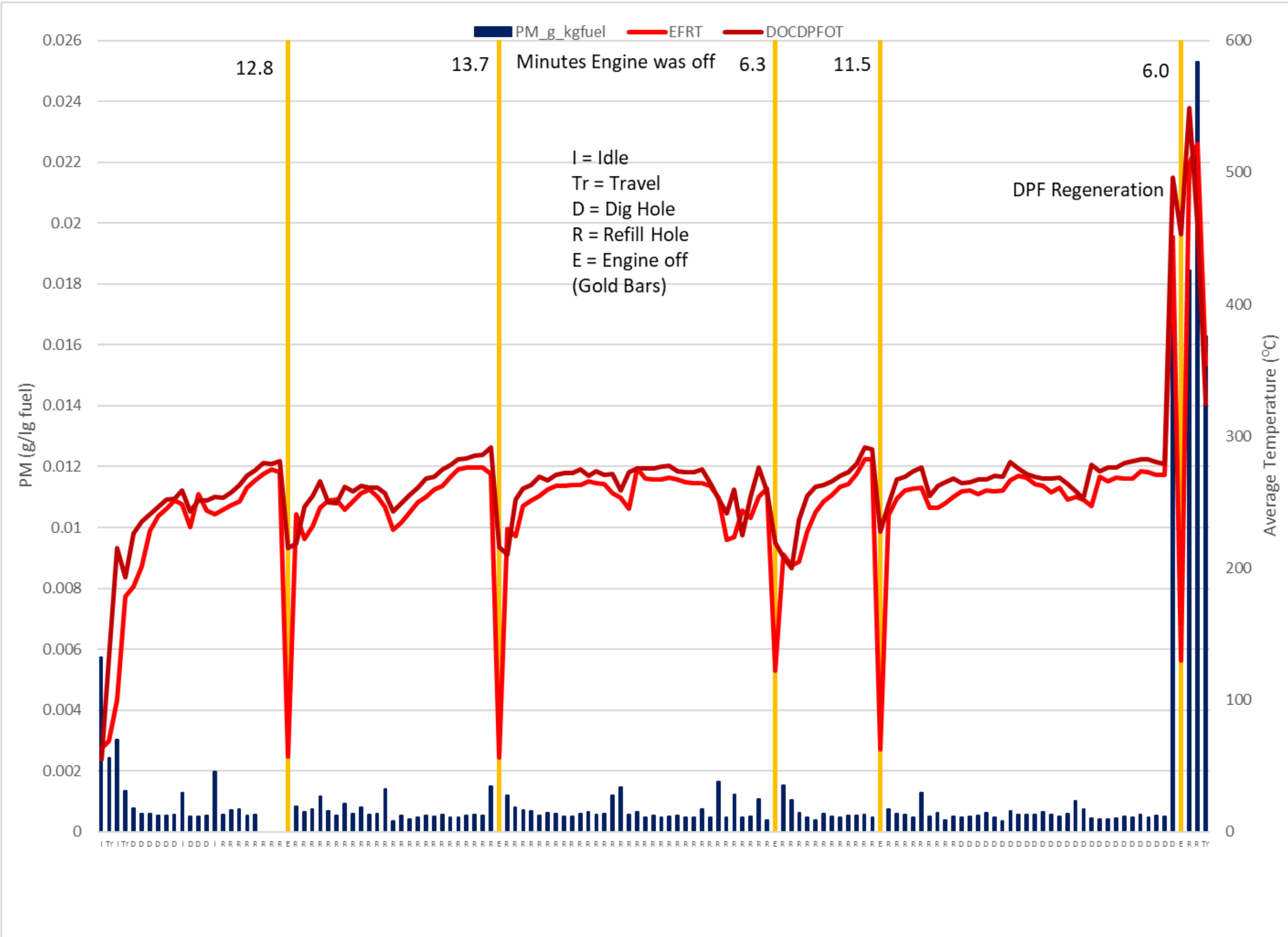

Figure 4-11: Fuel based PM emissions by mode of operation for 2014 tier 4F John Deere 824KII Wheel Loader

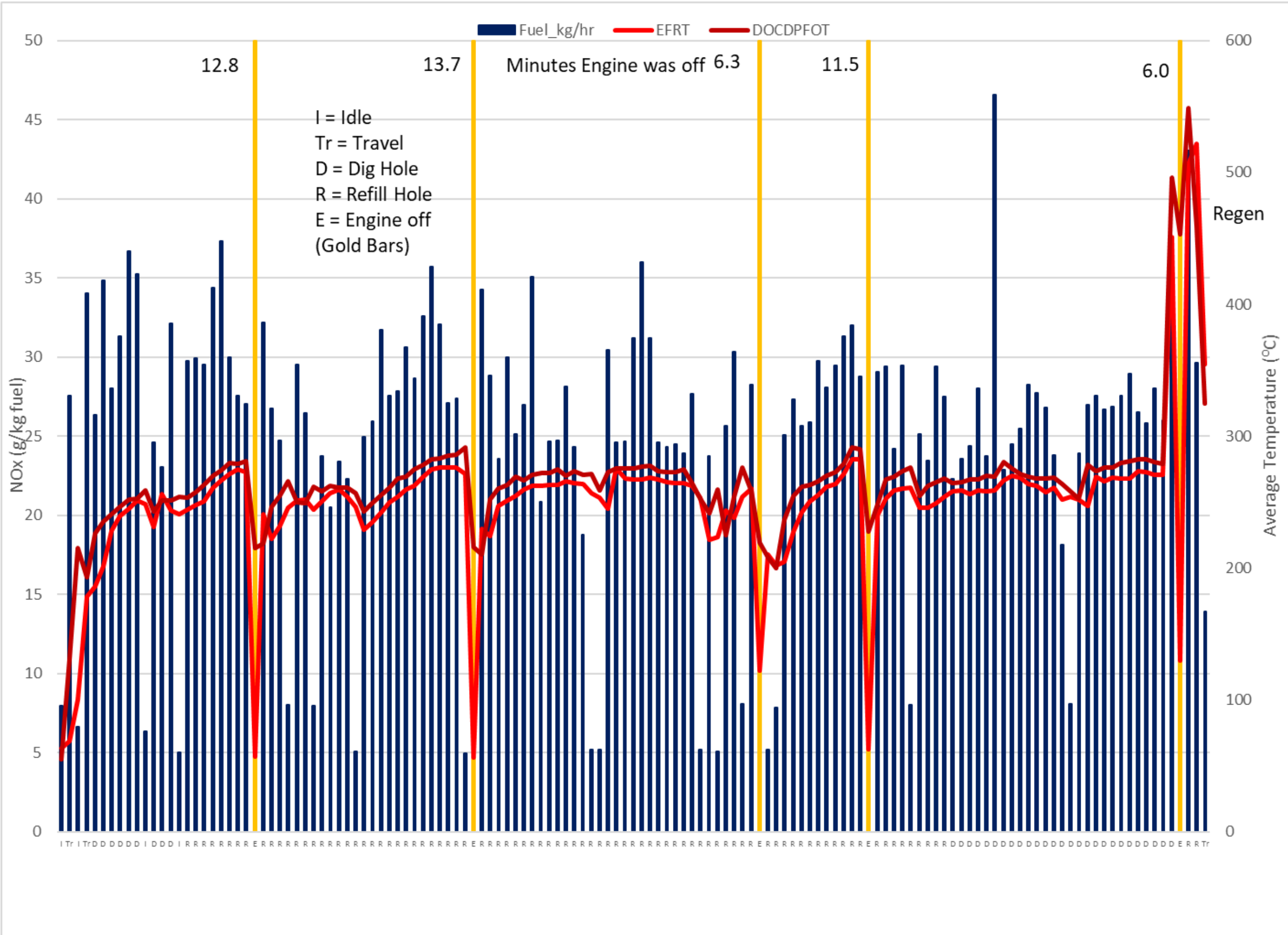

Figure 4-12: Fuel consumption rate by mode of operation for 2014 tier 4F John Deere 824KII Wheel Loader

