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Gaseous and particle emissions from construction engines are an important fraction of the total air pollutants and are gaining increasing regulatory attention. Quantification of NOx and PM is necessary to inventory the contribution of the construction equipment, such as used by Caltrans, to atmospheric loadings, particularly for those projects in non-attainment or maintenance areas. At present, however, there is no model mutually accepted by Caltrans and regulatory agencies that can be used for the estimation of construction emissions or the development of appropriate regulations. This is due in part to a lack of emissions data from construction equipment under in-use operating conditions. The lack of a sound scientific basis for regulation has resulted in legal cases and other obstacles that could potentially delay or inhibit important transportation projects.

The goal of this research program was to carry out initial construction equipment emissions testing and to develop an emissions model for construction equipment based on these in-use emissions measurements. The program included two main aspects: 1) in-field emissions and activity measurements; and 2) model development and validation. The emissions measurements were made on a second-by-second basis using a portable emissions measurement system (PEMS) to develop relationships between NOx and PM and other emissions and fuel use. These emissions data were subsequently used in the development of a model that allows the determination of emissions from different pieces of construction equipment or for construction projects as a whole.

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Evaluating the Emissions from Heavy-Duty Construction Equipment

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Executive Summary

Gaseous and particle emissions from construction engines are an important fraction of the total air pollutants and are gaining increasing regulatory attention. Quantification of NO_x and PM is necessary to inventory the contribution of the construction equipment, such as used by Caltrans, to atmospheric loadings, particularly for those projects in non-attainment or maintenance areas. At present, however, there is no model mutually accepted by Caltrans and regulatory agencies that can be used for the estimation of construction emissions or the development of appropriate regulations. This is due in part to a lack of emissions data from construction equipment under in-use operating conditions. The lack of a sound scientific basis for regulation has resulted in legal cases and other obstacles that could potentially delay or inhibit important transportation projects.

The goal of this research program was to carry out initial construction equipment emissions testing and to develop an emissions model for construction equipment based on these in-use emissions measurements. The program included two main aspects: 1) in-field emissions and activity measurements; and 2) model development and validation. The emissions measurements were made on a second-by-second basis using a portable emissions measurement system (PEMS) to develop relationships between NO_x and PM and other emissions and fuel use. These emissions data were subsequently used in the development of a model that allows the determination of emissions from different pieces of construction equipment or for construction projects as a whole. The model developed is a spreadsheet-based, user-friendly program that can be readily deployed by program staff at Caltrans, outside contractors or other government agencies.

Emissions measurements were made for 12 in-use pieces of construction equipment. These included applications from the Caltrans maintenance yards as well as equipment from a contractor site for highway construction. The equipment included a range of applications including front loaders, motor graders, scrapers, and other pieces of equipment. A preliminary fuel-specific emissions model was then developed that can predict an emissions inventory based on construction equipment.

A summary of the major findings and accomplishments of this program are as follows:

- Most construction equipment (of the approximate same size) exhibited similar emission profiles, however their activity differed somewhat;

- There were differences observed between cold-start and warm-start idle emissions among the different equipment;

- Normalizing emission output by fuel results in relatively small variations in emission levels under different levels of load.

This phase of the research program primarily focused on NOx emissions, along with CO and HC for some of the equipment. A second phase of work is currently underway to measure and model particulate matter (PM) from similar construction equipment. Once the PM measurements and model are complete, these will be integrated into the current model described in Section 4. Once this second phase is complete, it is expected that this model will facilitate the process for approving and characterizing a variety of construction projects across the state.

1.0 Introduction

Gaseous and particle emissions from construction engines are an important fraction of the total air pollutants and are gaining increasing regulatory attention. Quantification of NO_x and PM is necessary to inventory the contribution of the construction equipment, such as used by Caltrans, to atmospheric loadings, particularly for those projects in non-attainment or maintenance areas. At present, however, there is no model mutually accepted by Caltrans and regulatory agencies that can be used for the estimation of construction emissions or the development of appropriate regulations. This is due in part to a lack of emissions data from construction equipment under in-use operating conditions. The lack of a sound scientific basis for regulation has resulted in legal cases and other obstacles that could potentially delay or inhibit important transportation projects.

The primary purpose of this project was to make initial emissions measurements of construction equipment and measure their activity; using these data, the project also included the development of an initial user-friendly, but comprehensive emissions model that can be utilized in the development and implementation of construction equipment regulations. The program focused on two main aspects: 1) in-field emissions and activity measurements; and 2) model development and validation. The emissions measurements were made on a second-by-second basis using a portable emissions measurement system (PEMS). The resulting data were used to develop relationships between NO_x and other emissions and fuel use. This emissions data were then subsequently used in the development of a model that allow for the determination of emissions from different pieces of construction equipment or for construction projects as a whole. The preliminary model developed is a spreadsheet-based, user-friendly program that can be readily deployed by program staff at Caltrans, outside contractors or other government agencies.

To date, the model has been developed primarily for NOx emissions. The inclusion of PM emissions is part of an on-going phase 2. Once the entire model is complete after phase 2, it is anticipated that the model developed will have wide applicability and provide a more formal basis for regulatory development. It is important to understand that CE-CERT is already involved with a number of programs with CARB that are forming the basis for non-road regulations in the State of California and CE-CERT is in the process of formally conducted the evaluation of PEMS units for use in upcoming regulatory work with CARB. With CE-CERT's strong technical background, it is anticipated these emissions results and the resulting model will be widely accepted by a range of shareholders. The development of regulations based on sound science will help the environmental process associated with the implementation of new construction projects. This will in turn facilitate construction projects necessary for the development and maintenance of a transportation system that is safe, efficient and effective. At the same time, a more efficient regulatory process will allow more rapid adoption of regulations that will improve air quality and promote public health, while reducing legal and other costs.

2.0 Experimental Procedures

Emissions Measurement Systems

Over the course of the test program, two different analyzer systems were utilized for the measurement of the construction equipment. The two systems were based on commercially available instruments or instrument packages.

During the initial portion of the measurement program, emissions measurements were made with a Semtech D analyzer (see http://www.sensors-inc.com/). This system measures NO_x using a UV analyzer, total hydrocarbons (THC) using a flame ionization detector (FID), 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 190C consistent with the conditions for regulatory measurements. The analyzers provide measurements of the concentration levels in the raw exhaust. A picture of the Semtech D units is provided below.

Figure 2.1. Picture of Semtech D PEMS

A flow meter based on a pitot tube operational principal is used for the measurement of exhaust flow rates. The flow meter is housed in a 5” diameter pipe that is placed over the tailpipe exhaust for the equipment being tested. A picture of the exhaust flow meter is provided in Figure 2.2 below. The exhaust flow rates are multiplied by the concentration levels for the various emission components to provide emission rates in grams per second.

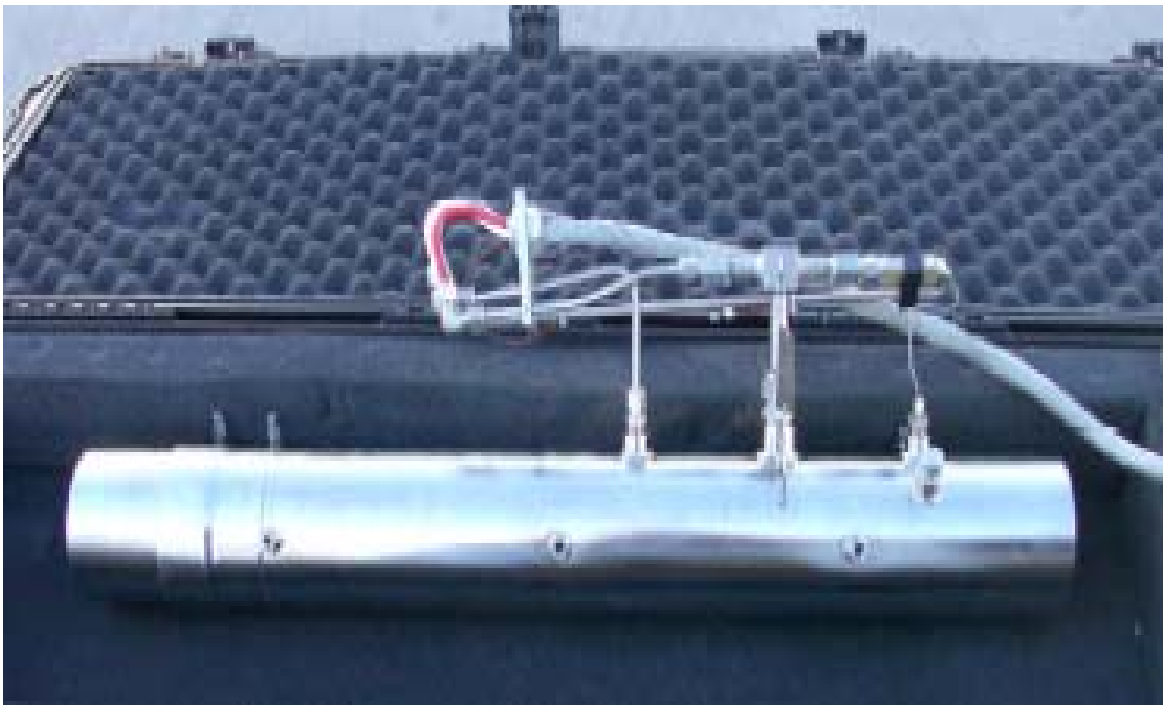

Figure 2.2. Picture of Semtech D Exhaust Flow Meter

The second system used later in the project was a Horiba PG-250 emissions analyzer. This system was used more extensively toward the middle and end of the testing. This unit utilizes a chemiluminescent analyzer for measuring NO_x, and NDIR analyzer for measuring CO and CO_2. The Horiba unit has the advantage that it is more compact and has a lower power requirements, which makes the unit easier to operate for longer periods of time as well as easier to deploy in the field. The disadvantage of the Horiba system is that the data have to be represented in fuel specific units with no absolute mass since this unit does not directly measure exhaust flow rate. Additionally, this unit does not provide a measurement of THC. However, THC is not a critical emissions component from construction engines.

Test Set-up

The test setup included the emissions analyzers (and associate exhaust flow meter), a power source, and a separate data acquisition system that was used for collecting some additional activity measurements.

The emissions analyzer system on the construction equipment was initially powered using a series of three or four deep-cycle marine batteries and a power inverter. The batteries were connected in series and allowed the Semtech unit to operate for a period of several hours. The power converter was used in conjunction with the batteries to provide the appropriate power to the Semtech unit.

After the initial testing using the battery system, the power system was upgraded to a small power generator that could provide sufficient power for the operation of the emissions units for entire day.

The emissions analyzers were housed in foam lined cased to provide protection from excessive vibration on the equipment and allow the analyzers to be effectively secured to the construction equipment. The cased were secured down to the equipment using straps and cross tied to ensure the analyzers were stable over the course of a test day. Figures 2.3 and 2.4 show typical installations of the emissions analyzer on the construction equipment. Figure 2.3 shows an installation of the Semtech D system with a deep-cycle battery power source and the exhaust flow meter on a motor grader. Figure 2.4 shows an installation of a Horiba system with the generator power source.

Figure 2.3. Installation of the Semtech D system on a Motor Grader

Figure 2.4. Installation of the PG250 system on a Front Loader

Preliminary Validation Testing

Before beginning the field testing, several tests were conducted to validate the operation of the PEMS and provide some cross comparisons of its operation with some of the other measurement techniques available at CE-CERT. For one such measurement, the Semtech was cross compared with the UC Riverside mobile emissions laboratory (MEL), which is a full dilution tunnel emissions system with laboratory grade analyzers on a mobile platform. MEL is a unique laboratory containing all of the instrumentation normally found in a conventional vehicle emissions laboratory, but the equipment is mounted inside a 53-foot over-the-road truck trailer, as shown in Figure 2-5. The laboratory contains a dilution tunnel, analyzers for gaseous emissions, and instrumentation for particulate measurements. The system is reconfigurable, and can measure real-time gaseous as well as particulate matter (PM). Although much of the system is custom-designed, the laboratory was designed to conform to the Code of Federal Regulations (CFR) requirements for gaseous and particulate emissions measurements (CFR Parts 86 and 89). The laboratory is designed to operate as a class 8 tractor is pulling it over the road (or on a closed track over a repeatable cycle); it is not simply a roadside testing laboratory.

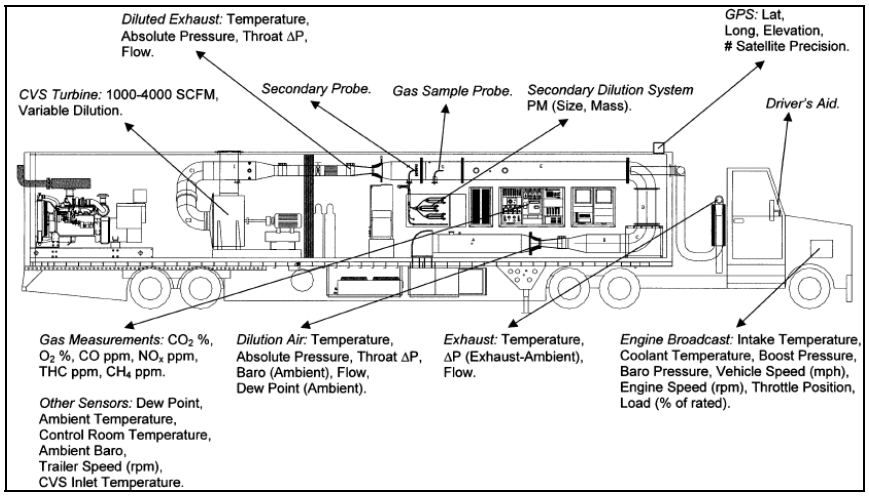

Figure 2-5. CE-CERT's Mobile Emissions Laboratory (MEL)

For these comparisons, the Semtech system was positioned to measure raw exhaust concentrations upstream of the MEL dilution system. The MEL has recently been used for on-road validation of the PEMS measurement allowance for the upcoming PEMS in-use NTE measurement regulatory program. The MEL measurements were made in the diluted exhaust and converted to equivalent raw exhaust concentrations by using the dilution ratio determined by the different of the total tunnel flow minus the flow of the intake dilution air.

The comparisons of the PEMS and the MEL showed some differences in concentration levels, as shown in Table 2-1 and plotted in Figure 2-6. The PEMS NO_x emission levels were biased 5-15% high relative to those of the MEL. This comparison for NO_x is in a similar range to that seen in previous comparisons between the MEL and PEMS. CO_2 measurements were all within 2%, except at the lowest load point. This is also consistent with previous comparisons and indicates good comparability for the CO_2 which is the basis for the fuel based comparisons. The deviations for CO and THC were higher than those for the other components. This is not surprising as CO and THC are generally found at relatively low levels in the diesel exhaust. Similar results have been found in other comparison studies.

	Semtech Results (ppm)				**MEL equivalent raw measurements (ppm)**			
Load point	NO_x	CO_2	CO	THC	NO_x	CO_2	CO	THC
100 %	1099.8	8.9	203.5	5.1	964.0	8.80	205.9	15.9
75 %	1112.0	7.92	135.4	NA	992.2	7.99	165.2	13.8
50 %	1004.0	6.88	125.0	24.4	919.9	7.01	143.9	20.1
25 %	640.8	5.23	98.84	42.7	595.2	5.30	88.3	27.0
10 %	344.3	3.56	119.5	76.4	325.4	3.82	127.7	42.4

Percentage differences (relative to MEL)

	NO_x	CO_2	CO	THC
M100	14.1%	1.4%	-1.1%	-68.1%
M75	12.1%	-1.0%	-18.1%	NA
M50	9.1%	-1.9%	-13.1%	21.6%
M25	7.7%	-1.4%	11.9%	57.8%
M10	5.8%	-6.7%	-6.4%	80.3%

Table 2-1. Emissions concentration level comparison between PEMS and MEL

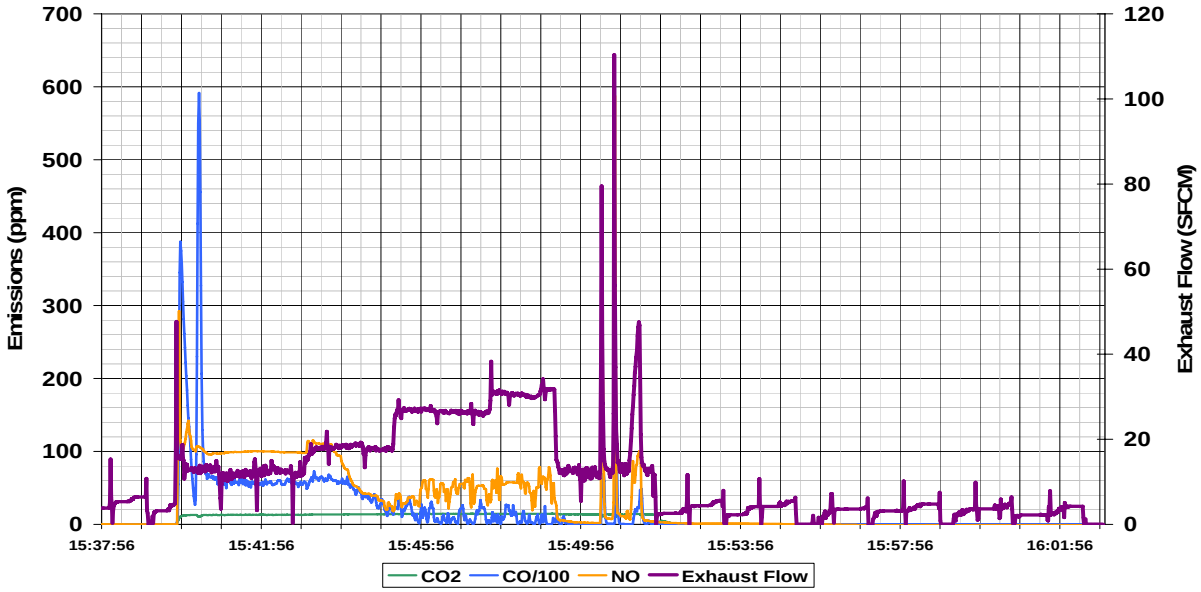

Figure 2-6. CE Emissions concentration level comparison between PEMS and MEL

Construction Equipment Tested for Emissions

During the course of the project, contacts were made with several Caltrans maintenance yards and arrangements were made for in-field measurements of different pieces of Caltrans equipment in road maintenance and other applications. Two pieces of equipment from the Caltrans Hemet yard were tested. The first piece of equipment was a motor grader being used for road maintenance. A picture of the installation is shown in Figure 2-3. This piece of equipment was tested on two separate occasions to ensure reliable operation. The data were found to be comparable to fuel specific emission factors obtained from EPA sources and to emissions measurements made in our engine dynamometer test laboratory.

Later, a total of seven additional pieces of equipment at the SR-91/SR-215/I-60 interchange construction site have been tested using the Horiba-based system. The seven pieces of equipment represent the primary subset of equipment that were accessible through the construction project at the interchange. One other piece of equipment was tested in a foundation trenching application due to its availability with the Horiba system. All of the tested equipment is listed in Table 2-2.

Table 2-2. Equipment Tested

Test Date	Manufacturer	Equipment	HP	Engine	PEMS	Size	Activity
12/14/05 1/9/06 5/30/06	Dresser A450E	Motor Grader	165@ 2500		SEM	7.6	San Jacinto – Road Clean-up
1/13/06	Komatsu WA180	Front End Loader	128@ 2400	S6D102E-1	SEM	5.9	San Jacinto – Trash Removal
3/22/06 4/6/06	CASE 621B*	Front End Loader	124@ 2000		HOR 1	6.8	Banning – Trash Removal
5/12/06	CASE 1150	Bulldozer	124@ 2000	6T-590	SEM	5.9	Clear Flooding Channel
5/19/06	Dresser 850 AWD	Motor Grader	177@ 2500		SEM	5.9	Cajon Pass
8/17/06	Volvo 60L	Back-Hoe	85@2 200	D4D	HOR 1	4.04	Foundation Trenching
8/24/06	CAT 966G	Wheel Loader	439@ 2200	3176	HOR 1	10.3	Loading Construction Fill
8/31/06	CAT 140H	Motor Grader	185@ 2000	3176C	HOR 1	10.3	Grading at Freeway Construction
9/29/06	CAT 623	Scraper	330@ 2100	C15	HOR 1	15.2	Preparing grade for on-ramp
10/19/06	John Deere 450CLC	Excavator	316@ 1800	6125H	HOR 1	12.5	Debris crushing, cliff refacing, fill removal
11/30/2006	Ingersoll Rand SD-100D	Soil Compactor	125@ 2200	Cummins B3.9	HOR 1	3.9	Compacting Fill Dirt for On Ramp
12/8/2006	CAT 980	Wheel Loader		CAT 3406	HOR 1		Filling rock crusher with material

SEM = Semtech system; HOR 1 = Horiba system

3.0 Results

The results for typical runs are provided below in Figures 3-1 and Figure 3-2. The data are presented on a fuel specific basis in emissions per kg of fuel on an instantaneous basis. The data for CO and CO_2 are multiplied by a multiplicative factor so that all pollutants can be shown on the same graph.

Figure 3-1 shows data collected with the Semtech system for a motor grader doing road clean up in the San Jacinto area. The first portion of the data represents the motor grader going for the main maintenance yard out to the site where the road clean up was done. This data shows peaks during accelerations, but generally less transient emissions. The later part of the data shows the operation during the time when the motor grader was going back and forth along the road cleaning debris. These emissions are more transient, shows peaks in the emissions at some portions of the data, but with the data not all peaking at the same time for all emissions.

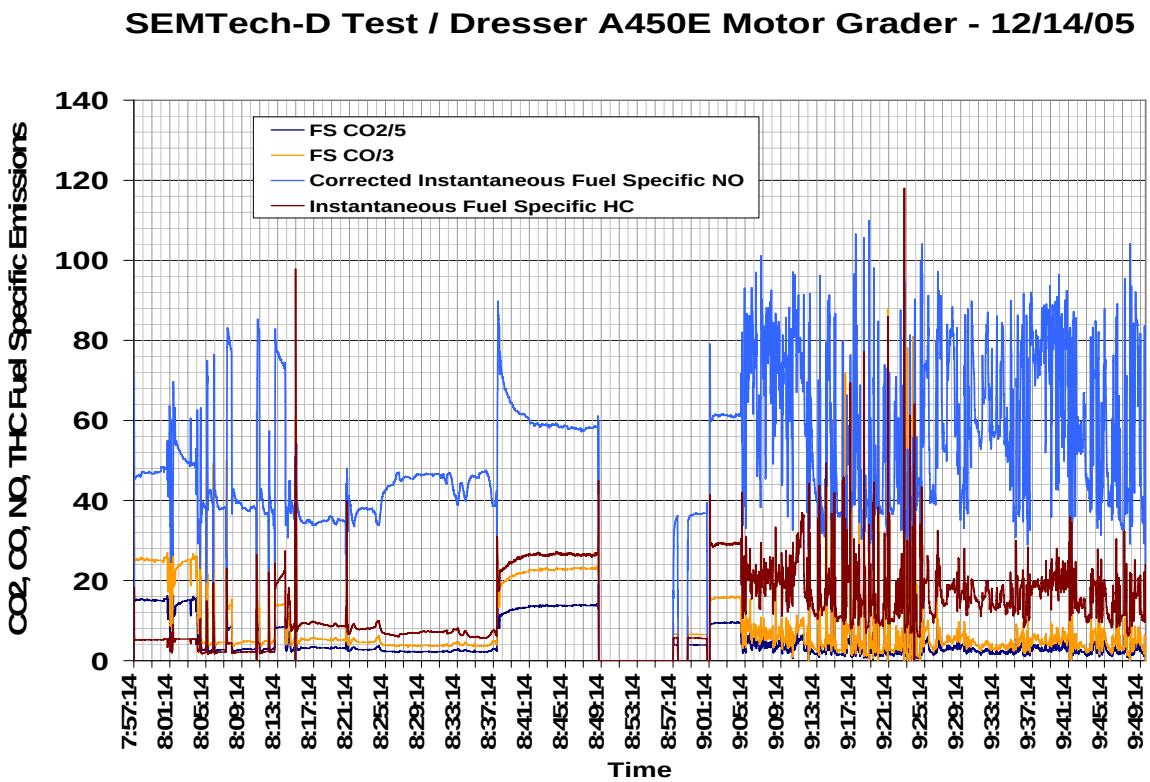

Figure 3-1. Fuel Specific CO_2, CO, NO, and THC Emissions for Motor Grader

Figure 3-2 shows a test run on a front end loader with the Horiba system. The front end loader was being utilized for trash removal for this test run. The data show peaks in CO emissions near the beginning and end of the run and peaks in NO_x near the end of the run. The CO_2 emissions are relatively flat since CO_2 is the predominant component of the exhaust originating from the fuel, so the amount of CO_2 emitting on a per fuel basis remains very constant.

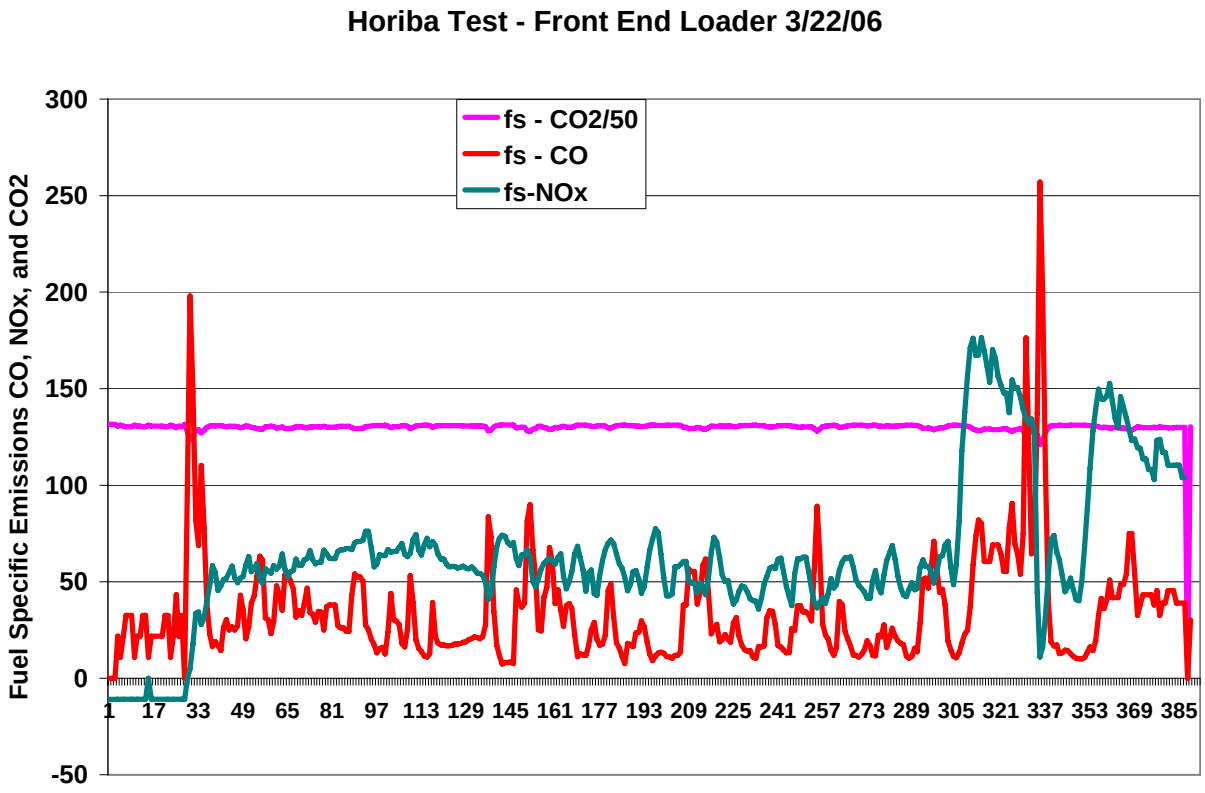

Figure 3-2. Fuel Specific CO, NO_x, and CO_2 Emissions for Front End Loader

4.0 Further Data Analysis and Modeling Results

One of the primary objectives of this research project is to create an emission model to better represent emissions produced in the field from heavy duty diesel construction vehicles. The test procedure and data collection was presented in previous sections. In this section, a description of the data analysis and emission modeling methodology is provided.

Data Analysis

The emissions data collected from the PEMS units are reported as concentration data. Fuel based emissions are calculated from emission concentration data, known emission densities and the carbon weight fraction of the fuel. Fuel data is estimated based on a carbon balance with emissions. The basic calculation is illustrated in equation 4-1.

$$\frac{emission,\ g}{fuel\ use,\ g} = \frac{emission \times \rho_{emission}}{\left(CO_2 \times \rho_{CO_2} \times CWF_{CO_2} + CO \times \rho_{CO} \times CWF_{CO}\right) / CWF_{fuel}} \quad (4\text{-}1)$$

where

$emission$ is the emission rate in ppm
$\rho_{emission}$ is the emission density in g/l
CO_2 is CO_2 emission rate in ppm
ρ_{CO_2} is the density of CO_2 in g/l
CWF_{CO_2} is the carbon weight fraction of CO_2
CO is CO emission rate in ppm
ρ_{CO} is the density of CO in g/l
CWF_{CO} is the carbon weight fraction of CO
CWF_{fuel} is the carbon weight fraction of fuel

Emission data from this study shows that fuel based emission rates are not constant throughout the length of a test. This variation can be seen in the example presented in Figure 4-1 which shows fuel rate, mass emission rates (dashed green), and fuel specific emissions (solid black) all on the same time scale. In Figure 4-1, the first subplot shows fuel use as a function of time. The fuel specific emission rate for CO_2 is shown in the second subplot and is fairly constant while the engine is on, as would be expected due to the strong relationship between CO_2 and fuel use. This is not the case for CO, HC and NOx depicted in the following subplots in Figure 4-1. Trends for these emissions show varying fuel specific emission rates. Comparing the fuel rate in the first subplot to emissions in the following subplots in Figure 4-1, it is evident that fuel specific emission rates (solid black) for CO, HC and NOx increase at low fuel rates. This trend is particularly noticeable during idle which is characterized by a higher fuel specific CO, HC and NO_x emission rate than under steady load. In Figure 4-1, this is most evident from the idle portion during seconds 2400 and 3100 and the constant load mode from the preceding seconds.

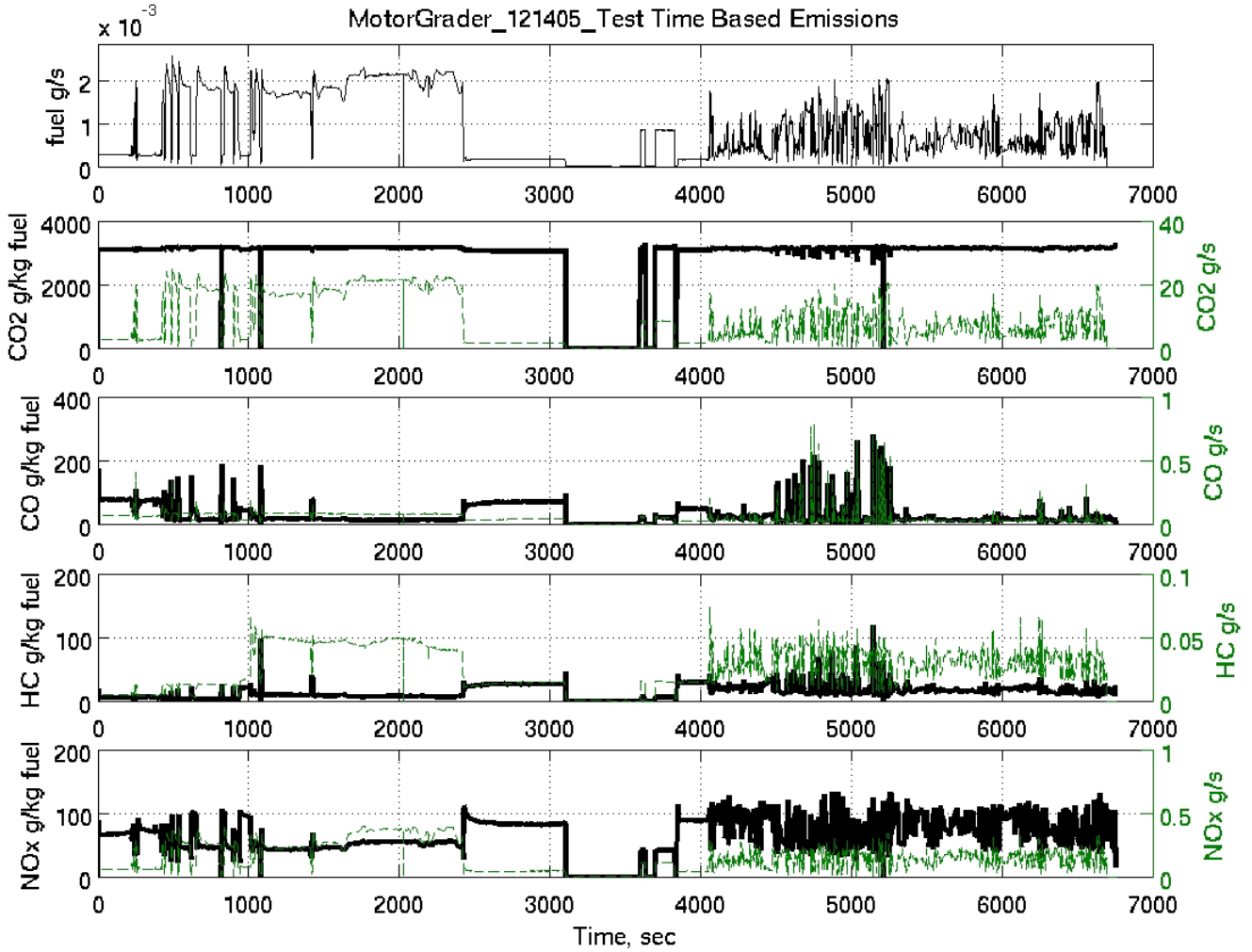

Figure 4-1 a) Fuel use, b-e) Mass emission rates by time (dashed green) and fuel based mass emission rates (solid black)

Figure 4-2 demonstrates the trend between fuel use and fuel specific emission rates for CO, HC and NO_x. This figure shows that at low fuel use, fuel specific emission rates are generally higher than at high fuel use and that after a certain level of fuel use has been achieved; fuel specific emission rates tend to level off and become constant. This trend will facilitate the modeling process by limiting the fuel specific emission factors required for each vehicle.