4.4 Matlab Analysis

In the prior project[1] George Scora created a Matlab program to separate the continuous second-by-second data into mini events based upon the engine rpm. Plots of the second-by-second data were used to determine reasonable limits for idle events, which for some equipment include two or three separate ranges as some equipment have normal and high idle ranges, with the latter primarily for power take applications. Most of the data was obtained for equipment in normal operation, by the owners of the equipment, and generally did not have detailed data about the specific physical work being done or how long the engine had been off before testing was started. Therefore, George did not include the first 300 seconds of data, and specifically excluded high idle events as they were generally limited, when developing the correlation of emissions with kg-fuel burned for idle and non-idle events. George provided his Matlab programs and the programs were modified to include the first 300 seconds of data so cold starts are included for the Tier 4F equipment. High idle events and DPF regenerations, if present, are also included by not specifically excluding them. George also had specified that the first and last 10 seconds of each mini event should be excluded to minimize possible spurious numbers because of time alignment issues. Based on CE-CERT experience we believe the data alignment is within 2 to 3 seconds. Therefore, the programs were modified to exclude only the first and last 5 seconds of each mini event.

The Matlab program produces a CVS file containing integrated engine and emission data over each idle and non-idle event throughout the day of testing. Based upon these files, and the hand logs, summary tables are prepared containing start and stop times for each event, duration of the event, activity, fuel use, power, engine speed, and emissions in g/hr, g/kg-fuel, and g/bhp-h. The summary tables for each day of testing are in the appendix.

Other Matlab programs perform regression analysis of the integrated data in the CVS file to determine the relationship between total integrated emissions over each event and total fuel used for each emission component over each event. While total fuel used over the time interval of a given event is the same for all emission components, because of loss of emission data for various reasons, fuel used during the time valid emission data is recorded has to be calculated for each emission component. Since there are no emissions when the engine is off the regressions are forced to an intercept of 0.

4.5Matlab regression analysis of tier 4F data

The regression analysis of the mini events in the CVS file regresses fuel use in kg of fuel versus time in hours and each measured emission component in g versus fuel in kg for each piece of equipment on each day of operation. The results are displayed with the individual points on a chart with the least squares regression lines through the points and a table on the side indicating the equipment, the slope of the regression line and the R^2 for the regression line.

The initial analysis included all of the mini events. As noted above, this includes all of the mini events including those with “unique” conditions, such as cold or hot starts or DPF regenerations, if they are present. Cold starts will typically occur only once during normal operations and hot starts may not occur at all or there may be multiple hot starts. Depending on the type of emission controls on the equipment, and prior operations, there may not be a DPF regeneration, or DPF regenerations may be continuous and thus not distinguishable from normal operation emissions. Therefore, inclusion of these emissions in the model requires that they be added as a separate condition not related to the regression coefficients for normal operation. Therefore, the mini events for unique conditions should be separated from the normal operation conditions and analyzed separately to determine appropriate coefficients for inclusion in the prototype model. Initially it was assumed that statistical methods could be used to determine which mini events need to be removed from the overall data for separate analysis. However, because of to many unique events or too few mini events this did not prove feasible. Therefore, plots of the second-by-second emission and relevant temperature data versus time in seconds were examined to determine which data to remove from the total data for separate analysis.

Figure 4-13 is a plot of the second-by-second data for test 51_2018-02-02_CAT_335F and Figure 4-14 is a plot of the second-by-second data for test 68_2018-08-15_JD_824KII. For Figure 4-13 the data between the vertical CS bars was removed and placed in a dataset named 51_2018-02-02_CAT_335F_CS and all data between the vertical HS bars was removed and placed in a dataset named 51_2018-02-02_CAT_335F_HS. The file from which the data was removed was renamed as 51_2018-02-02_CAT_335F_OR. In all cases for selecting what data to remove the x-axis was adjusted to cover a range of approximately 2000 to 4000 seconds following the beginning of a cold start (CS), hot start (HS), or DPF regeneration. For Figure 4-14 the data between the vertical CS bars was removed and placed in a dataset named 68_2018-08-15_JD_824KII_CS, all data between the vertical HS bars was removed and placed in a dataset named 68_2018-08-15_JD_824KII_HS, and all data between the vertical DPFR bars was removed and placed in a dataset named 68_2018-08-15_JD_824KII_DPFR. The file from which the data was removed was renamed 68_2018-08-15_JD_824KII_OR.