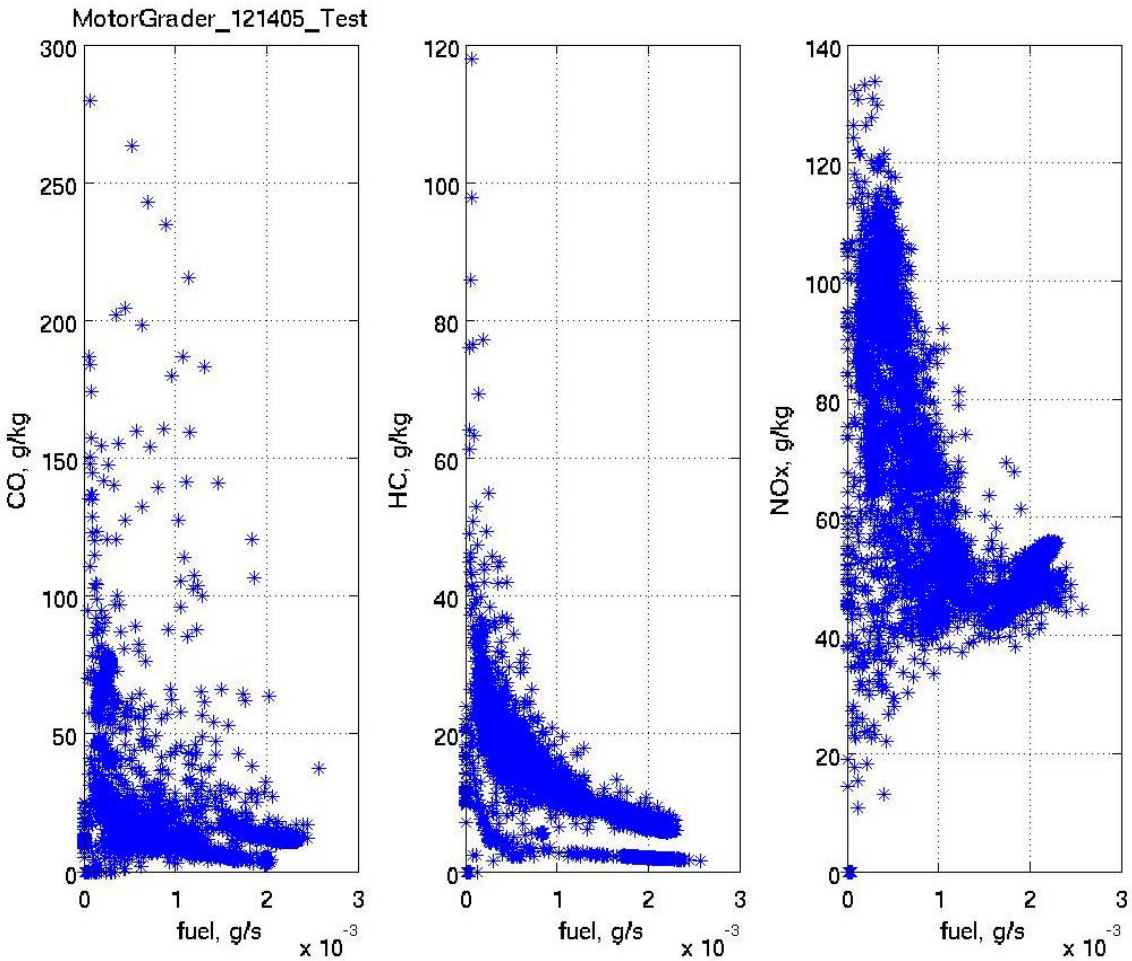

Figure 4-2 Fuel specific emission rates by fuel rate for: a) CO, b) HC and c) NOx

Cold start emission differences were detected in some tests and with some specific emissions species. Figure 4-34-3 and Figure 4-44-4 show fuel by time in the first subplot and HC emissions by fuel in the second subplot. In Figure 4-34-3, HC is in units of grams/second and in Figure 4-44-4, HC is in units of grams HC/kg fuel. In both of these figures, corresponding points in each subplot have different corresponding colors. Figure 4-34-3 and Figure 4-44-4 show that during the first roughly 1000 seconds of activity (red points), that HC versus fuel trend is shifted from the prevailing trend. This change in the fuel based emission rate likely relates to cold start behavior.

In this data set, there is no direct indicator of equipment operating temperature. In Figure 4-34-3 and Figure 4-44-4, a 700 second idle and 500 second engine off period are observed at time 2400 to 3600 seconds. During this time period the engine has time to cool down and in the following seconds at time 3600 to 3850 (depicted in green), a slight warm start temperature effect is observed which is evident by the green points in the HC by fuel subplots.

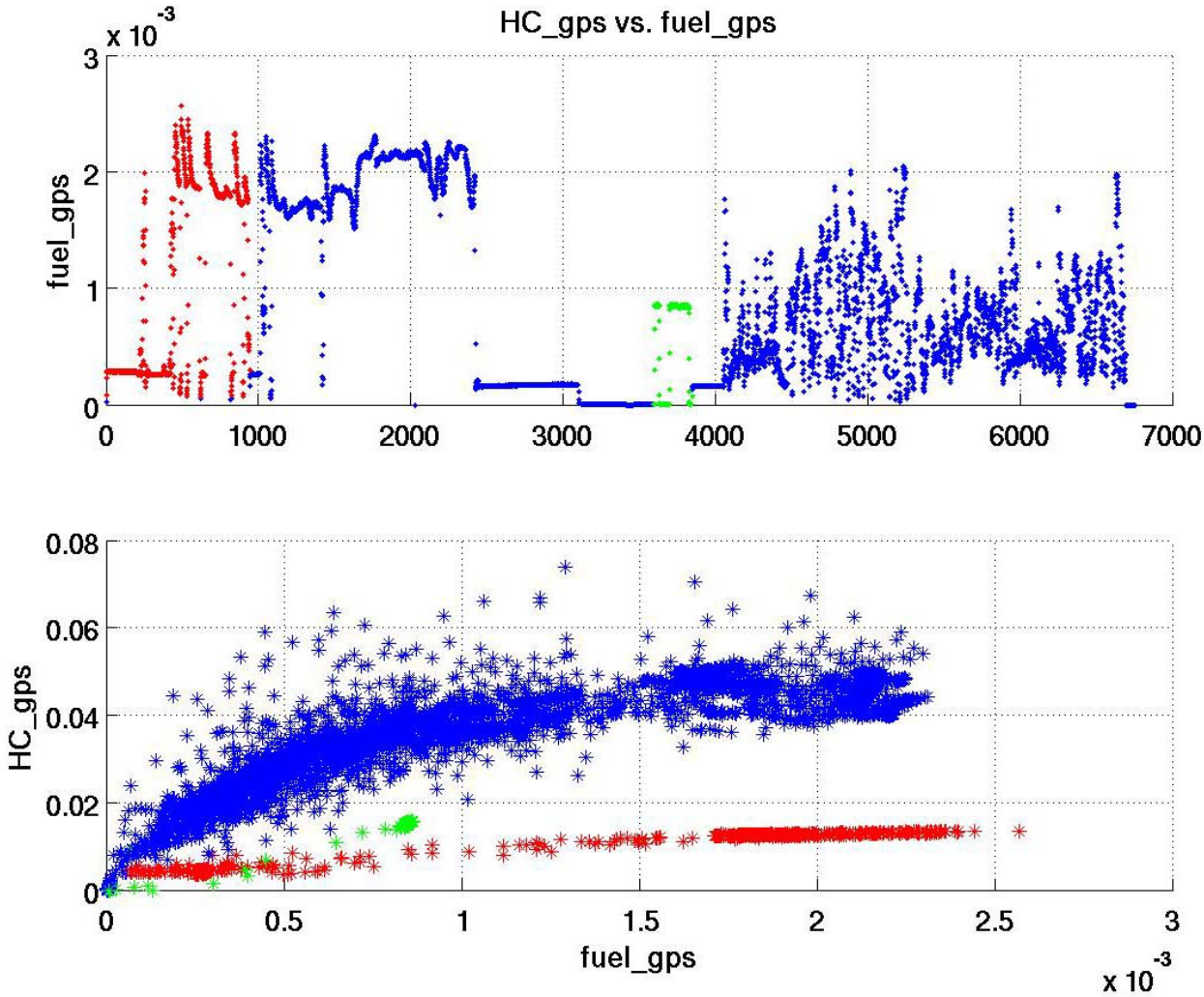

Figure 4-3 a) Fuel use, b) HC mass emissions (HC grams / second) colored by time index

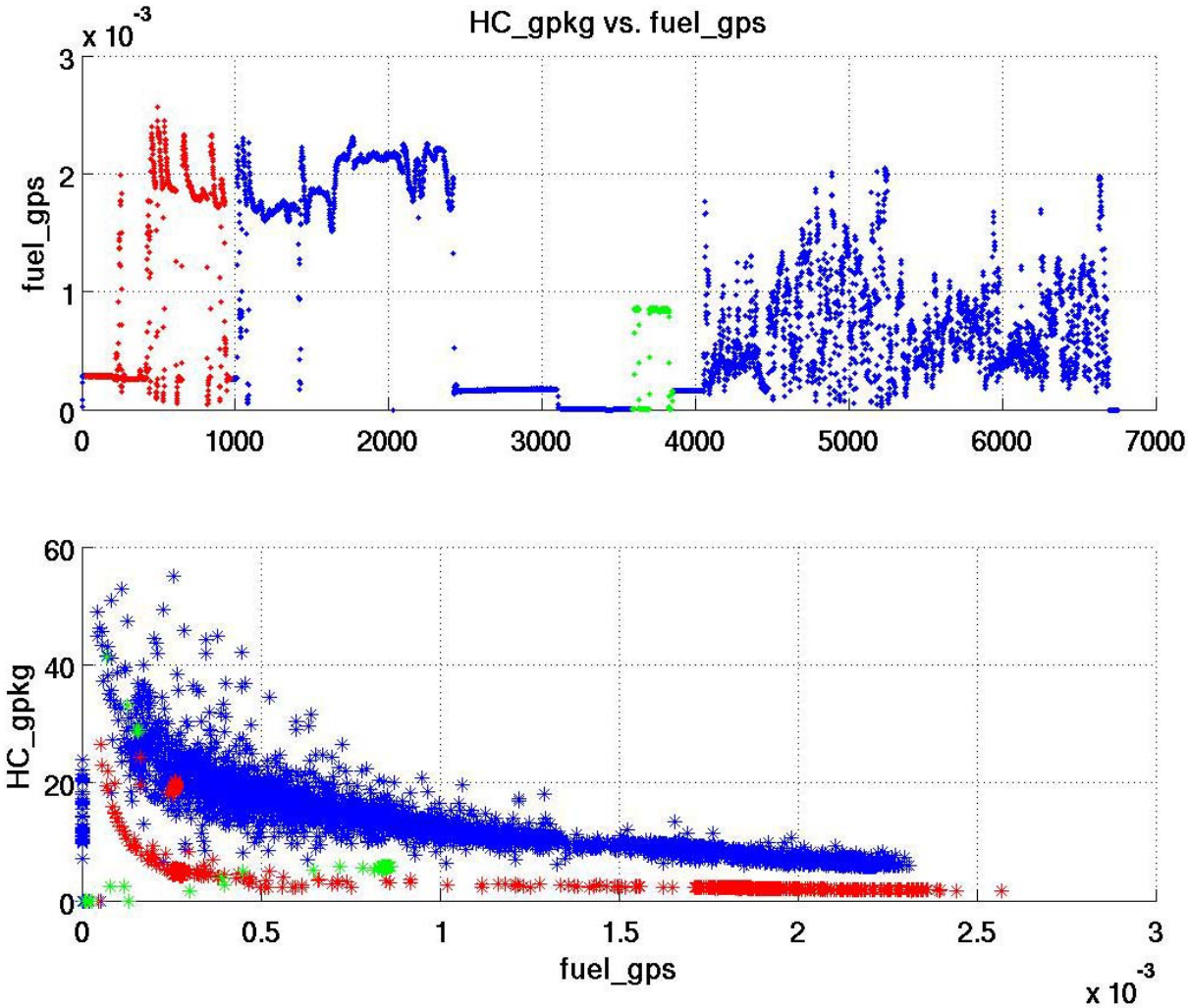

Figure 4-4 a) Fuel use, b) Fuel based HC mass emissions (grams HC / kilograms fuel) colored by time index

Figure 4-54-5 and Figure 4-64-6 present NOx and CO emissions by fuel colored by cold start (red) and warm start (green) regions. These plots show that although the NOx and CO emission by fuel show a strong trend together, they fall within the overall trend of the warm start emissions for each of the plots.

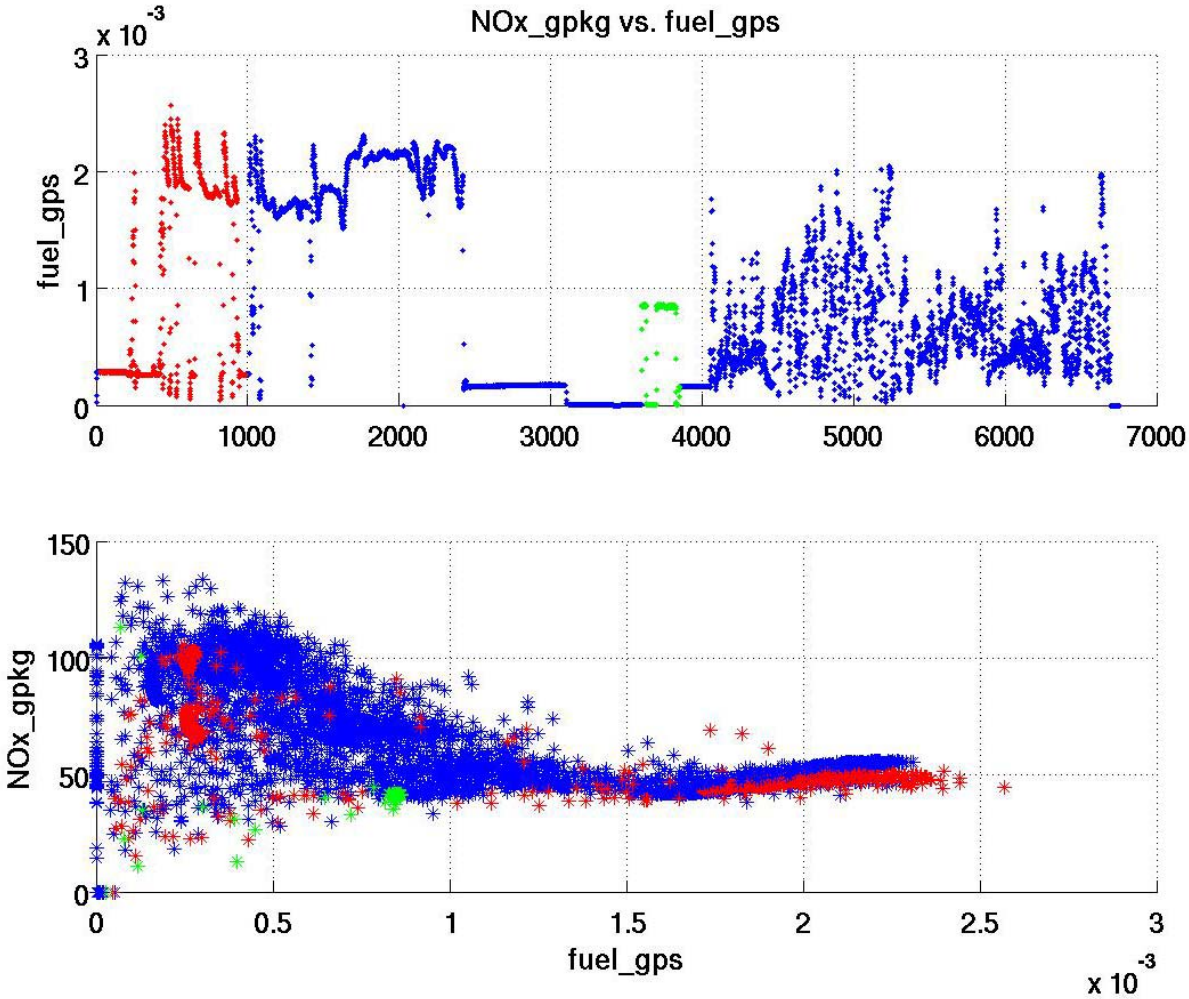

Figure 4-5 a) Fuel use, b) Fuel based NOx mass emissions (grams NOx / kilograms fuel) colored by time index

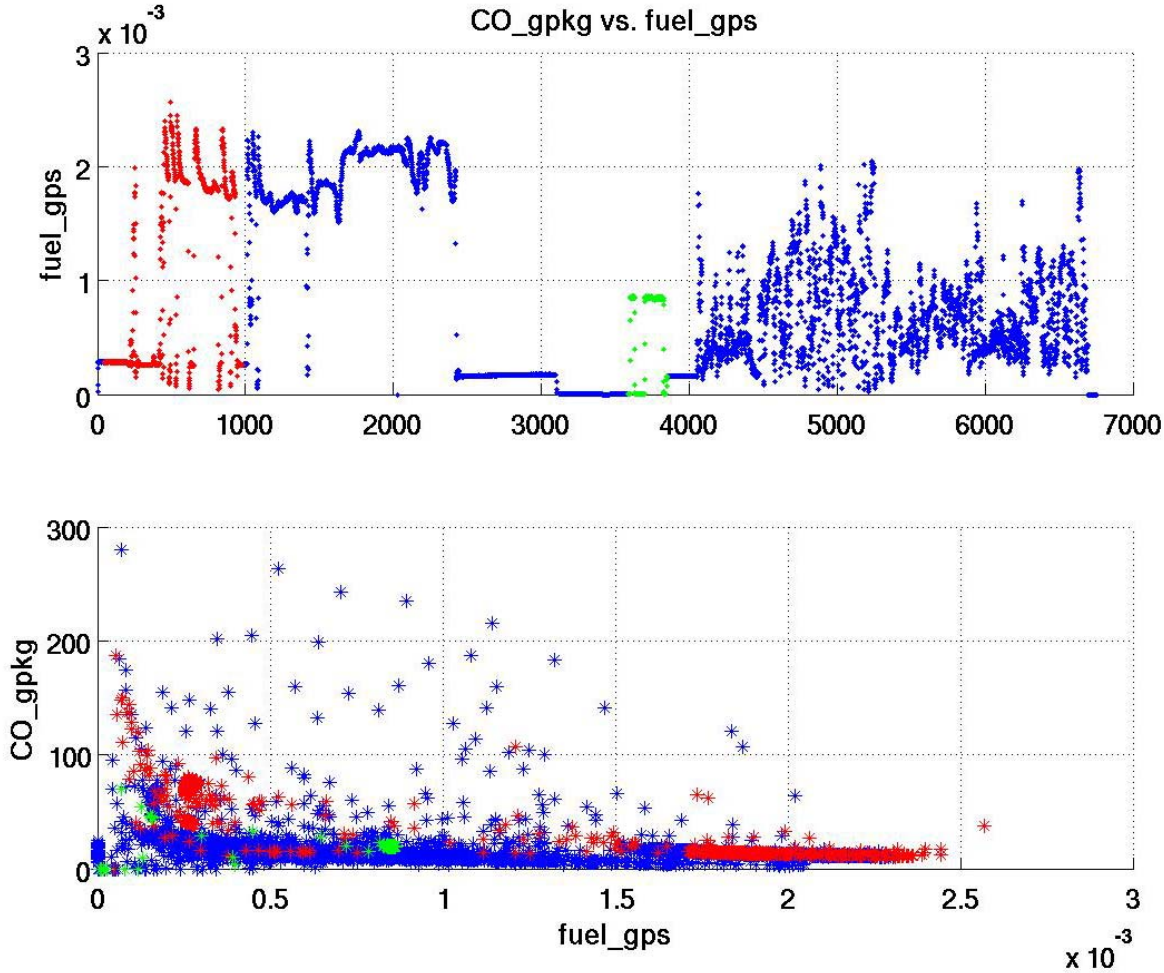

Figure 4-6 a) Fuel use, b) Fuel based CO mass emissions (grams CO / kilograms fuel) colored by time index

Cool down effects were also observed during some of the idling events in some tests. Figure 4-7 shows an example of fuel based emission rates during an idle event which followed a period of higher load activity during which the engine was running hot. During the idle event (seconds 3550 to 4150), the engine cools to a lower idling temperature, affecting some fuel based emission rates.