Figure 4-13: Second-by-second data for test 51_2018-02-02_CAT_335F

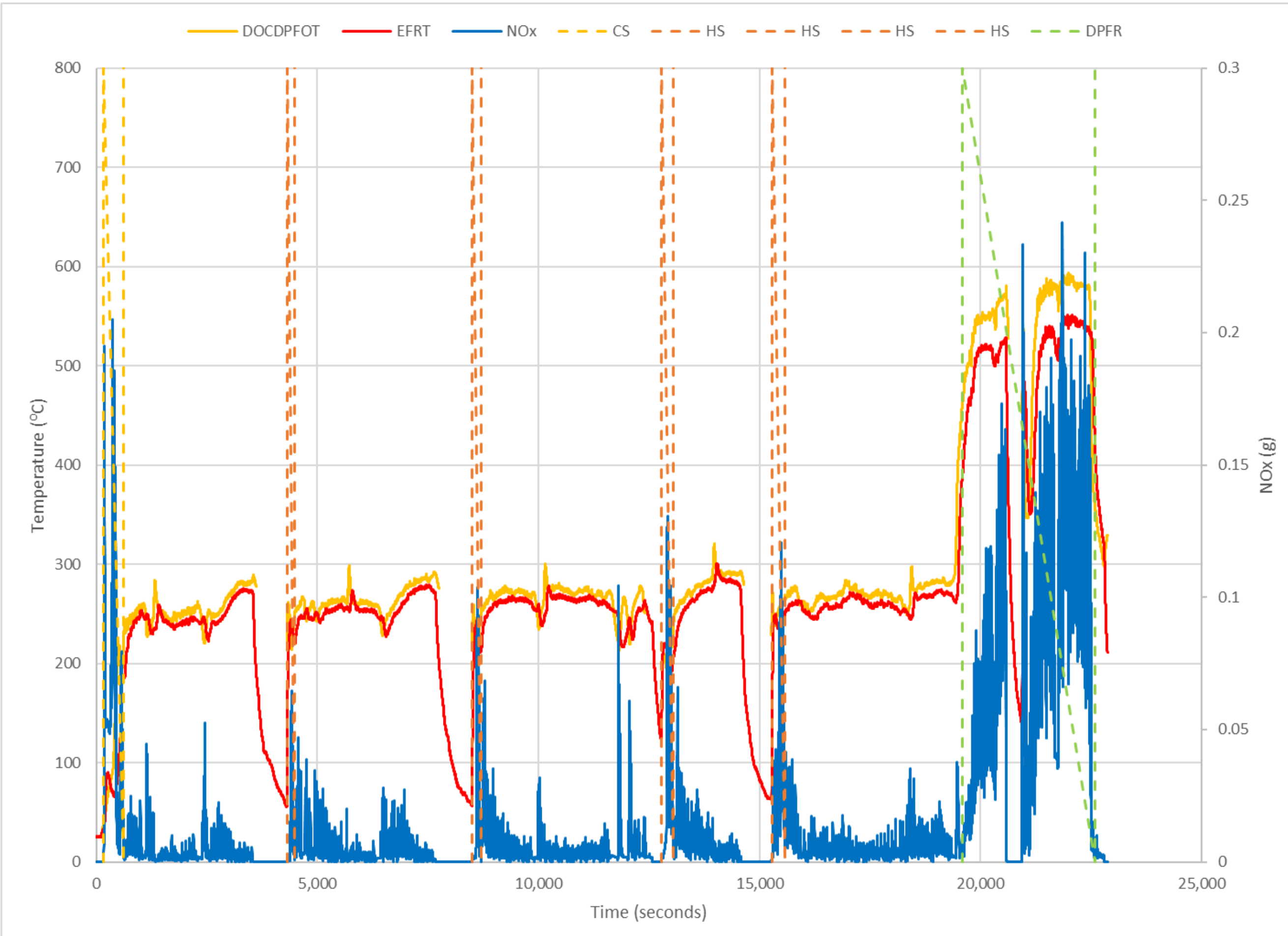

Figure 4-14: Second-by-second data for test 68_2018-08-15_JD_824KII

Equipment which uses an active regeneration typical have a regen signal light that lets the operator know that a DPF regeneration is in process. During the testing the only equipment where the operator noted that a DPF regeneration was occurring was for the John Deere 824KII Wheel Loader on 8/15/2018 and the CAT D8T Crawler Tractor on 12/18/2018.When the second-by-second plots were made to separate out the cold starts, hot starts, and DPFR events it was noted that, based on temperature profiles, there were times when the temperatures were in the regen region even though the operator didn't indicate seeing a regen signal light. The tests where these observations were made are shown in Figure 4-13 through Figure 4-19. The regions where the temperatures are indicative of a regen were separated from the data and placed in an *_DPFR file.

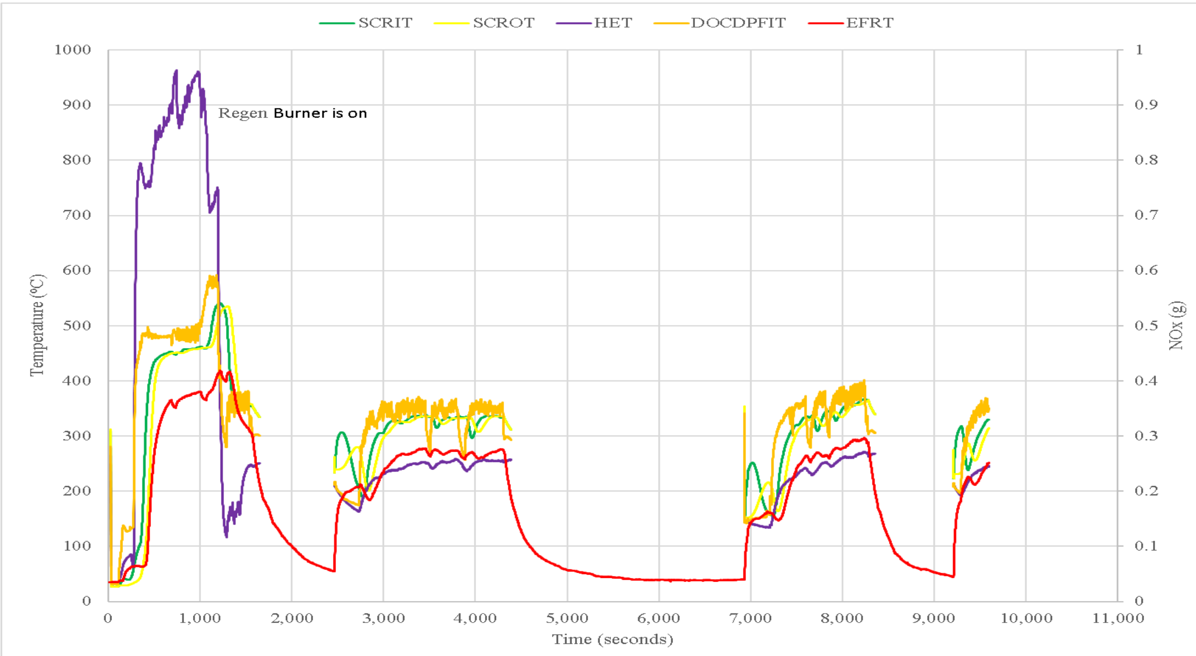

Figure 4-15: Second-by-second plot of 56_2018-07-12_CAT_336F

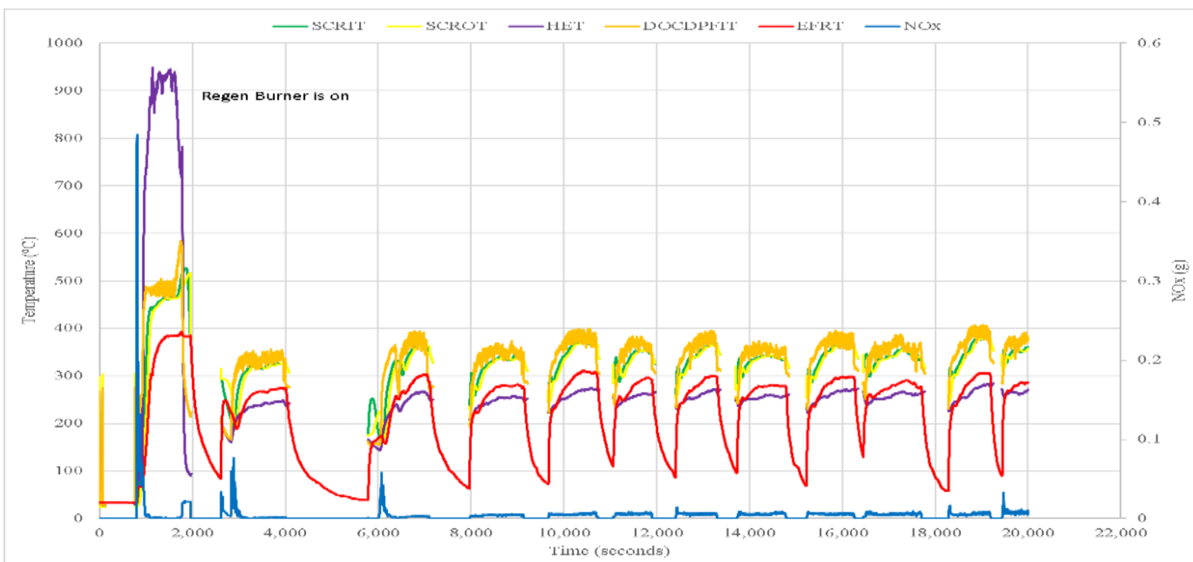

Figure 4-16: Second-by-second plot of 58_2018-07-13_CAT_336F

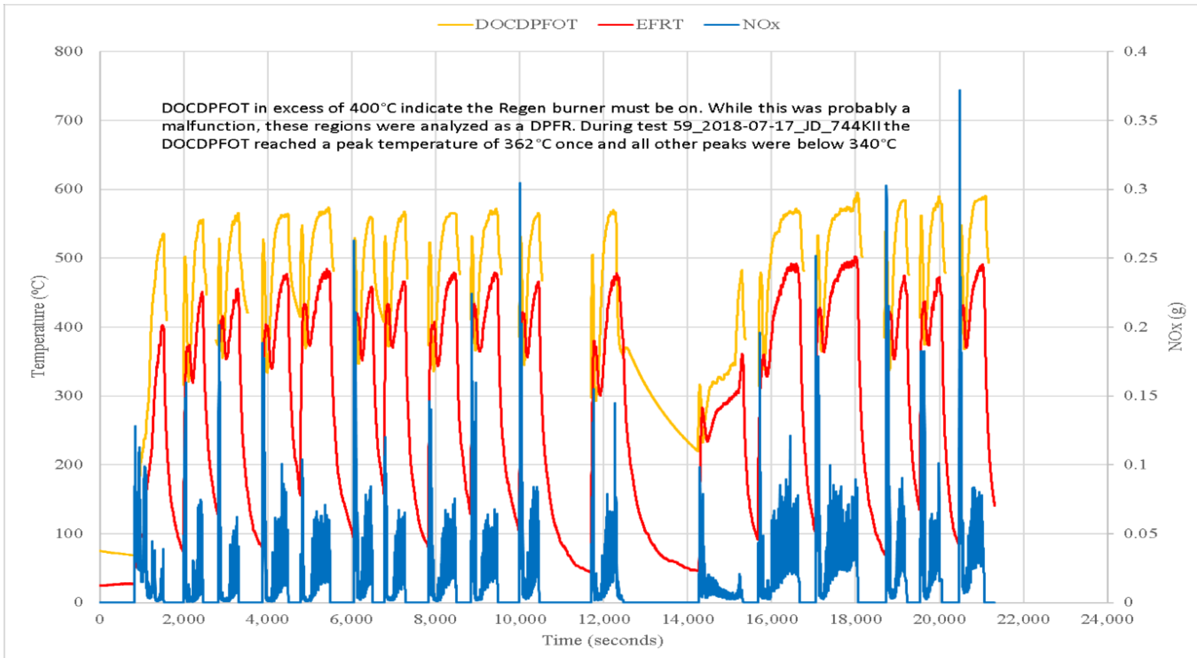

Figure 4-17: Second-by-second plot of 60_2018-07-18_JD_744KII

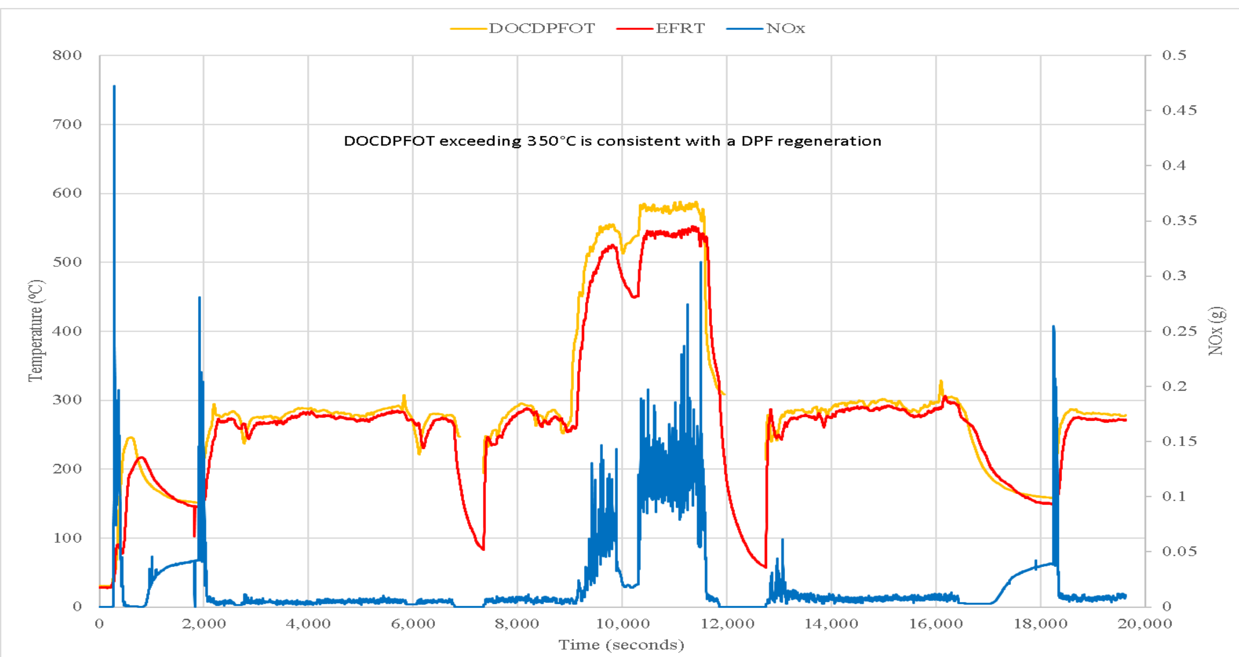

Figure 4-18: Second-by-second plot of 64_2018-08-02_JD_1050K

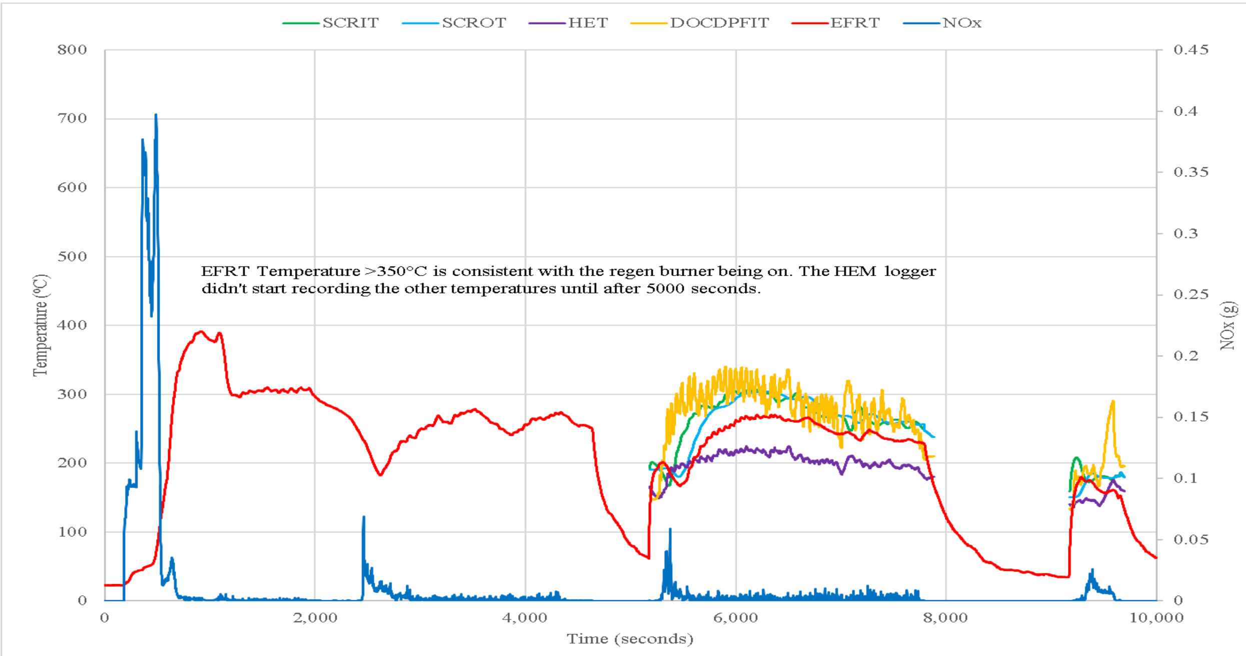

Figure 4-19: Second-by-second plot of 69_2018-12-17_CAT_D8T

The engines in this program with a displacement of 7.01 liters or less used a passive regeneration system. These units do not have a regen signal light. Some cases had DOCDPFOT which were assumed to be a passive regeneration, such as in Figure 4-20. No attempt was made to segregate any region for an *_DPFR file.