The interesting thing to note in the example in Figure 4-7 is that CO g/kg fuel and HC g/kg fuel increase during idle while NOx g/kg fuel decreases. The CO g/kg fuel rate increases by 50% (from roughly 40 g/kg fuel to 60 g/kg fuel) during the idle period while the NOx g/kg fuel rate decreases by 20% (from roughly 100 g/kg fuel to 80 g/kg fuel). The HC g/kg fuel rate increases by 25% (from roughly 20 g/kg fuel to 25 g/kg fuel). In this example, the fuel based emission rates seem to reach steady state values after roughly 500 seconds of idle.

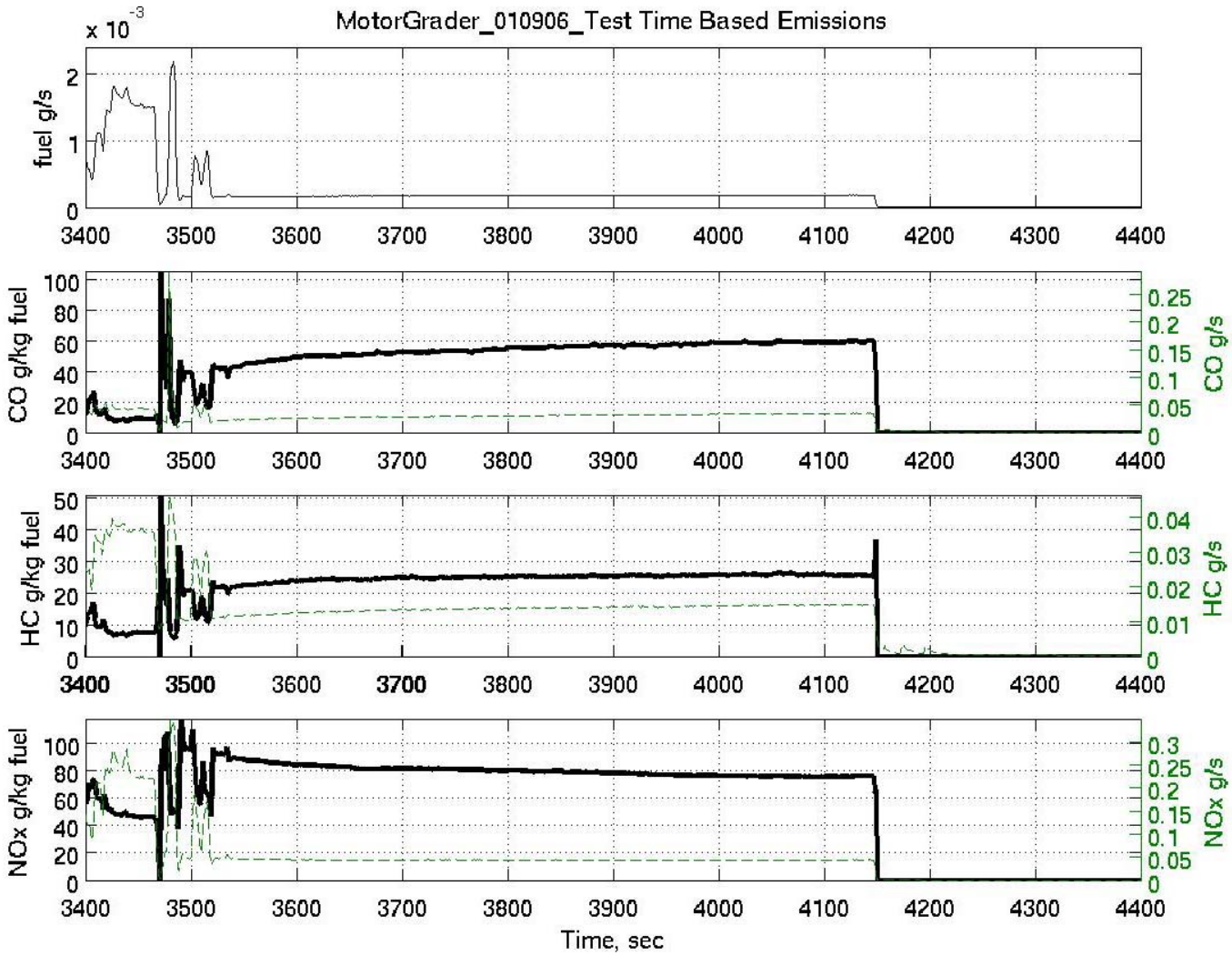

Figure 4-7 a) Fuel use, b-d) Fuel based mass emissions by time showing cool down effect

Histograms showing the frequencies of fuel based emission rates for all of the construction vehicle test data were created. These plots reflect not only the variance in fuel based emission factors throughout the cycle, but also the activity which were most frequent during the tests. An example of such a histogram is given in Figure 4-84-8 for the NO_x pollutant. Figure 4-84-8 shows several peaks, most notably around 45.6-53.8 g/kg, 66.1 g/kg and 82.5 g/kg. The peak around 45.6-53.8 g/kg correlates to conditions under load, the peak around 66.1 g/kg correlates to cold start idle and the peak around 82.5 g/kg correlates to hot idle.

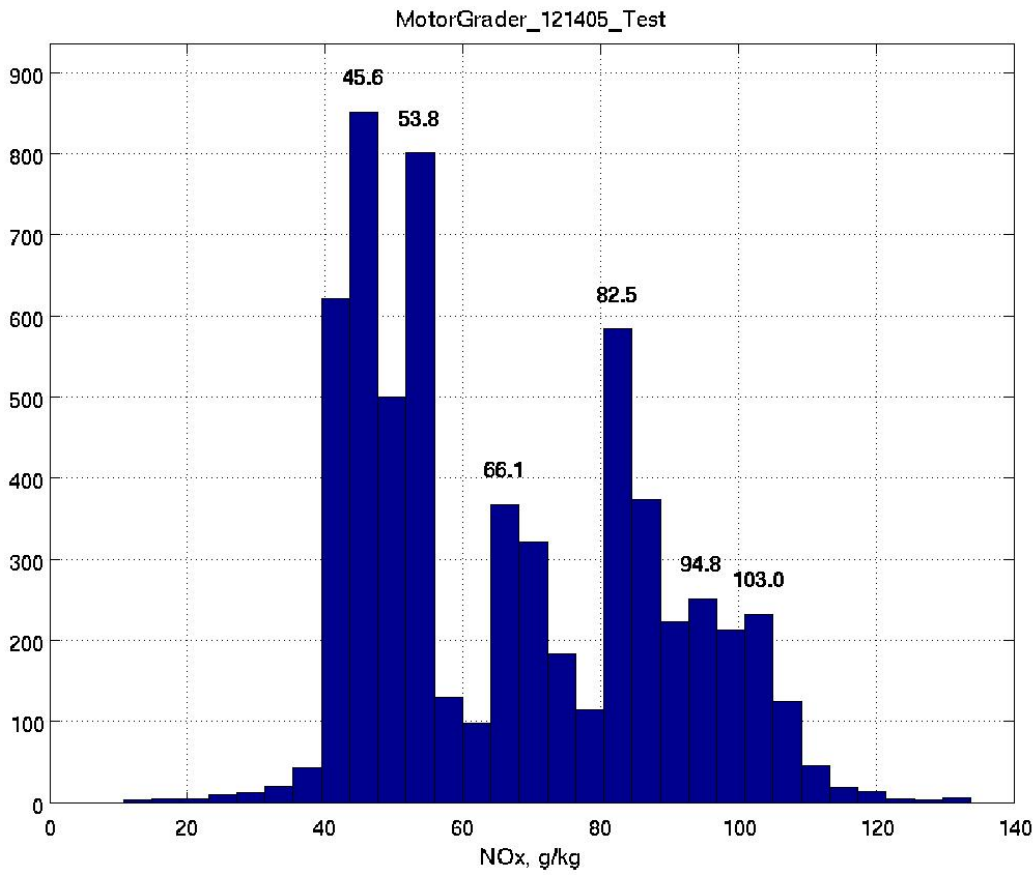

Figure 4-8 NOx emission factor frequency histogram

Modeling Methodology

The data analysis in the previous section demonstrates that fuel-specific emissions are generally higher at idle and level off under load. It was interesting to note that the fuel-specific emission rates did not change very much under different levels of load. This is also evident from other works (Frey, 2008) as shown in the example for NOx in Figure 4-9.

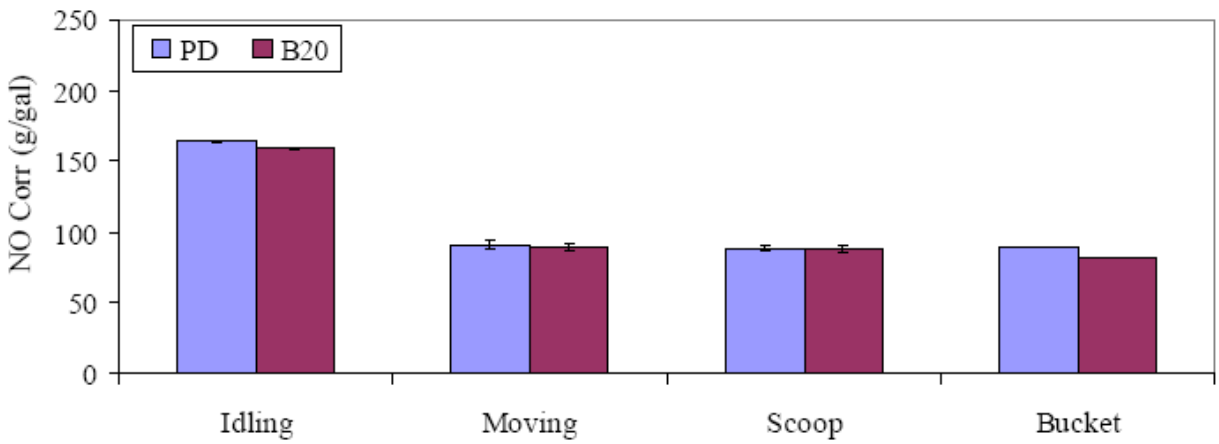

Figure 4-9 Fuel-specific NOx emission factors for different load levels for an example vehicle (from Frey 2008)

For this reason, we have developed a preliminary modeling framework for construction equipment emissions model based on two sets of fuel based emission factors, one for idle mode and one for loaded conditions.

The equipment categories that were created from the data collected and the *average* fuel specific emission factors during the testing are presented in

Table 4-1 (i.e., these factors include both idle and loaded conditions). These emission factors reflect the total construction vehicle activity that occurred during the test period for all pieces of equipment within a test group. Assuming that the machinery tested during this test period were operated in a typical fashion, these emission factors would be representative of typical emission factors for these construction vehicle categories.

	Average, grams emission / kg fuel			
	CO2	CO	HC	NOx
Motorgrader	3142.2	16.6	10.1	48.4
Loader	3132.2	15.7	6.2	43.6
Backhoe	3144.6	3.6	-	21.2
Dozer	3181.3	6.0	5.6	91.4
Excavator	3134.3	10.1	-	23.3
Scraper	3130.7	12.4	-	29.7
Compactor	3129.8	13.0	-	19.8

Table 4-1 Average fuel based emission factors for all test data by vehicle type

From the data analysis presented in the previous section, the idle and load modes were determined to be distinct in a number of tests for most emission species tested and for several construction vehicles. Therefore, we have broken out the emissions factors for these two modes.

Table 4-2 and

Table 4-3 present the emission factors for these two modes of operation for all the vehicle categories where they were able to be determined.

	Idle, grams emission / kg fuel			
	CO2	CO	HC	NOx
Motorgrader	3063.0	62.0	25.8	81.5
Loader	3203.0	9.5	10.0	79.0
Backhoe			-	
Dozer		21.0		
Excavator			-	8.0
Scraper	3135.0	10.0	-	15.0
Compactor			-	

Table 4-2 Fuel based emission rates during idle by vehicle type

	Load, grams emission / kg fuel			
	CO2	CO	HC	NOx
Motorgrader	3160.0	10.3	8.5	47.4
Loader	3190.0	9.4	6.2	48.1
Backhoe	3142.5	4.5	-	19.8
Dozer	3178.9	2.4	4.7	96.5
Excavator	3134.3	8.5	-	24.3
Scraper	3130.7	12.4	-	30.3
Compactor	3136.0	14.7	-	16.7

Table 4-3 Fuel based emission rates during load events by vehicle type

These fuel-based emission rate factors can be used in conjunction with information for fuel use to estimate the total mass of emissions, as shown in equation 4-2.

$$emission,\ g \quad = \quad \left[\frac{emission,\ g}{fuel\ \ use,\ kg}\right]_{base} \times \ fuel\ \ use,\ kg \qquad (4\text{-}2)$$

where

$\left[\frac{emission,\ g}{fuel\ use,\ kg}\right]_{base}$ is a fuel based mass emission factor

If fuel use is unknown, it can be estimated using fuel use activity factors that will be determined for various machine activities as shown in equation 4-3. These fuel use activity factors will be representative of typical machine activity for various types of construction machinery.

$$fuel\ use,\ g \quad = \quad duration\ \ of\ \ activity,\ h \times \left[\frac{fuel\ \ use,\ g}{duration\ \ of\ \ activity,\ h} \right] \qquad (4\text{-}3)$$

where

$duration\ \ of\ \ activity,\ h$ is the duration of the machine activity in hours

$\left[\frac{fuel\ use,\ g}{duration\ \ of\ \ activity,\ h} \right]$ is the ratio of fuel use in grams to the duration of machine activity in hours.

The model is set up in an Excel spreadsheet and can be used in one of two ways. The first application is used to calculate emissions given only fuel consumed in each construction vehicle category. For this calculation, fuel use is entered in cells C:9 through C:15 for each vehicle category as shown in Figure 4-10 and in yellow. Emission results are calculated based on the average fuel-specific emission factors as presented in Table 4-1 and in Figure 4-10. Estimated emission results in kilograms appear in cells C:20 through F:26 as seen in Figure 4-10 and in green for each construction vehicle category. Vehicle totals appear in the total line below the individual construction vehicle emission results. Emission results calculated in this manner assume that vehicle activity is similar to that found in the test vehicles for this project during the testing period.

	A	B	C	D	E	F	G	Q	R	S	T	U	V
1		**Construction Model**											
2													
3		**Constants**											
4		fuel density	kg/L	0.85									
5								**Emission Factors Average and by Mode**					
6		**Vehicle Fuel Use Input**						**Average**					
7			fuel use	idle time	load time				CO2/fuel	CO/fuel	HC/fuel	NOx/fuel	
8			gallons	percent	percent				g/kg	g/kg	g/kg	g/kg	
9		Motorgrader	25					Motorgrader	3142.20	16.56	10.11	48.35	
10		Loader	50					Loader	3132.21	15.74	6.23	43.63	
11		Backhoe	50					Backhoe	3144.57	3.58		21.19	
12		Dozer	5					Dozer	3181.26	5.97	5.57	91.44	
13		Excavator	12					Excavator	3134.29	10.11		23.32	
14		Scraper	15					Scraper	3130.65	12.43		29.65	
15		Compactor	21					Compactor	3129.78	12.98		19.75	
16													
17		**Output Using Average**						**Idle**					
18			CO2	CO	HC	NOx			CO2/fuel	CO/fuel	HC/fuel	NOx/fuel	
19			kg	kg	kg	kg			g/kg	g/kg	g/kg	g/kg	
20		Motorgrader	252.73	1.33	0.81	3.89		Motorgrader	3063.00	62.00	25.75	81.50	
21		Loader	503.86	2.53	1.00	7.02		Loader	3203.00	9.50	10.00	79.00	
22		Backhoe	505.84	0.58	0.00	3.41		Backhoe					
23		Dozer	51.17	0.10	0.09	1.47		Dozer		21.00			
24		Excavator	121.01	0.39	0.00	0.90		Excavator				8.00	
25		Scraper	151.08	0.60	0.00	1.43		Scraper	3135.00	10.00		15.00	
26		Compactor	211.45	0.88	0.00	1.33		Compactor					
27		Total	1797.1	6.4	1.9	19.5							
28													
29		**Output Using Mode**						**Load**					
30			CO2	CO	HC	NOx			CO2/fuel	CO/fuel	HC/fuel	NOx/fuel	
31			kg	kg	kg	kg			g/kg	g/kg	g/kg	g/kg	
32		Motorgrader	0.00	0.00	0.00	0.00		Motorgrader	3160.00	10.25	8.50	47.35	
33		Loader	0.00	0.00	0.00	0.00		Loader	3190.00	9.37	6.20	48.07	
34		Backhoe	0.00	0.00	0.00	0.00		Backhoe	3142.50	4.45		19.80	
35		Dozer	0.00	0.00	0.00	0.00		Dozer	3178.90	2.40	4.70	96.50	
36		Excavator	0.00	0.00	0.00	0.00		Excavator	3134.29	8.50		24.30	
37		Scraper	0.00	0.00	0.00	0.00		Scraper	3130.65	12.43		30.30	
38		Compactor	0.00	0.00	0.00	0.00		Compactor	3136.00	14.70		16.70	
39		Total	0.00	0.00	0.00	0.00							
40													

Figure 4-10 Spreadsheet Construction Model for Fuel Use not Specified by Mode

The second application of the spreadsheet model is useful when the fraction of time under idle and load are known. For this application, in addition to the fuel use inputs for each construction vehicle category from the first application, the percent of time during idle and load are entered in cells D:9 through E:15 as shown in Figure 4-11 and Figure 4-12. If the percent time in idle and load is greater than 100, then this fact will be highlighted in the spreadsheet in the adjacent cell as seen in Figure 4-11.