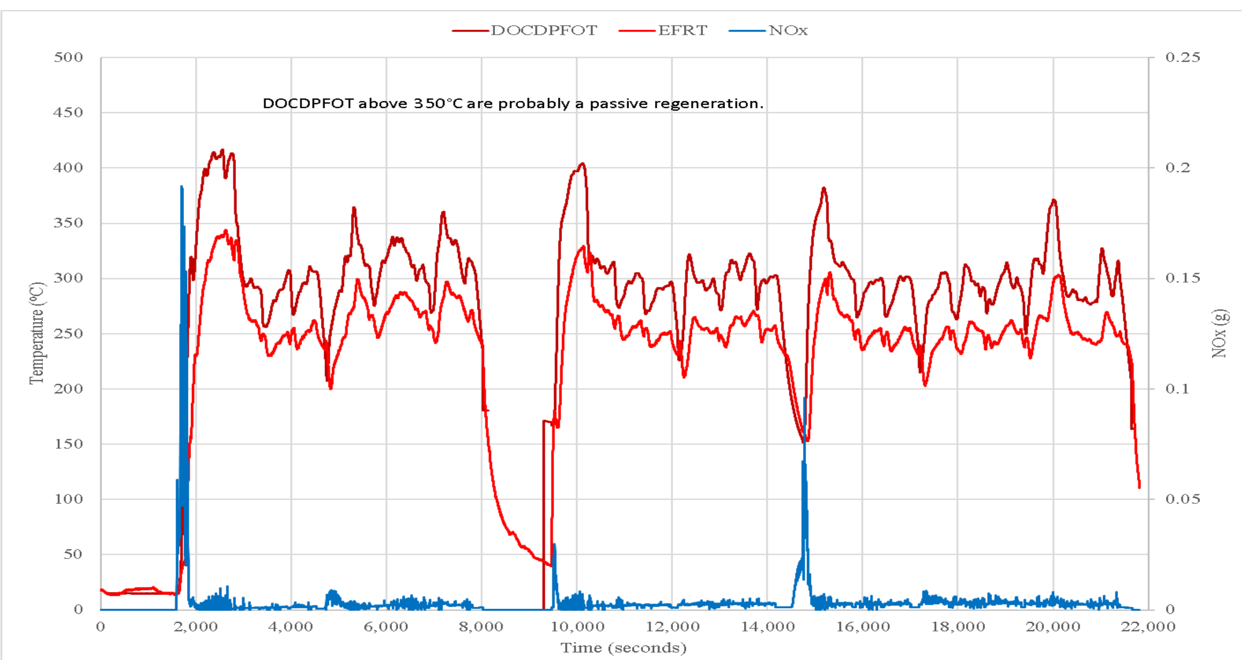

Figure 4-20: Second-by-second plot of 48_2018-01-31_CAT_335F

5 Prototype Model

5.1 Introduction

This section is essentially a verbatim copy from the January 2015 report to Caltrans entitled "Developing a Model to Quantify Emissions from Heavy-Duty Construction Equipment as Related to Job Site Activity Data". It is included so one doesn't have to refer back to that report. Because the present program permits estimating cold start, hot start, and DPF regeneration emissions there are some modifications to the discussion below which will be in bold italic type.

5.2 Modeling Methodology

The ORE model estimates emissions by applying fuel based emission factors to the amount of fuel consumed during the idle and work mode of operation. There are two basic calculations that occur in the model: 1) calculations to determine the fuel consumption during both modes of operation, and 2) calculations applying fuel-specific emission factors to the fuel consumed during each mode of operation.

Calculations to determine the amount of fuel consumed during the idle and work modes are based on user inputs and modeling parameters. In equations 1 through 6, the known variables are indicated in blue. Using equations 1 through 3, the amount of time spent at idle can be determined and is given by equation 4 in terms of the known variables. The model uses equations 4, 5 and 6 to determine fuel consumed during the idle and work mode for each piece of equipment.

$$Time_{Total} = Time_{Idle} + Time_{Work} \qquad \text{Eq. 1}$$

$$Idle_{Frac} = \frac{Time_{Idle}}{Time_{Total}} \qquad \text{Eq. 2}$$

$$Fuel_{Total} = FR_{Idle} \times Time_{Idle} + FR_{Work} \times Time_{Work} \qquad \text{Eq. 3}$$

$$Time_{Idle} = \frac{Fuel_{Total}}{\left(FR_{Idle} + FR_{Work} \times \left(\frac{1}{Idle_{Frac}} - 1\right)\right)} \qquad \text{Eq. 4}$$

$$Fuel_{Idle} = FR_{Idle} \times Time_{Idle} \qquad \text{Eq. 5}$$

$$Fuel_{Work} = Fuel_{Total} - Fuel_{Idle} \qquad \text{Eq. 6}$$

Where

$Time_{Total}$, $Time_{Idle}$, $Time_{Work}$ = Time in mode, (hrs)

$Idle_{Frac}$ = Fraction of time spent at idle

$Fuel_{Total}$, $Fuel_{Idle}$, $Fuel_{Work}$	=	Fuel consumption by mode, (kg)
FR_{Idle}, FR_{Work}	=	Fuel consumption rate by mode, (kg/hr)

The model applies fuel consumed in each mode to fuel-specific emission factors for each mode, as shown in equation 7, to determine mass emissions by mode.

$$Emiss_{mode,pollutant} = EF_{mode,pollutant} \times Fuel_{mode} \qquad \text{Eq. 7}$$

Where

$Emiss_{mode,pollutant}$	=	Mass emission for specified mode and pollutant, (g)
$EF_{mode,pollutant}$	=	Fuel based emission factor for specified mode and pollutant, (g/kg fuel)
$Fuel_{mode}$	=	Fuel consumption for specified mode, (kg)

~~***In addition to the idle and work mode, the framework of the model accommodates parameters for the emissions contributions from cold-starts and DPF regenerations.***~~ The ORE model estimates emissions by applying fuel based emission factors to the amount of fuel consumed during the idle and work mode of operation. There are two basic calculations that occur in the model: 1) calculations to determine the fuel consumption during both modes of operation, and 2) calculations applying fuel-specific emission factors to the fuel consumed during each mode of operation.

Calculations to determine the amount of fuel consumed during the idle and work modes are based on user inputs and modeling parameters. In equations 1 through 6, the known variables are indicated in blue. Using equations 1 through 3, the amount of time spent at idle can be determined and is given by equation 4 in terms of the known variables. The model uses equations 4, 5 and 6 to determine fuel consumed during the idle and work mode for each piece of equipment.

$$Time_{Total} = Time_{Idle} + Time_{Work} \qquad \text{Eq. 1}$$

$$Idle_{Frac} = \frac{Time_{Idle}}{Time_{Total}} \qquad \text{Eq. 2}$$

$$Fuel_{Total} = FR_{Idle} \times Time_{Idle} + FR_{Work} \times Time_{Work} \qquad \text{Eq. 3}$$

$$Time_{Idle} = \frac{Fuel_{Total}}{\left(FR_{Idle} + FR_{Work} \times \left(\frac{1}{Idle_{Frac}} - 1\right)\right)} \quad \text{Eq. 4}$$

$$Fuel_{Idle} = FR_{Idle} \times Time_{Idle} \quad \text{Eq. 5}$$

$$Fuel_{Work} = Fuel_{Total} - Fuel_{Idle} \quad \text{Eq. 6}$$

Where

$Time_{Total}, Time_{Idle}, Time_{Work}$	=	Time in mode, (hrs)
$Idle_{Frac}$	=	Fraction of time spent at idle
$Fuel_{Total}, Fuel_{Idle}, Fuel_{Work}$	=	Fuel consumption by mode, (kg)
FR_{Idle}, FR_{Work}	=	Fuel consumption rate by mode, (kg/hr)

The model applies fuel consumed in each mode to fuel-specific emission factors for each mode, as shown in equation 7, to determine mass emissions by mode.

$$Emiss_{mode,pollutant} = EF_{mode,pollutant} \times Fuel_{mode} \quad \text{Eq. 7}$$

Where

$Emiss_{mode,pollutant}$	=	Mass emission for specified mode and pollutant, (g)
$EF_{mode,pollutant}$	=	Fuel based emission factor for specified mode and pollutant, (g/kg fuel)
$Fuel_{mode}$	=	Fuel consumption for specified mode, (kg)

~~***In addition to the idle and work mode, the framework of the model accommodates parameters for the emissions contributions from cold-start and DPF regeneration events. The development dataset does not provide sufficient information to properly populate these parameters so they are currently set to zero. The emission contribution from cold-start and DPF regeneration events are applied to total emissions only as shown in Equation 8, and are not distributed over the idle and work modes.***~~

Comment: The above is deleted because, while it is possible to determine coefficients for cold starts, hot starts, and DPF regenerations when they are segregated from the rest of the experimental data there is no way for the model to determine if these events occur for the equipment they are evaluating.

Emissions from individual units of equipment are aggregated to determine fleet emissions. Parameters used by the model for estimating emissions are presented in Table 2-3 and Table 2-54. ***(Table 5-1 and Table 5-2).*** The emission factors are mapped to equipment category and activity mode in the model using a combination key. For each combination of equipment type and activity mode, several modeling parameters are defined. The model currently contains five ***(six)*** equipment types based on three emission certification tier groups: Tier 2, Tier 2 with DPF, Tier 3, Tier 3 with DPF and Tier 4 Interim ***(Tier 4F)***; and two activity modes: idle and non-idle or work.

Table 5-1: Modeling parameters mapped to idle and work modes

Parameter	Mode	Description
CO_gpkg	Idle, Work	Carbon Monoxide emissions in grams per kilogram fuel
THC_gpkg	Idle, Work	Total Hydrocarbon emissions in grams per kilogram fuel
NOx_gpkg	Idle, Work	Oxides of Nitrogen emissions in grams per kilogram fuel
PM_gpkg	Idle, Work	Particulate Matter emissions in grams per kilogram fuel
Fuel_kgphr	Idle, Work	Fuel consumption rate in kilograms fuel consumed per hour
CO2_gpkg	Idle, Work	Carbon Dioxide emissions in grams CO_2 per kilogram fuel

5.1 Model Calibration

Version 1 of the model was calibrated based on the model development dataset consisting of 27 units of construction equipment. Figure 5-1 through Figure 5-3 show calibration results for the 10 units (23 tests) of construction equipment tested in this Tier 4F program. As before, the results of this comparison reflect the variation in emission trends within the equipment category since the model is calibrated to the equipment category and not individual test equipment. Each of these figures are based on the data left after all cold starts, hot starts, and DPFR have been removed. The calibrations for NO_x and CO are slightly poorer than the calibrations for the 27 units. This is most likely due to the measured emissions approaching the lower limit of detection and thus having more uncertainty in the measurements. The PM do not appear to calibrate. The lack of calibration is because in 15 out of the 23 tests there was no measured PM for some portion of the total fuel burned because of instrument problems, while the predicted PM is based on the total fuel burned times the EF in g/kg-fuel.

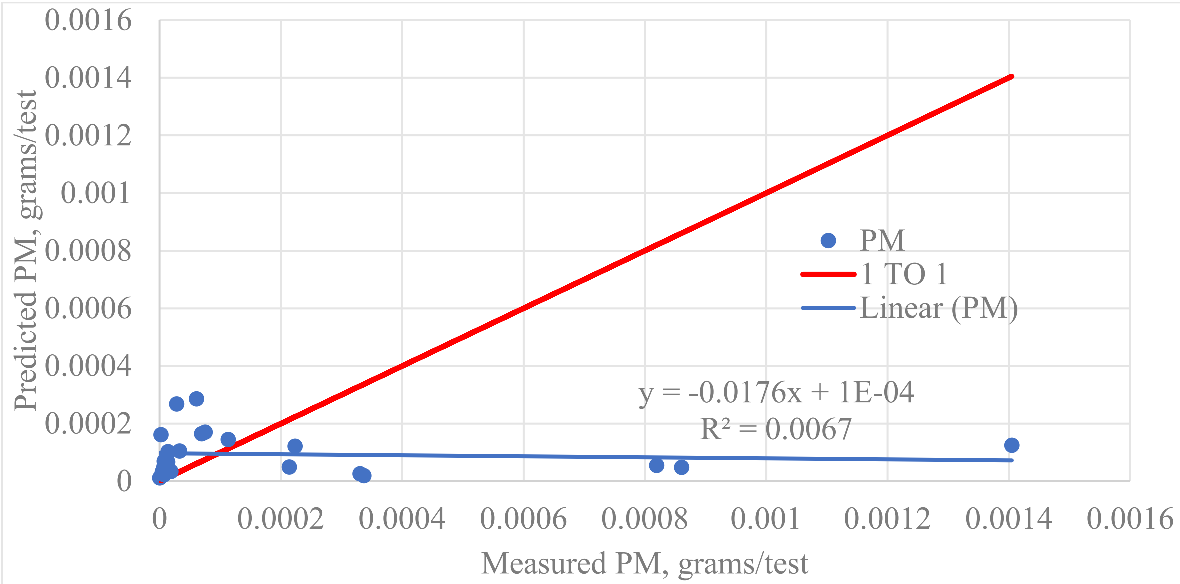

Figure 5-1: PM calibration results for 10 units (23 tests) in development dataset.

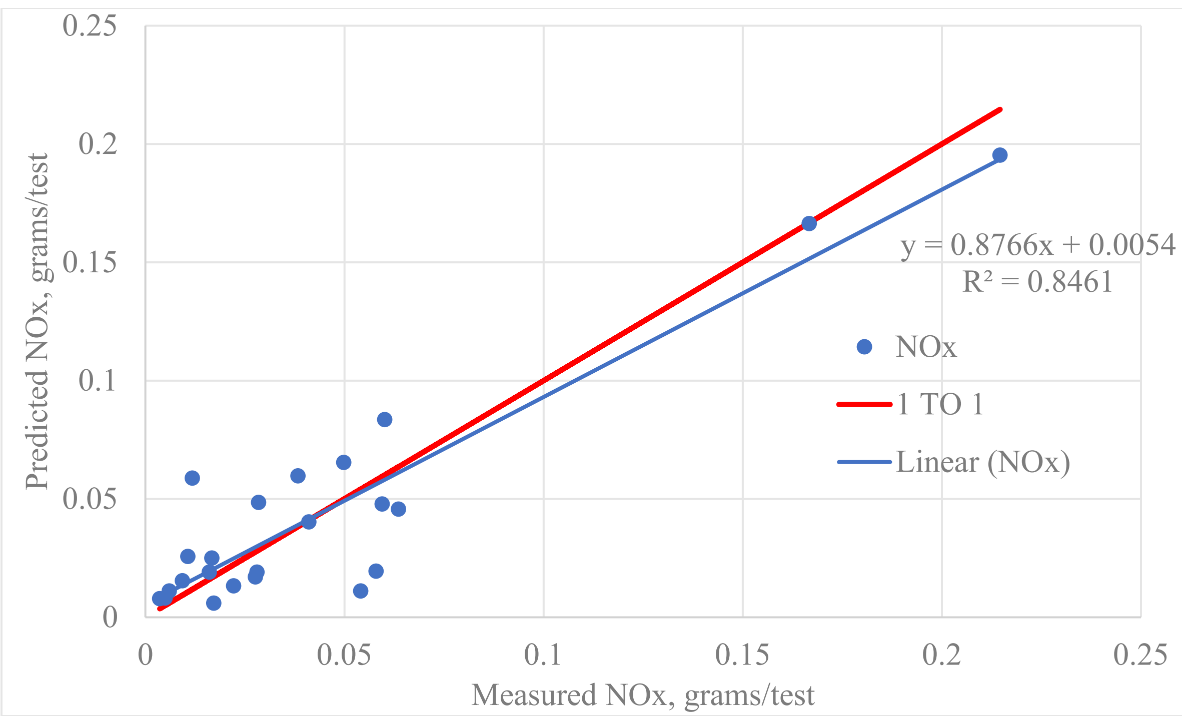

Figure 5-2 NO_x calibration results for 10 units (23 tests) in development dataset.