Vehicle Fuel Use Input				
	fuel use	idle time	load time	
	gallons	percent	percent	error
Motorgrader	25	2	98	100
Loader	50	5	95	100
Backhoe	50	10	92	102
Dozer	5	10	90	100
Excavator	12	14	86	100
Scraper	15	5	95	100
Compactor	21	6	94	100

Figure 4-11 Fuel Use Input

The spreadsheet uses the fuel and fraction of time breakdown information to estimate fuel use during each mode. Using the idle and load emission factors presented in Table 4-2 and 4-3 as well as Figure 4-12, idle and load emissions are calculated, aggregated and presented in cells C:31 through F:37 in green as seen in Figure 4-12. Totals for the emission results using mode specified emission factors are presented in cells B:38 through F:38 in Figure 4-12, the line below the individual vehicle results. For the second application, both the emissions using the average emission factors and the emissions using mode information are calculated.

Construction Model

Constants

fuel density	kg/L	0.85

Vehicle Fuel Use Input

	fuel use gallons	idle time percent	load time percent	error
Motorgrader	25	2	98	100
Loader	50	5	95	100
Backhoe	50	8	92	100
Dozer	5	10	90	100
Excavator	12	14	86	100
Scraper	15	5	95	100
Compactor	21	6	94	100

Output Using Average

	CO2 kg	CO kg	HC kg	NOx kg
Motorgrader	252.73	1.33	0.81	3.89
Loader	503.86	2.53	1.00	7.02
Backhoe	505.84	0.58	0.00	3.41
Dozer	51.17	0.10	0.09	1.47
Excavator	121.01	0.39	0.00	0.90
Scraper	151.08	0.60	0.00	1.43
Compactor	211.45	0.88	0.00	1.33
Total	1797.1	6.4	1.9	19.5

Output Using Mode

	CO2 kg	CO kg	HC kg	NOx kg
Motorgrader	254.01	0.91	0.71	3.86
Loader	513.26	1.51	1.03	7.98
Backhoe	465.07	0.66	0.00	2.93
Dozer	46.02	0.07	0.07	1.40
Excavator	104.06	0.28	0.00	0.85
Scraper	151.09	0.59	0.00	1.43
Compactor	199.16	0.93	0.00	1.06
Total	1732.67	4.95	1.81	19.51

Emission Factors Average and by Mode

Average

	CO2/fuel g/kg	CO/fuel g/kg	HC/fuel g/kg	NOx/fuel g/kg
Motorgrader	3142.20	16.56	10.11	48.35
Loader	3132.21	15.74	6.23	43.63
Backhoe	3144.57	3.58		21.19
Dozer	3181.26	5.97	5.57	91.44
Excavator	3134.29	10.11		23.32
Scraper	3130.65	12.43		29.65
Compactor	3129.78	12.98		19.75

Idle

	CO2/fuel g/kg	CO/fuel g/kg	HC/fuel g/kg	NOx/fuel g/kg
Motorgrader	3063.00	62.00	25.75	81.50
Loader	3203.00	9.50	10.00	79.00
Backhoe				
Dozer		21.00		
Excavator				8.00
Scraper	3135.00	10.00		15.00
Compactor				

Load

	CO2/fuel g/kg	CO/fuel g/kg	HC/fuel g/kg	NOx/fuel g/kg
Motorgrader	3160.00	10.25	8.50	47.35
Loader	3190.00	9.37	6.20	48.07
Backhoe	3142.50	4.45		19.80
Dozer	3178.90	2.40	4.70	96.50
Excavator	3134.29	8.50		24.30
Scraper	3130.65	12.43		30.30
Compactor	3136.00	14.70		16.70

Figure 4-12 Spreadsheet Construction Model for Fuel Use with Mode Specification

5.0 Summary and Conclusions

This research program was focused on construction equipment emissions testing and development of an initial emissions model for construction equipment based on these in-use emissions measurements. The two key activities included: 1) in-field emissions and activity measurements; and 2) model development and validation. The emissions measurements were made on a second-by-second basis using a portable emissions measurement system (PEMS) to develop relationships between pollutant emissions and fuel use. These emissions data were subsequently used in the development of a model that allows the determination of emissions from different pieces of construction equipment or for construction projects as a whole. The model developed is a spreadsheet-based, user-friendly program that can be readily deployed by program staff at Caltrans, outside contractors or other government agencies.

In total, emissions measurements were made for 12 in-use pieces of construction equipment. These included applications from the Caltrans maintenance yards as well as equipment from a contractor site for highway construction. The equipment included a range of applications including front loaders, motor graders, scrapers, and other pieces of equipment.

Key findings thus far include:

- Most construction equipment (of the approximate same size) exhibited similar emission profiles, however their activity differed somewhat;

- There were differences observed between cold-start and warm-start idle emissions among the different equipment;

- Normalizing emission output by fuel results in relatively small variations in emission levels under different levels of load.

This phase of the research program primarily focused on NOx emissions, along with CO and HC for some of the equipment. A second phase of work is currently underway to measure and model particulate matter (PM) from similar construction equipment. Once the PM measurements and model are complete, these will be integrated into the current model described in Section 4. Once this second phase is complete, it is expected that this model will facilitate the process for approving and characterizing a variety of construction projects across the state.

6.0 References

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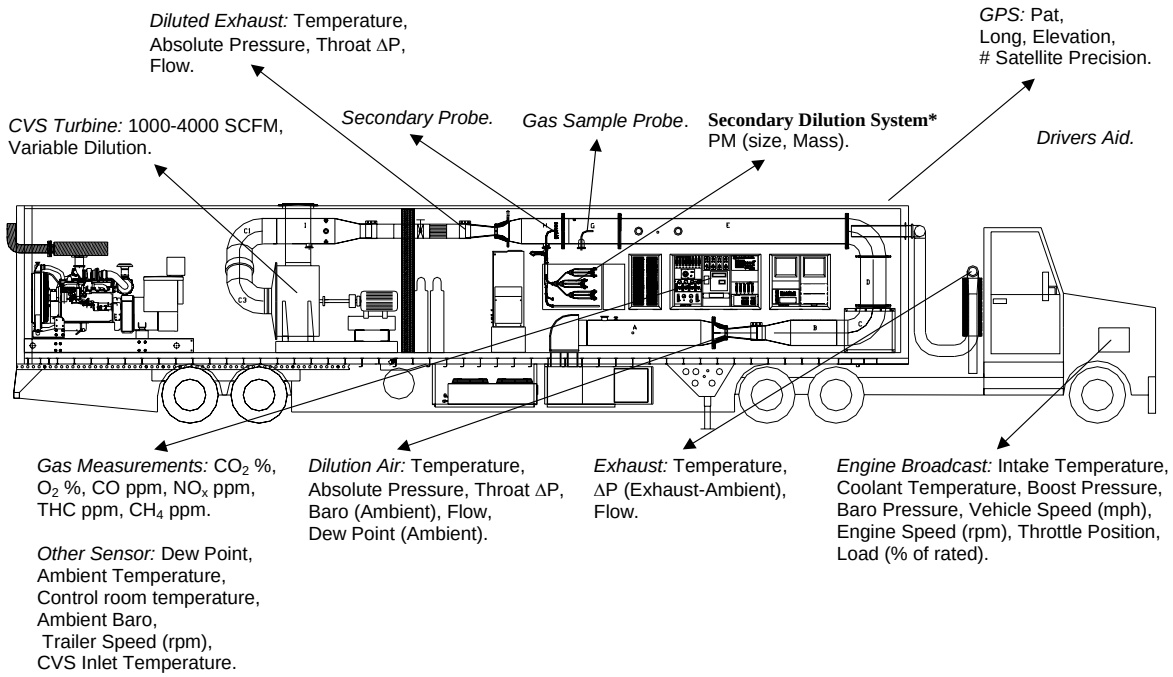
Appendix A – Background Information on UCR's Mobile Emission Lab

Extensive detail is provided in Reference 1; so this section is provided for those that may not have access to that reference. Basically the mobile emissions lab (MEL) consists of a number of operating systems that are typically found in a stationary lab. However the MEL lab is on wheels instead of concrete. A schematic of MEL and its major subsystems is shown in the figure below. Some description follows.



Major Systems within the Mobile Emission Lab

The primary dilution system is configured as a full-flow constant volume sampling (CVS) system with a smooth approach orifice (SAO) venturi and dynamic flow controller. The SAO venturi has the advantage of no moving parts and repeatable accuracy at high throughput with low-pressure drop. As opposed to traditional dilution tunnels with a positive displacement pump or a critical flow orifice, the SAO system with dynamic flow control eliminates the need for a heat exchanger. Tunnel flow rate is adjustable from 1000 to 4000 scfm with accuracy of 0.5% of full scale. It is capable of total exhaust capture for engines up to 600kW. Colorado Engineering Experiment Station Inc. initially calibrated the flow rate through both SAOs for the primary tunnel.

The mobile laboratory contains a suite of gas-phase analyzers on shock-mounted benches. The gas-phase analytical instruments measure NO_x, methane (CH_4), total hydrocarbons (THC), CO, and CO_2 at a frequency of 10 Hz and were selected based on optimum response time and on road stability. The 200-L Tedlar bags are used to collect tunnel and dilution air samples over a complete test cycle. A total of eight bags are suspended in the MEL allowing four test cycles to

be performed between analyses. Filling of the bags is automated with Lab View 7.0 software (National Instruments, Austin, TX). A summary of the analytical instrumentation used, their ranges, and principles of operation is provided in the table below. Each modal analyzer is time-corrected for tunnel, sample line, and analyzer delay time.

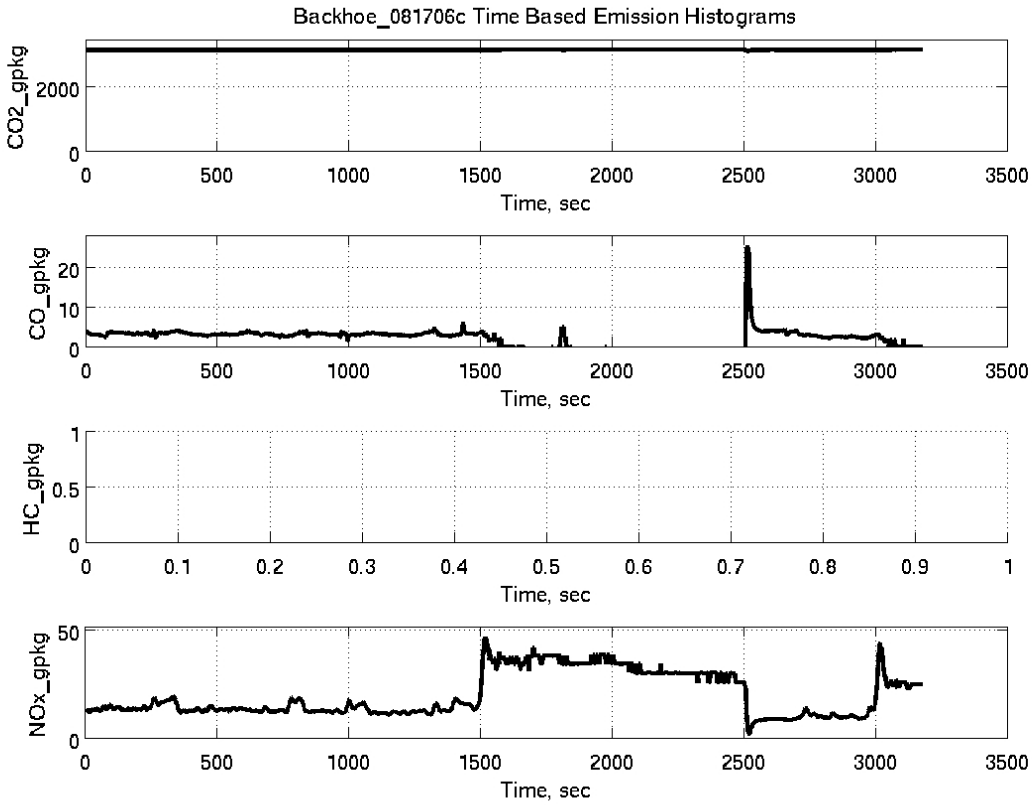
Gas Component	Range	Monitoring Method
NO_x	10/30/100/300/1000 (ppm)	Chemiluminescence
CO	50/200/1000/3000 (ppm)	NDIR
CO_2	0.5/2/8/16 (%)	NDIR
THC	10/30/100/300/1000 & 5000 (ppmC)	Heated FID
CH4	30/100/300/1000 (ppmC)	FID

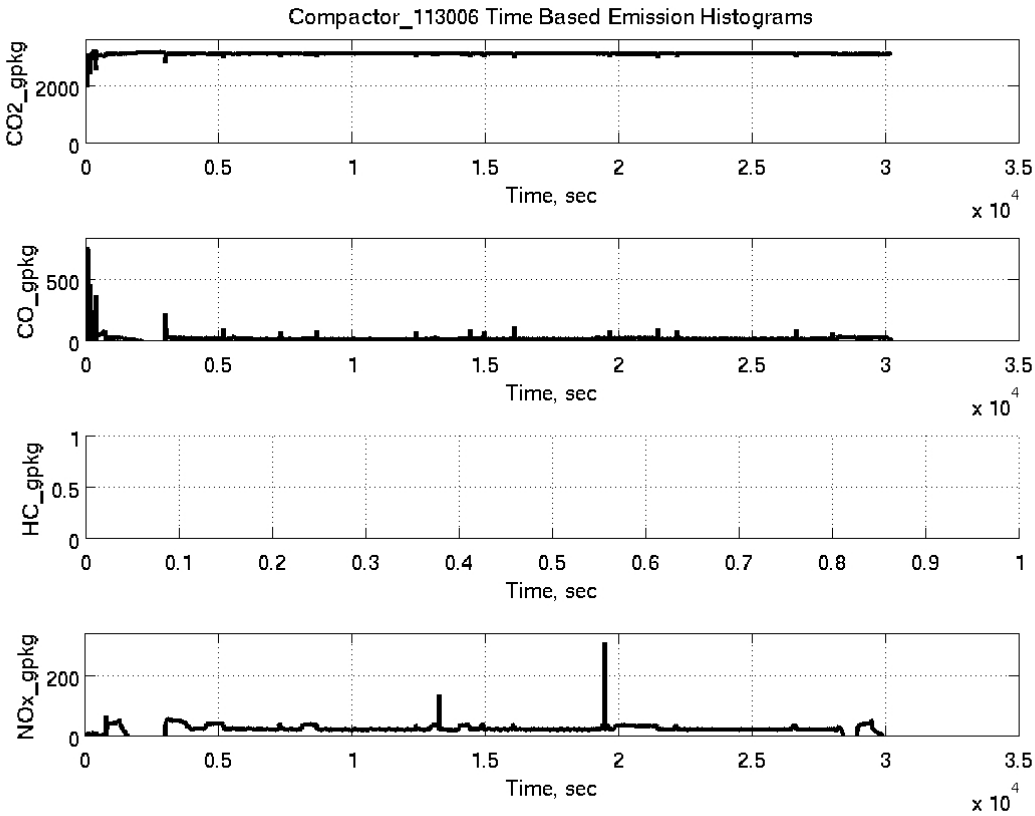
Summary of gas-phase instrumentation in MEL

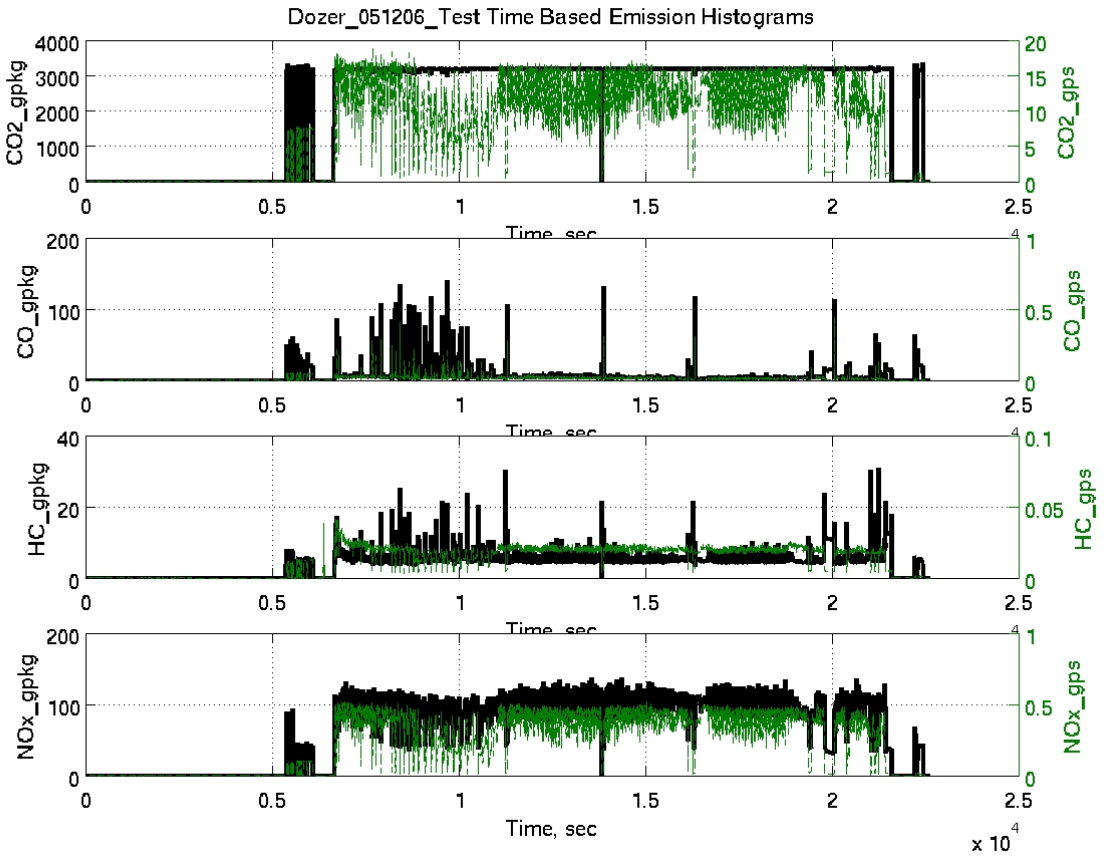
The real-time data are presented for each test on each vehicle, in order of ascending vehicle age. In the real-time data, the first ~700 seconds of steady state driving is on the SR-99. The next 200 seconds of driving in the 40 mph range represent the second segment of driving. The segment from 900 to 1300 seconds at speeds of 55 mph and higher is on the I-5. The final 1000 seconds is the driving on surface streets on Hammer Road.