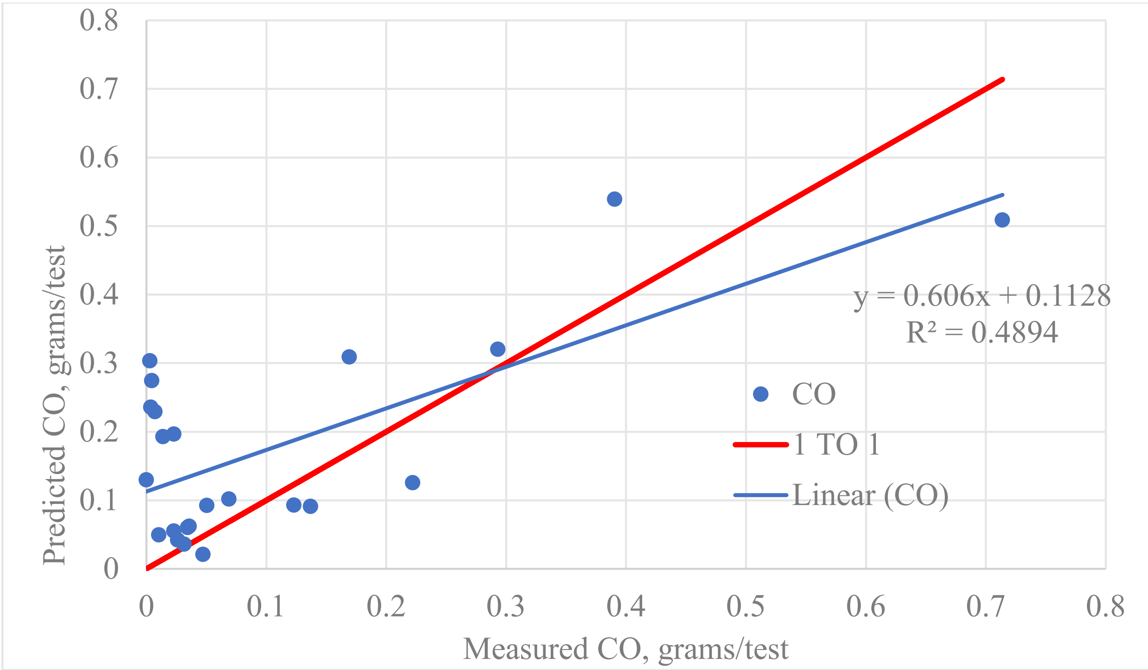

Figure 5-3: CO calibration results for 10 units (23 tests) in development dataset

5.2 Programming the Model

The model was developed in Excel in the form of an .xlsx workbook containing VBA macros and the four basic worksheets: “About”, “Main”, “Export” and “EF”. The “About” worksheet contains basic model information and credits. The model is run from the “Main” worksheet which contains the model’s Graphical User Interface (GUI), presented in Section ***5.3.1***. Using the GUI, the user can input model run information, load previous model run parameters, execute the model and export the results and model run parameters to an output file. As the model is run, model output data is presented in the GUI on the “Main” worksheet and in the “Export” worksheet. The “EF” worksheet contains the emission factors which support the model. The following section explains the GUI. For detailed information on running the model, please review the updated “Off-Road Equipment (ORE) – User’s Guide”

5.2.1 Graphical User Interface (GUI)

The Graphical User Interface (GUI), presented in Figure 5-4 was developed using ActiveX Controls and visual basic for applications (VBA) standard with Excel software. The GUI provides a user friendly interface for setting up and executing model runs. Model runs consist of single or multiple instances of off-road equipment. For each instance of equipment, an equipment entry is made and a number of model run parameters are defined. The modeled fleet is defined as the combination of all the instances of equipment defined in a run. Instructions for running the ORE model are presented in the “Off-Road Equipment (ORE) Model - User’s Guide”. An overview of the components of the GUI is presented in Figure 5-4 and the text that follows.

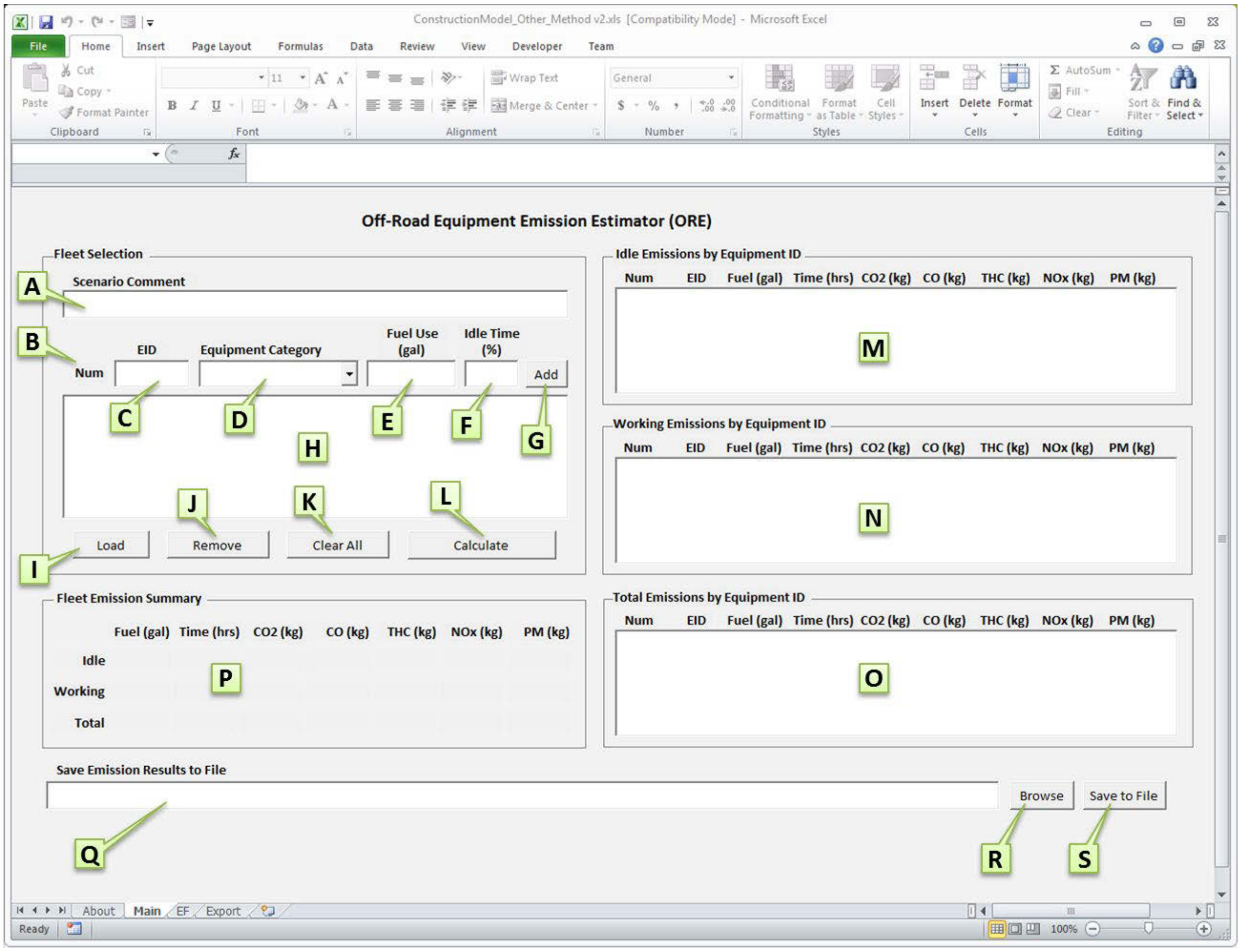

Figure 5-4: ORE GUI overview

A: The scenario comment box provides an area to add commentary for a particular run. This information is passed to the "Export" sheet and saved in the export file.