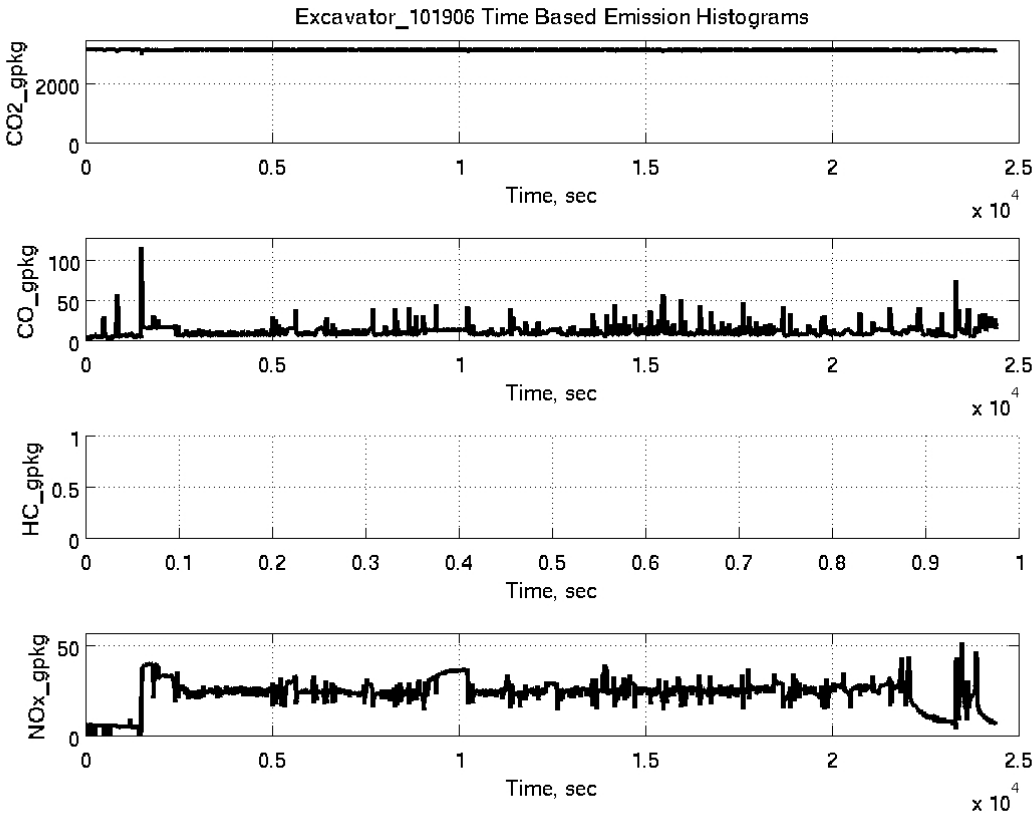
Appendix B – Real-Time Emissions for Construction Equipment

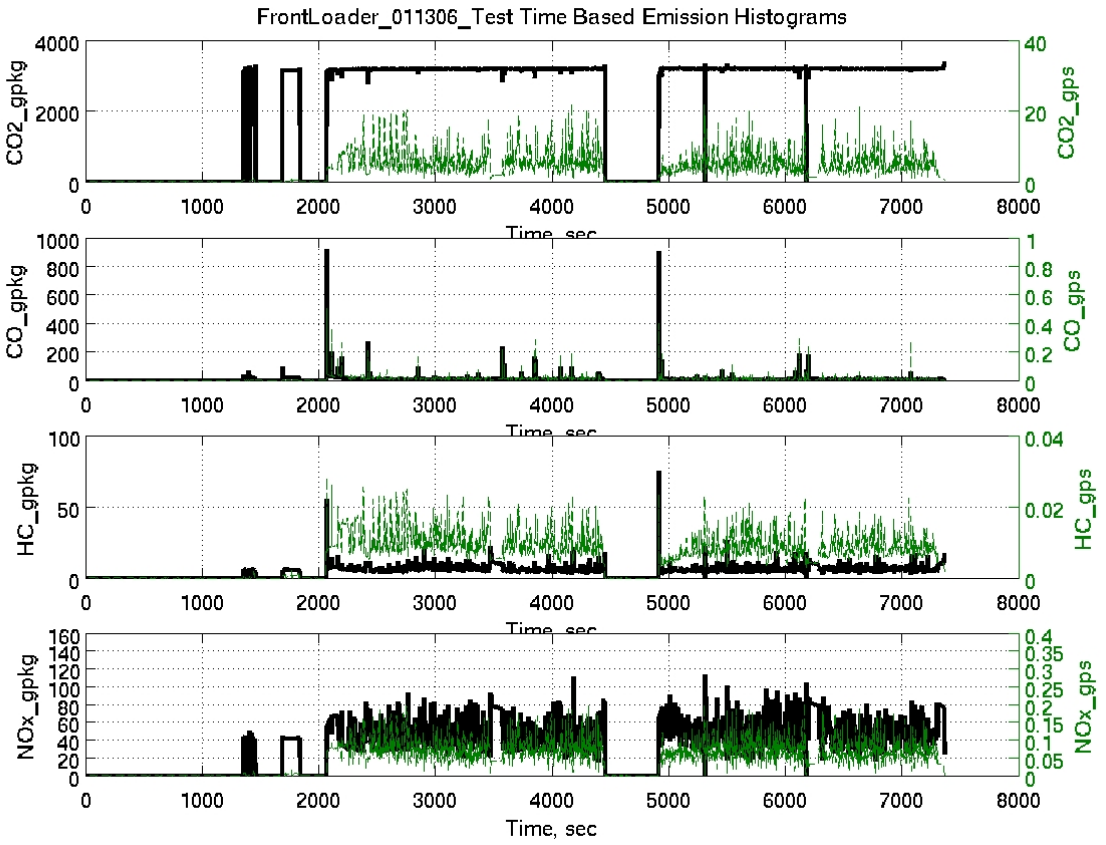
The following figure present real-time emissions for the construction equipment tested under this project. Data is presented either in units of grams of emission per kilogram of fuel abbreviated as gpkg, in grams emission per second abbreviated as gps or both. The axes are color coded corresponding with the data.

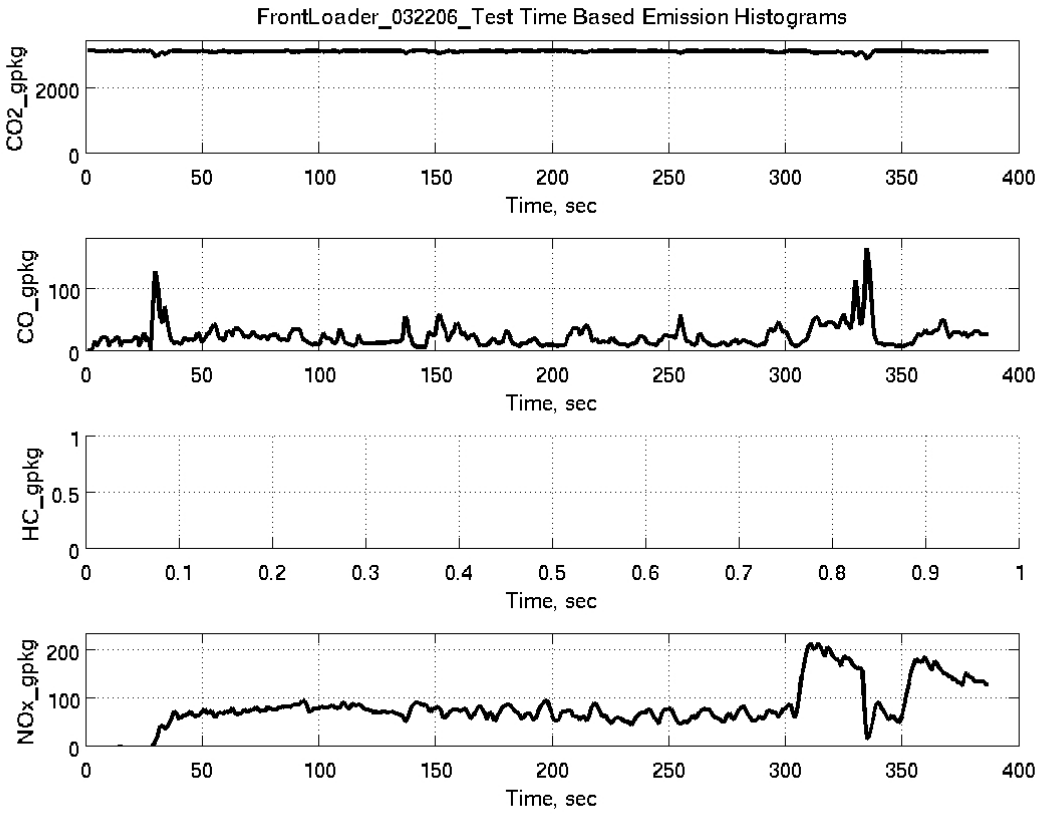


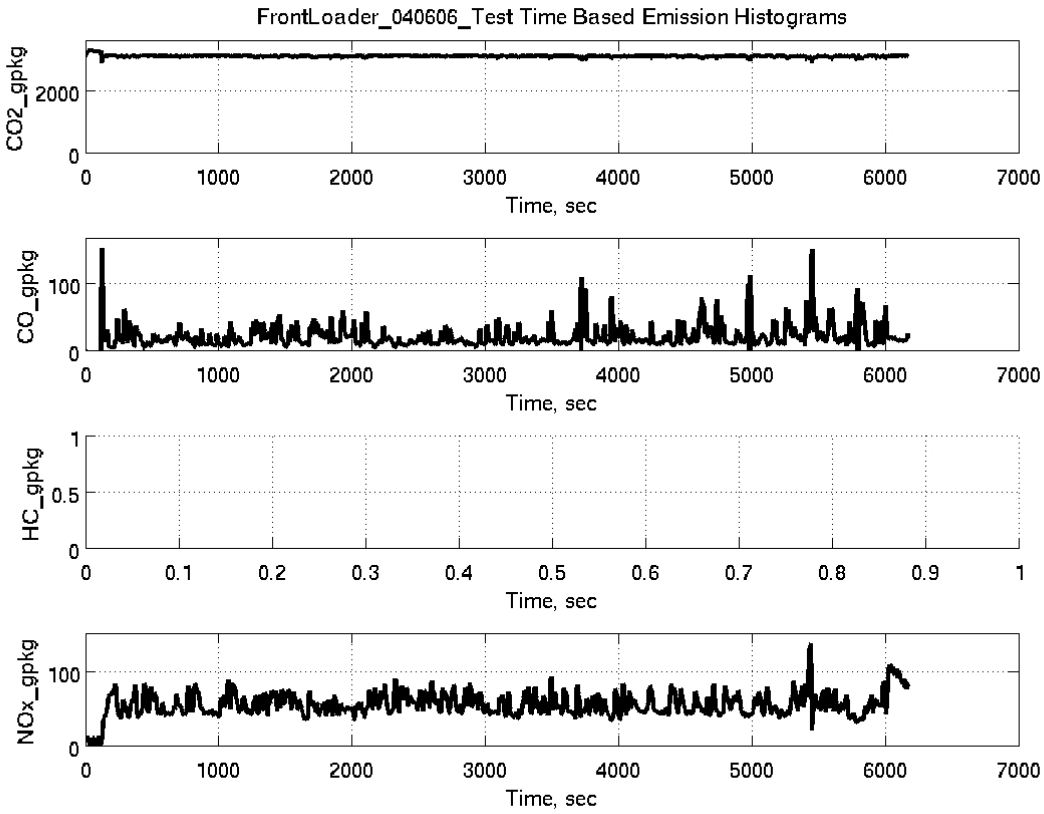

Compactor_113006 Time Based Emission Histograms
CO2_gpkg
2000
0
0
0.5
1
1.5
2
2.5
3
3.5
Time, sec
x 10^4
CO_gpkg
500
0
0
0.5
1
1.5
2
2.5
3
3.5
Time, sec
x 10^4
HC_gpkg
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, sec
NOx_gpkg
200
0
0
0.5
1
1.5
2
2.5
3
3.5
Time, sec
x 10^4

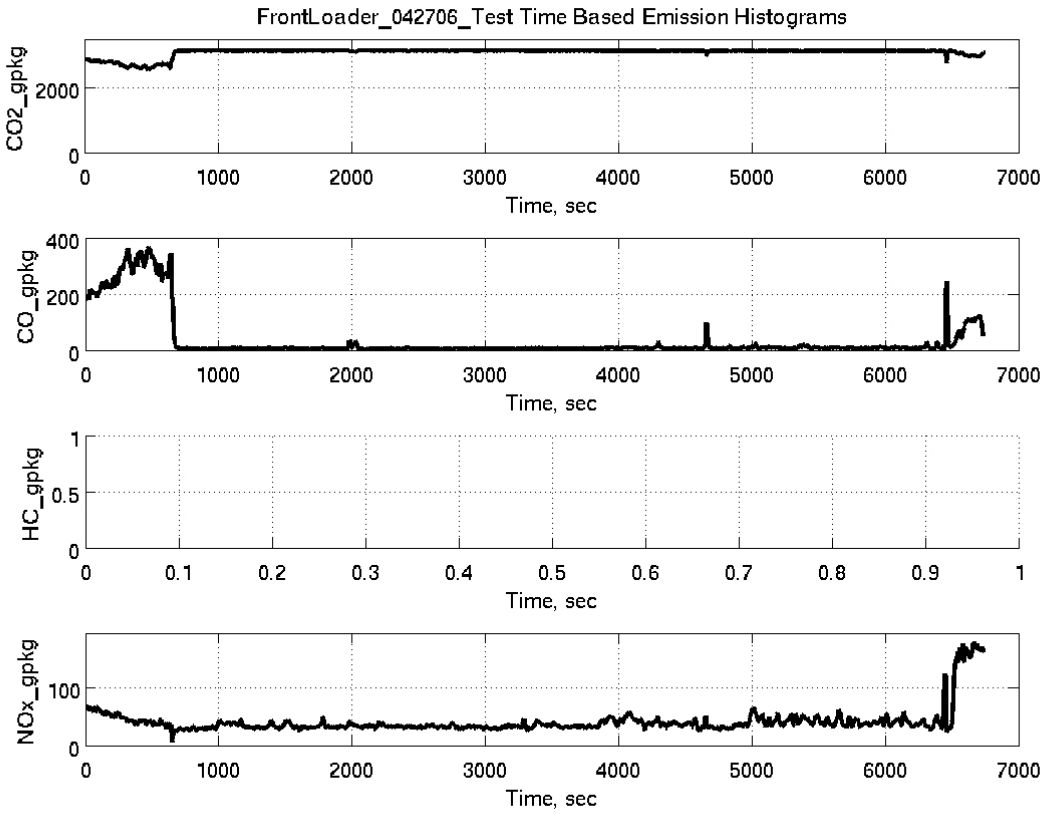

Dozer_051206_Test Time Based Emission Histograms
CO2_gpkg
CO2_gps
CO_gpkg
CO_gps
HC_gpkg
HC_gps
NOx_gpkg
NOx_gps
Time, sec
x 10^4

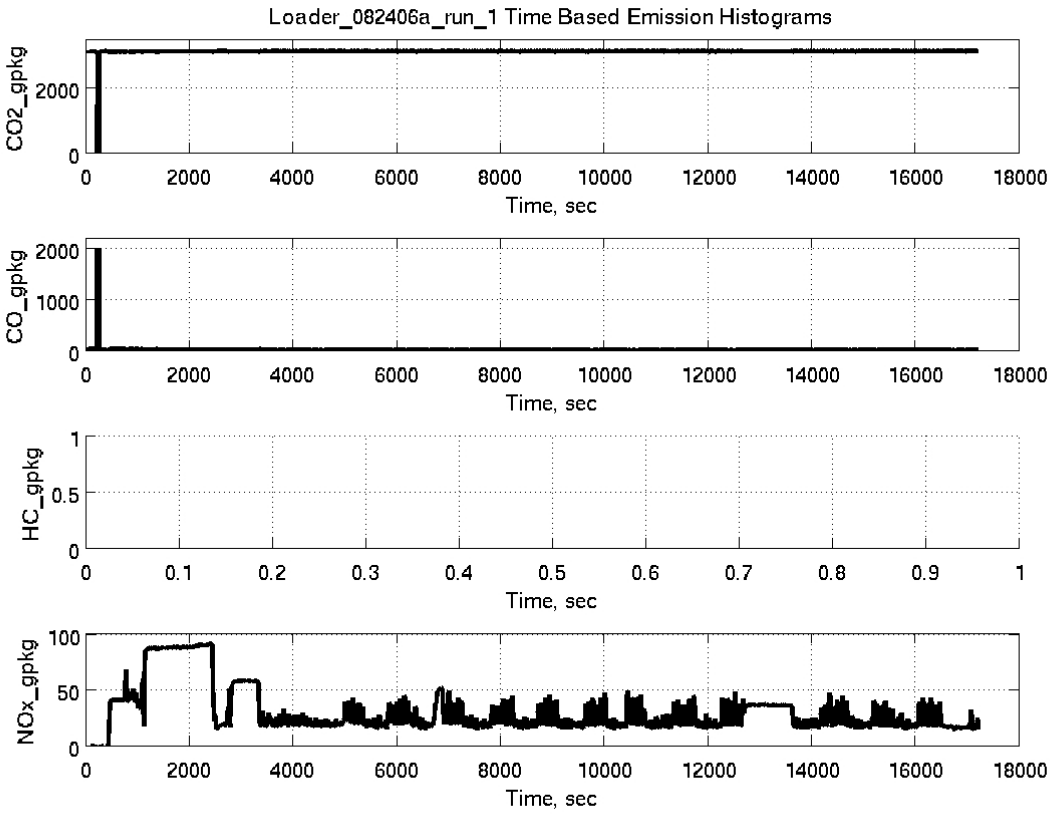

Excavator_101906 Time Based Emission Histograms
CO2_gpkg
2000
0
0
0.5
1
1.5
2
2.5
Time, sec
x 10^4
CO_gpkg
100
50
0
0
0.5
1
1.5
2
2.5
Time, sec
x 10^4
HC_gpkg
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, sec
NOx_gpkg
50
0
0
0.5
1
1.5
2
2.5
Time, sec
x 10^4