B: The "Num" column displays a position count provided by the model for each entry of user input data.

C: The "EID" box provides an area to add an alpha-numeric Equipment ID (EID) for an equipment entry.

D: The "Equipment Category" selection box allows the user to choose a particular equipment type (i.e. engine tier category) for an equipment entry.

E: The "Fuel Use" box allows the user to specify the amount of fuel in gallons consumed by each equipment entry during the modeled period of interest.

F: The "Idle Time" box allows the user to specify the percent of time an equipment entry is at idle during the modeled period of interest.

G: The "Add" button adds an equipment entry to the "Fleet Selection" list (labeled H) based on the entry parameters specified in C through F.

H: The "Fleet Selection" list contains the current equipment entries defined in the equipment fleet for the current model run. The equipment fleet can contain several thousand entries. The limit of the GUI to hold equipment entries has not been tested. It is important to note that model runs are based on the fleet information contained in the GUI and not in the export worksheet.

I: The "Load" button allows the user to populate the "Fleet Selection" list from a model run output file which contains information for a fleet of equipment units. In this manner, the user does not have to specify individual entries each time to recreate a model run.

J: The "Remove" button allows the user to remove selected entries from the "Fleet Selection" list. Entries are selected with the mouse and may include one or more entries. Use the Ctrl key to select multiple entries or the Shift key to select a range of entries.

K: The "Clear All" button removes all entries from the "Fleet Selection" list from the GUI. Note that this also removes all data from the "Export" sheet.

L: The "Calculate" button initiates the model run. For the model run, the model iterates through entries in the fleet list box, searches for the appropriate emission factors from the supporting emission factor worksheet "EF", applies those parameters to the entry data and provides the results of that calculation in the GUI in the list sections **M** through **P**. At this time, the "Export" worksheet is also updated with the latest calculated results.

M: This section of the GUI provides individual equipment results for the idle mode portion of activity. The idle mode portion of activity is determined by the % idle time specified by the user and the fuel rate for both the idle and non-idle activity modes for the equipment type.

N: This section of the GUI provides individual equipment results for the non-idle or work mode portion of activity. The work mode portion of activity is determined by the % idle time specified by the user and the fuel rate for both idle and non-idle activity modes for the equipment type.

O: This section of the GUI provides total emissions for individual equipment entries in the fleet. The total emissions for each equipment entry are the idle and work emissions combined for each equipment entry.

P: This section of the GUI provides total emissions for the equipment fleet defined in the run. These emissions are the aggregated results of the total emissions for the individual equipment entries from section **O**.

Q: This box shows the save file path and name which is selected with the "Browse" button **R**.

R: This "Browse" button allows the user to browse for a save file path and name.

S: This button saves the data in the "Export" worksheet to a .csv file added using the GUI "Browse" button **R** and shown in the save file text box **Q**. A file saved in this manner can be used to populate the GUI equipment list entries using the "Load" button **I**.

5.3 Model Expandability

The model was developed on a limited data set and contains estimates for ~~five~~ ***six*** distinct equipment types based on emission certification standards and aftertreatment technology. Analysis of emission data did show variability in emission trends in the non-idle mode for some equipment categories as defined in the model. Although there was insufficient data to further break-down the equipment categories in this study, subsequent testing could produce a dataset which could be used to increase the focus of the equipment categories. The emphasis for the model is to estimate the emission performance characteristics of a general equipment category and not a specific piece of equipment.

5.4Tier 4F Emission Factor Results

Table 5-2 shows the emission factors which can be calculated from the available Tier 4F data. While each of these factors would be different if another ten units were tested, the variation would be the least for the "Normal Operation" as there would not be a variable number of cold starts, hot starts, or DPF regenerations. While most emissions during cold starts, hot starts, and DPF regenerations for engines with displacements >7.01 liters, may be higher than for "normal operation" it is likely that in most cases there will not be a significant number of these events and therefore not a significant increase in the total emissions over the course of a day's equipment operation. Therefore, the Tier 4F emission factors in the Off-Road Equipment Emission Estimator (ORE) Version 2.0 are for "Normal Operation"

Table 5-2: Tier 4F Emission Factors Calculated from the measured data.

			Using all Data	DPFR Only	Cold Starts Only	Hot Starts Only	"Normal Operation"
Tier 4F	Idle	CO_gpkg	11.50872	5.21751	17.01495	10.83106	10.73125
Tier 4F	Idle	CO2_gpkg	3151.365	3158.974	3141.061	3152.475	3152.6
Tier 4F	Idle	Fuel_kgphrs	3.87128	10.25897	4.2844	3.04299	3.80681
Tier 4F	Idle	NOx_gpkg	15.47843	19.94598	30.78434	11.22144	17.70535
Tier 4F	Idle	PM_gpkg	0.00589	0.00639	0.0142	0.01026	0.00533
Tier 4F	Idle	THC_gpkg	0	0	0	0	0
Tier 4F	Work	CO_gpkg	3.31737	2.02423	3.42467	2.7049	3.70482
Tier 4F	Work	CO2_gpkg	3163.768	3165.872	3162.413	3165.264	3163.217
Tier 4F	Work	Fuel_kgphrs	30.23784	41.85832	18.81696	20.17956	28.50152
Tier 4F	Work	NOx_gpkg	0.95264	5.5955	14.8424	2.41444	0.53111
Tier 4F	Work	PM_gpkg	0.00329	0.01025	0.01057	0.00664	0.00197
Tier 4F	Work	THC_gpkg	0	0	0	0	0
THC factor is 0 for all cases because THC analyzer didn't function properly							
"Normal Operation" = All DPFR, cold starts, and hot starts removed from all data							

6 References

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7 Appendices

7.1 Data Summary

Summary of the data for each test day are attached as PDF files.

48_2018-01-31_CAT_335F.pdf
49_2018-02-01_CAT_335F.pdf
50_2018-02-01_CAT_335F.pdf
51_2018-02-02_CAT_335F.pdf
52_2018-05-30_CAT_930M.pdf
53_2018-05-31_CAT_930M.pdf
54_2018-06-28_CAT_430F2.pdf
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57_2018-07-12_CAT_336F.pdf
58_2018-07-13_CAT_336F.pdf
59_2018-07-17_JD_744KII.pdf
60_2018-07-18_JD_744KII.pdf
61_2018-07-26_JD_310SL.pdf
62_2018-07-27_JD_310SL.pdf
63_2018-08-01_JD_1050K.pdf
64_2018-08-02_JD_1050K.pdf
65_2018-08-09_Hitachi_210GLC.pdf
66_2018-08-10_Hitachi_210GLC.pdf
67_2018-08-14_JD_824KII.pdf
68_2018-08-15_JD_824KII.pdf
69_2018-12-17_CAT_D8T.pdf
70_2018-12-18_CAT_D8T.pdf

7.2 Matlab regression analyses

Figures A1 thru A8 in

Matlab_Orig_Figs.pptx

show the Matlab regression results without removal of cold starts, hot starts, or DPF regeneration events.

Figures A9 thru A17 in

Matlab_OR_Figs.pptx

show the Matlab regression results with removal of cold starts, hot starts, and DPF regeneration events.

Figures A18 thru A25 in

Matlab_CS_Figs.pptx

show the Matlab regression results for cold start events.

Figures A26 thru A33 in

Matlab_HS_Figs.pptx

show the Matlab regression results for hot start events.

Figures A34 thru A41 in

Matlab_DPFR_Figs.pptx

show the Matlab regression results for diesel particulate regenerations events.