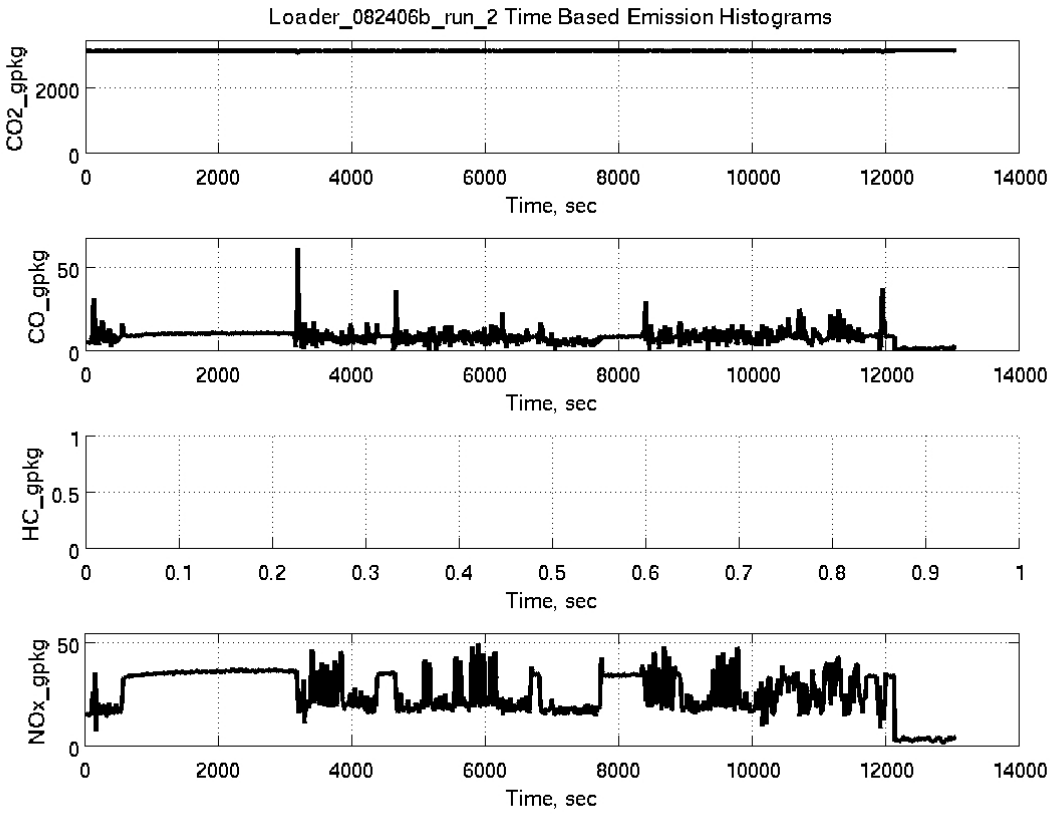

FrontLoader_011306_Test Time Based Emission Histograms
CO2_gpkg
CO2_gps
CO_gpkg
CO_gps
HC_gpkg
HC_gps
NOx_gpkg
NOx_gps
Time, sec

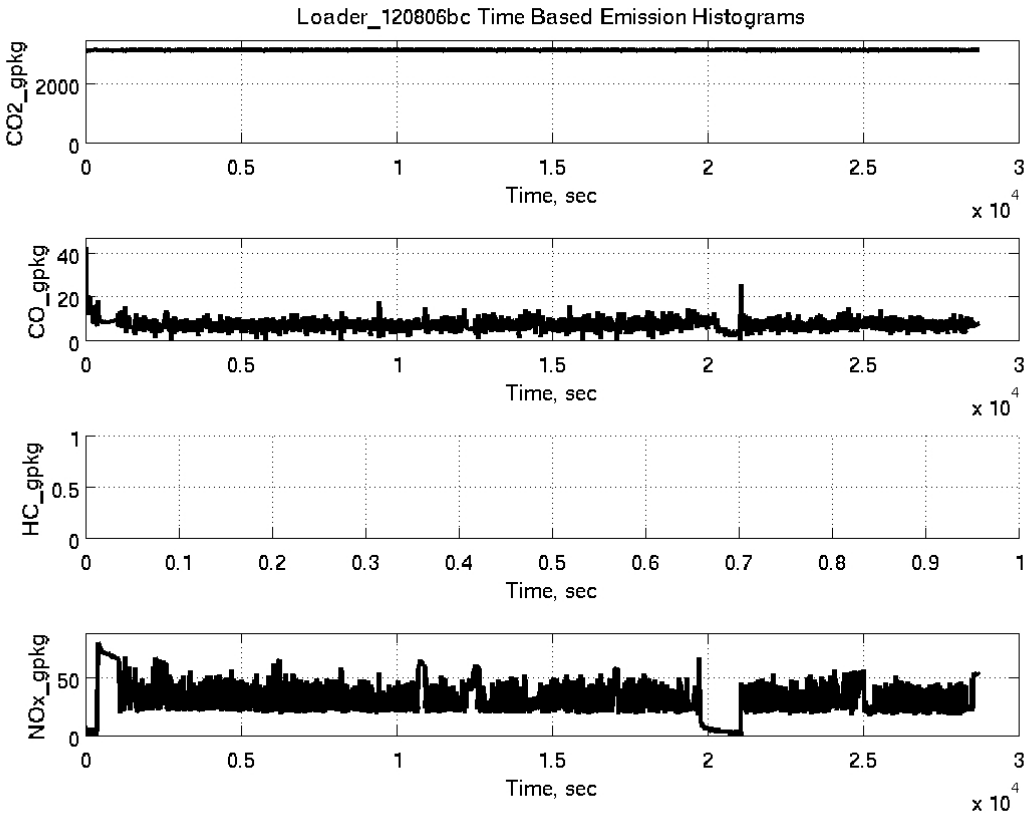

FrontLoader_032206_Test Time Based Emission Histograms
CO2_gpkg
2000
0
0
50
100
150
200
250
300
350
400
Time, sec
CO_gpkg
100
0
0
50
100
150
200
250
300
350
400
Time, sec
HC_gpkg
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, sec
NOx_gpkg
200
100
0
0
50
100
150
200
250
300
350
400
Time, sec

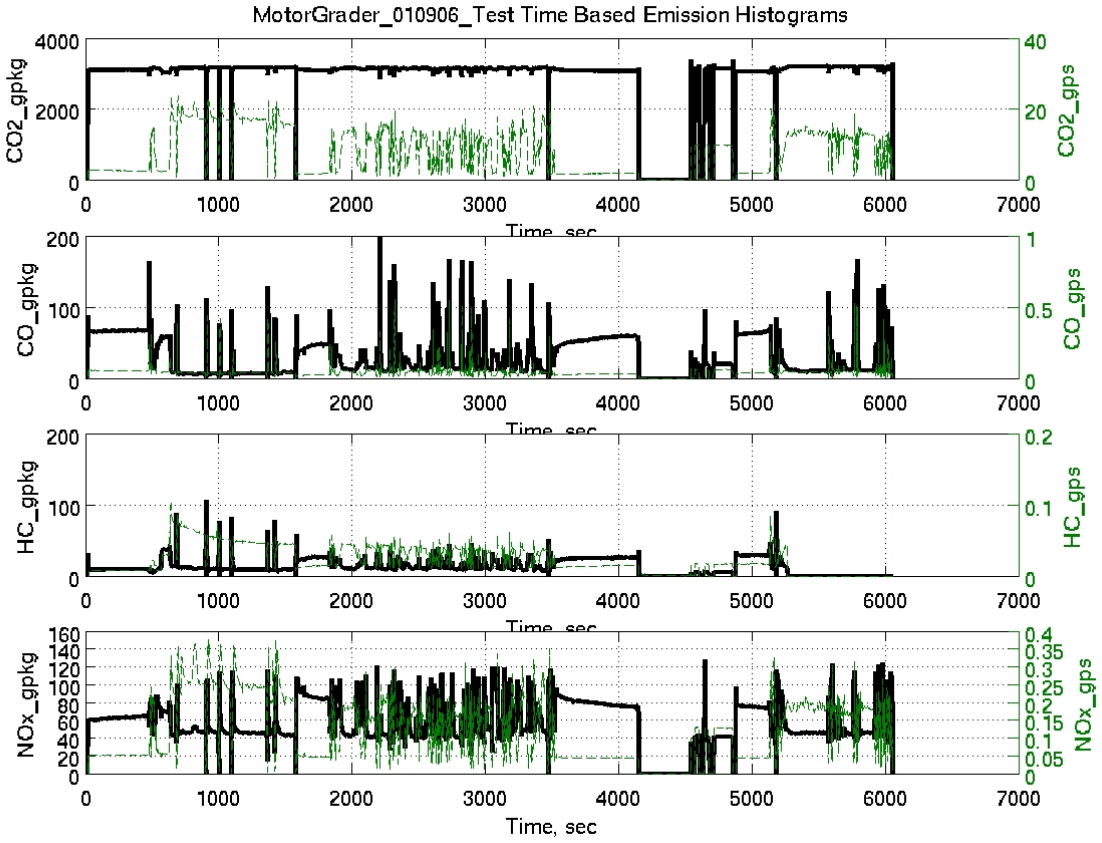

FrontLoader_040606_Test Time Based Emission Histograms
CO2_gpkg
2000
0
0
1000
2000
3000
4000
5000
6000
7000
Time, sec
CO_gpkg
100
0
0
1000
2000
3000
4000
5000
6000
7000
Time, sec
HC_gpkg
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, sec
NOx_gpkg
100
0
0
1000
2000
3000
4000
5000
6000
7000
Time, sec

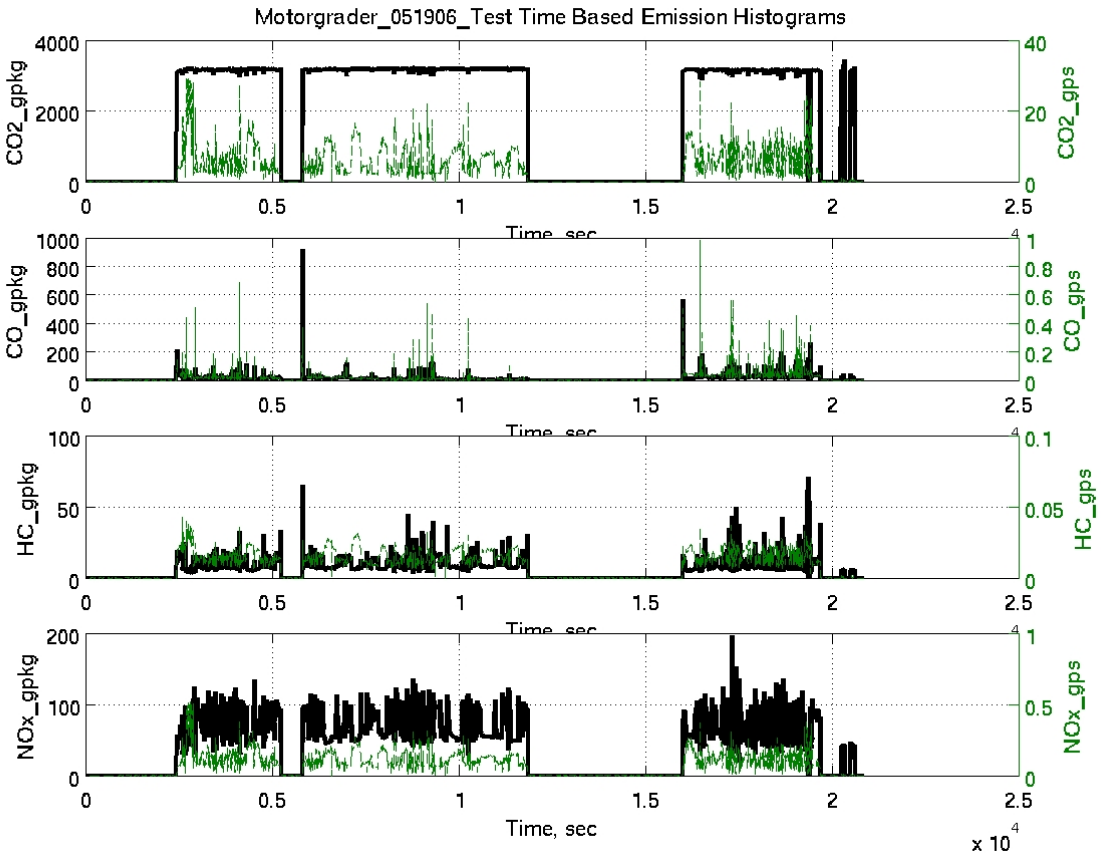

FrontLoader_042706_Test Time Based Emission Histograms
CO2_gpkg
2000
0
0
1000
2000
3000
4000
5000
6000
7000
Time, sec
CO_gpkg
400
200
0
0
1000
2000
3000
4000
5000
6000
7000
Time, sec
HC_gpkg
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, sec
NOx_gpkg
100
0
0
1000
2000
3000
4000
5000
6000
7000
Time, sec

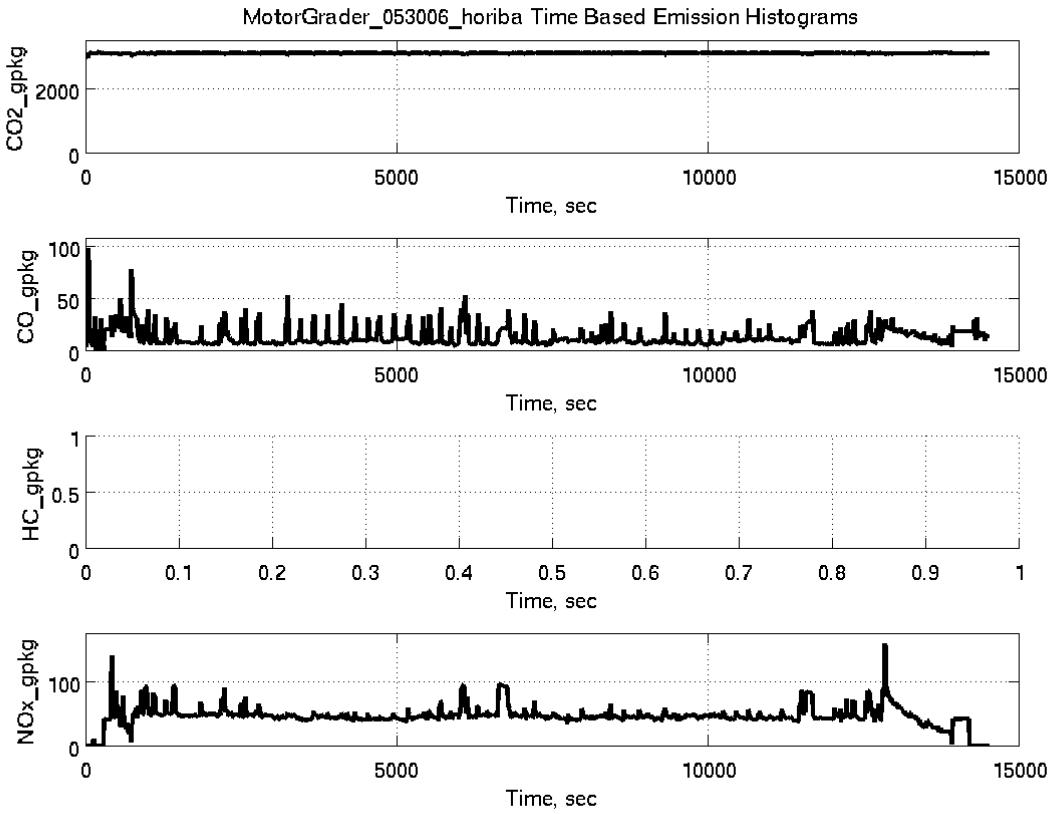

Loader_082406a_run_1 Time Based Emission Histograms
CO2_gpkg
2000
0
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Time, sec
CO_gpkg
2000
1000
0
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Time, sec
HC_gpkg
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, sec
NOx_gpkg
100
50
0
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Time, sec

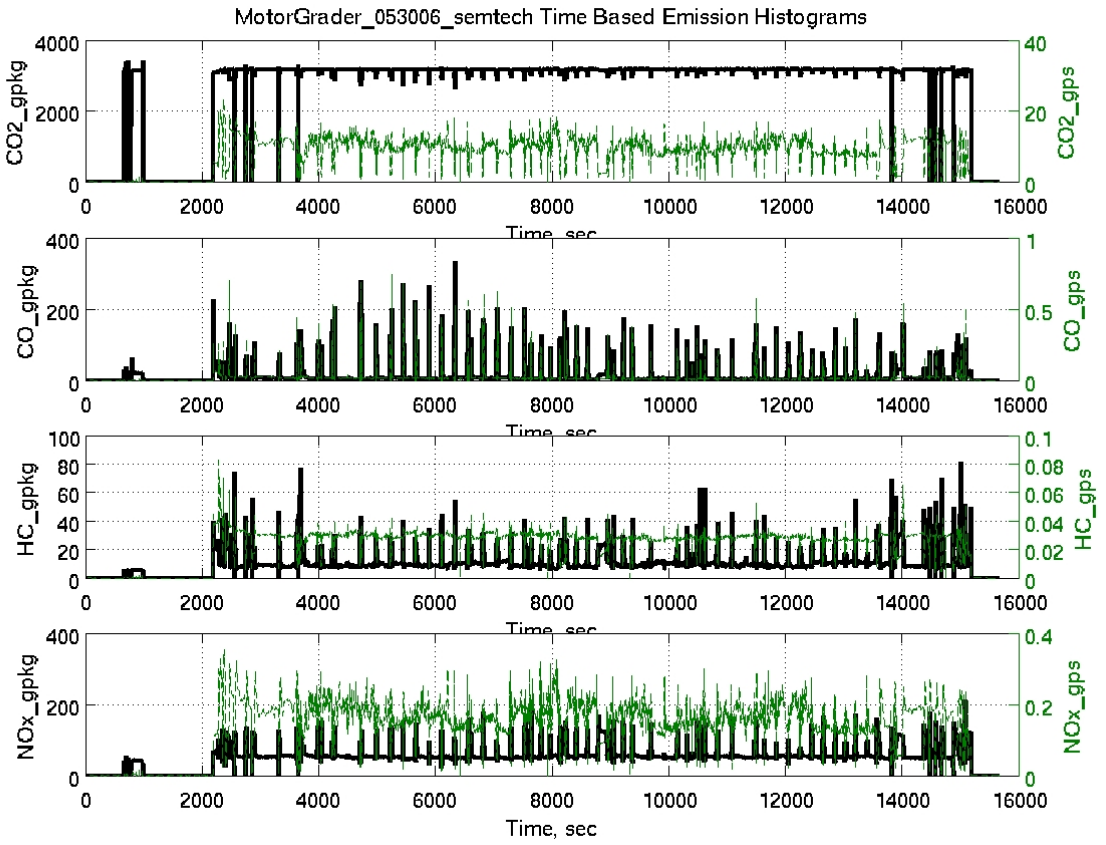

Loader_082406b_run_2 Time Based Emission Histograms
CO2_gpkg
2000
0
0
2000
4000
6000
8000
10000
12000
14000
Time, sec
CO_gpkg
50
0
0
2000
4000
6000
8000
10000
12000
14000
Time, sec
HC_gpkg
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, sec
NOx_gpkg
50
0
0
2000
4000
6000
8000
10000
12000
14000
Time, sec

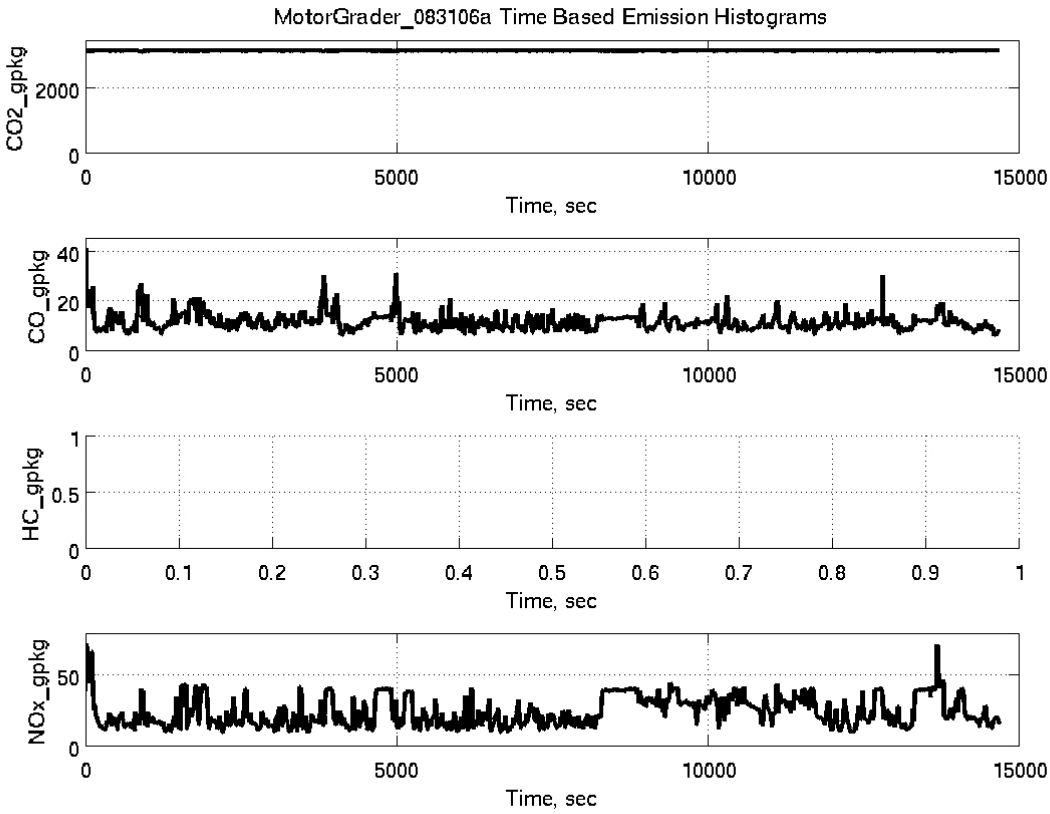

Loader_120806bc Time Based Emission Histograms
CO2_gpkg
2000
0
0
0.5
1
1.5
2
2.5
3
Time, sec
x 10^4
CO_gpkg
40
20
0
0
0.5
1
1.5
2
2.5
3
Time, sec
x 10^4
HC_gpkg
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, sec
NOx_gpkg
50
0
0
0.5
1
1.5
2
2.5
3
Time, sec
x 10^4

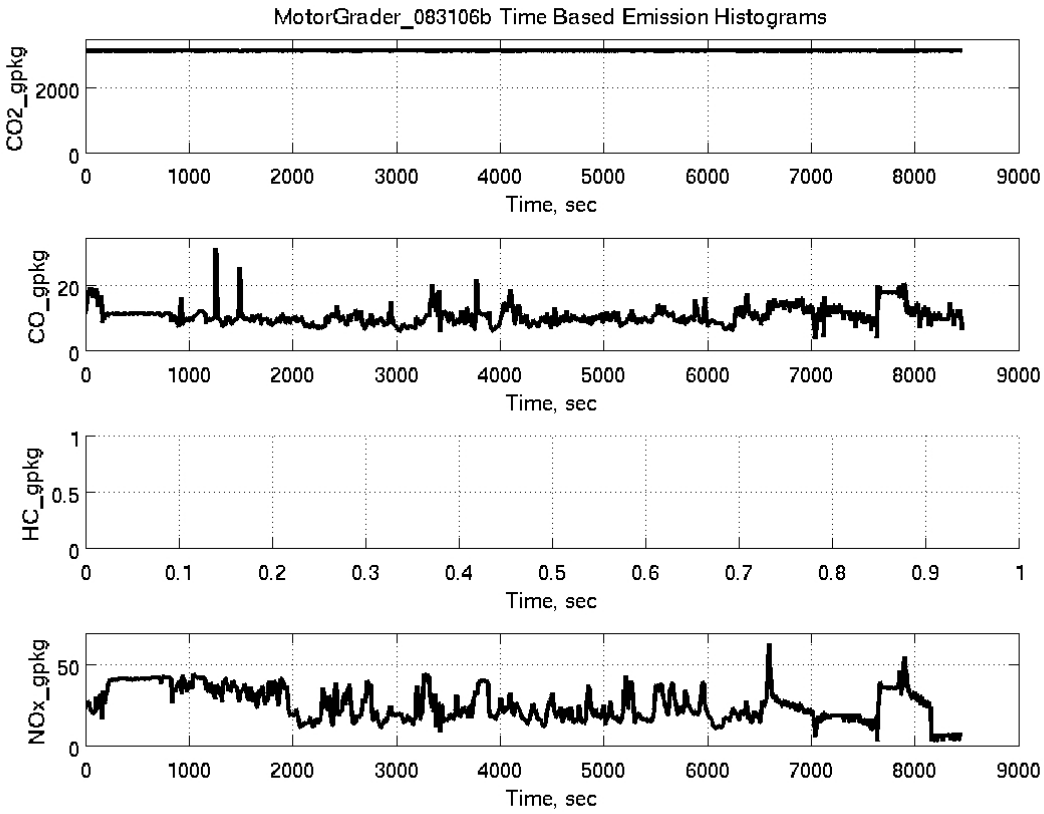

MotorGrader_010906_Test Time Based Emission Histograms
CO2_gpkg
CO2_gps
CO_gpkg
CO_gps
HC_gpkg
HC_gps
NOx_gpkg
NOx_gps
Time, sec

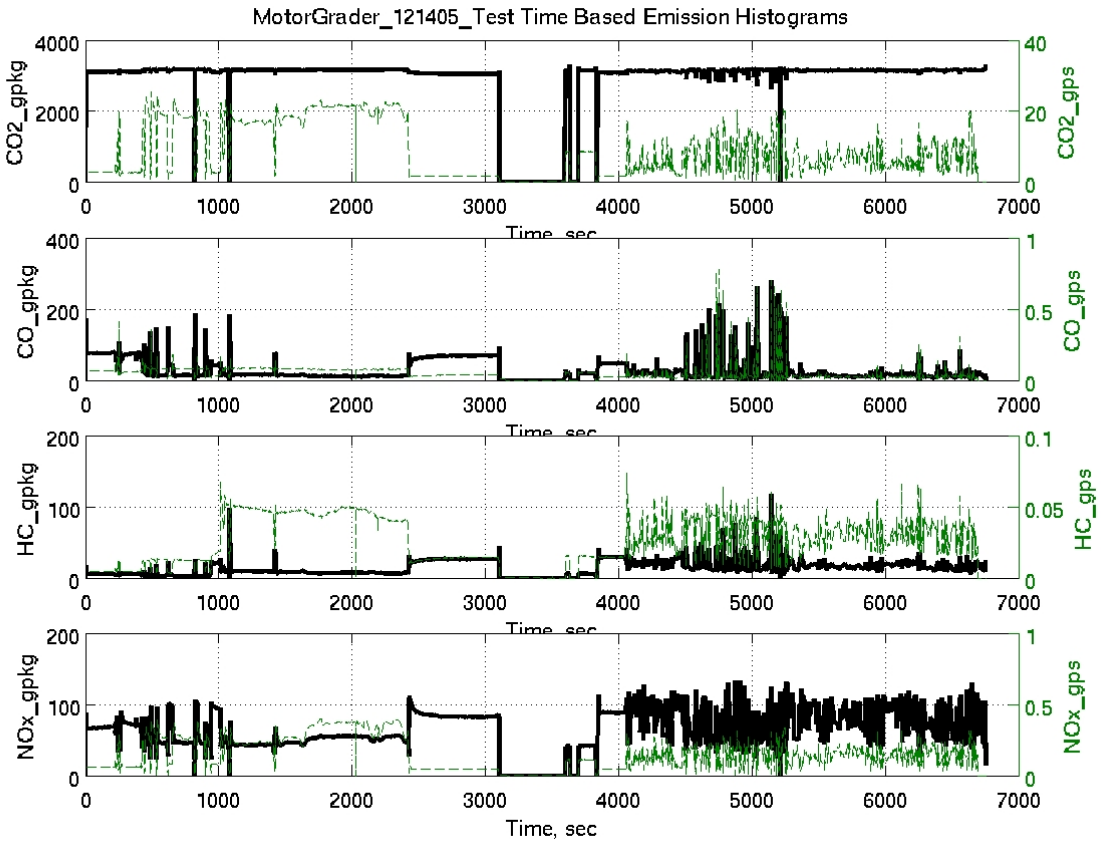

Motorgrader_051906_Test Time Based Emission Histograms
CO2_gpkg
CO2_gps
CO_gpkg
CO_gps
HC_gpkg
HC_gps
NOx_gpkg
NOx_gps
Time, sec
x 10^4

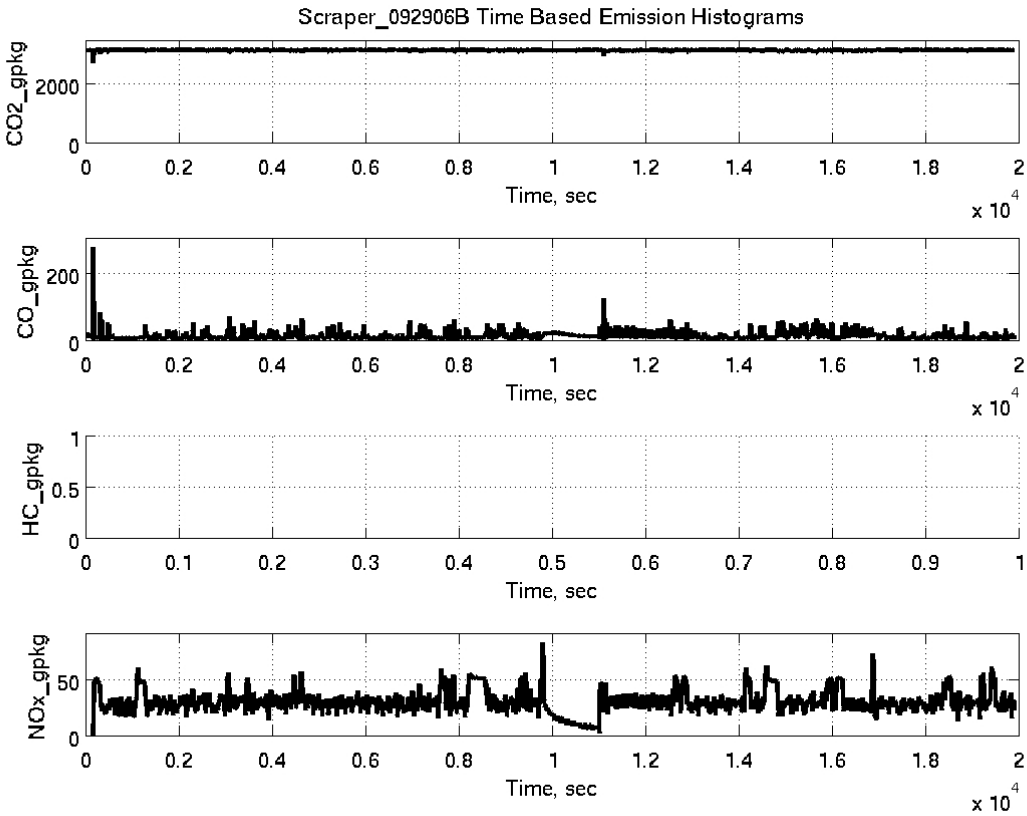

MotorGrader_053006_horiba Time Based Emission Histograms
CO2_gpkg
2000
0
0
5000
10000
15000
Time, sec
CO_gpkg
100
50
0
0
5000
10000
15000
Time, sec
HC_gpkg
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, sec
NOx_gpkg
100
0
0
5000
10000
15000
Time, sec

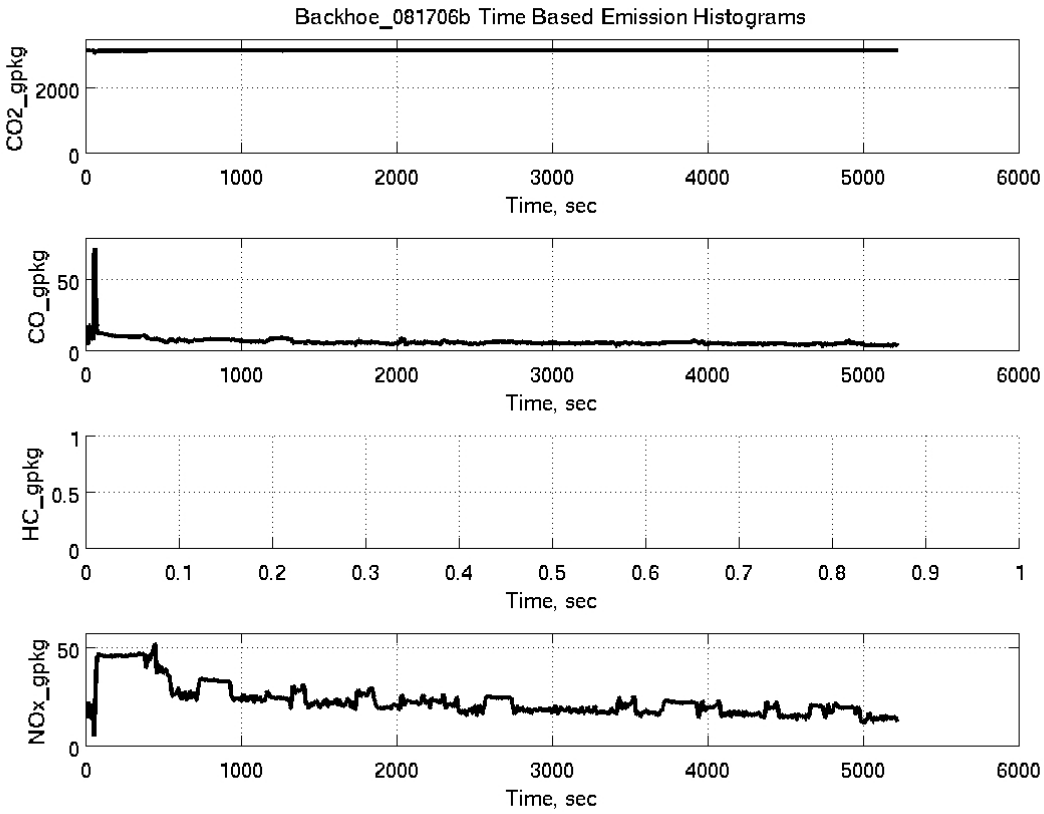

MotorGrader_053006_semtech Time Based Emission Histograms
CO2_gpkg
CO2_gps
CO_gpkg
CO_gps
HC_gpkg
HC_gps
NOx_gpkg
NOx_gps
Time, sec


MotorGrader_083106a Time Based Emission Histograms
CO2_gpkg
2000
0
0
5000
10000
15000
Time, sec
CO_gpkg
40
20
0
0
5000
10000
15000
Time, sec
HC_gpkg
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, sec
NOx_gpkg
50
0
0
5000
10000
15000
Time, sec


MotorGrader_083106b Time Based Emission Histograms
CO2_gpkg
2000
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Time, sec
CO_gpkg
20
0
Time, sec
HC_gpkg
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, sec
NOx_gpkg
50
0
Time, sec


MotorGrader_121405_Test Time Based Emission Histograms
CO2_gpkg
CO2_gps
CO_gpkg
CO_gps
HC_gpkg
HC_gps
NOx_gpkg
NOx_gps
Time, sec


Scraper_092906B Time Based Emission Histograms
CO2_gpkg
2000
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Time, sec
x 10^4
CO_gpkg
200
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Time, sec
x 10^4
HC_gpkg
1
0.5
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
Time, sec
NOx_gpkg
50
0
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
Time, sec
x 10^4


Backhoe_081706b Time Based Emission Histograms
CO2_gpkg
2000
0
0
1000
2000
3000
4000
5000
6000
Time, sec
CO_gpkg
50
0
0
1000
2000
3000
4000
5000
6000
Time, sec
HC_gpkg
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Time, sec
NOx_gpkg
50
0
0
1000
2000
3000
4000
5000
6000
Time, sec