# ABSTRACT

SANDHU, GURDAS SINGH. Methods for Quality Assurance of Portable Emissions Measurement System Data and Methods for Field Comparison of Alternative Fuels. (Under the direction of Dr. Christopher Frey).

The use of Portable Emission Measurement Systems (PEMS) has grown in popularity, with many PEMS of various configurations in use with organizations such as universities, governments, consulting firms, and others. However, in practice, there is not a standardized methodology for processing of 1Hz data obtained from a PEMS, which can lead to potential errors or inconsistencies in how data are used. This work discusses specific quality assurance methods for identifying and, where possible, correcting data quality problems, and procedures for formatting, synchronizing, and analyzing data. A sensitivity analysis is conducted to show that fuel use and emissions rate numbers are highly sensitive to engine RPM and Manifold Absolute Pressure (MAP) for both diesel and gasoline vehicles. An algorithm for finding and correcting errors in reported Intake Air Temperature values is presented. Vehicle Specific Power (VSP) based modal model results are shown to be affected by road grade estimation and an algorithm is provided for estimating road grade using the slope of least square fit line for elevation data vs distance travelled. Synchronization of data streams from multiple independent instruments is shown to significantly affect VSP based fuel use and NOx emissions rate. A technique based on visual comparison plus use of Pearson's Coefficient of Correlation is demonstrated to be effective in synchronizing independent data streams.

The second part addresses the question of how to assess claims about effect of alternative fuels (for example, B20 and fuel additives) on vehicle fuel use and emissions rate. A solution using quality assurance procedures, field measurement techniques, and driving cycle bases modal fuel use and emissions rates is presented. Three diesel trucks are tested with baseline fuel and subsequently alternative fuel. It is shown that the use of the fuel additive under test did not produce significantly different results compared to the baseline.

Methods for Quality Assurance of Portable Emissions Measurement System Data and Methods for Field Comparison of Alternative Fuels

by
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## DEDICATION

To my parents, Jaswant Kaur Sandhu and Harnek Singh Sandhu, who taught me to be curious

and

To the chairperson of my advisory committee, Dr. Christopher Frey, who encouraged me to learn

# BIOGRAPHY

Gurdas Singh Sandhu was born in the late seventies in Jamshedpur, a town in eastern India. He acquired a Bachelor of Engineering in Instrumentation Engineering in 2001 from Sant Longowal Institute of Engineering and Technology. Thereafter, for the next seven years, worked with a young engineering startup named Quantum Age Tech Solutions (QAT) where he learnt how to build automated computer controlled test and measurement systems. At QAT, he led development teams that : (a) designed and developed the pre-processor and post-processor for a tire noise simulation software; and (b) development of a tire extruded rubber offline profilometer. During the same time, he also successfully developed business in overseas markets for the tire noise simulation software and negotiated exclusive India representation for Boltcalc, a bolted joint analysis software from a UK based company.

In 2008, Gurdas chose to pursue his long standing desire to learn about and make a positive contribution to the environmental challenges facing the present generation. He joined North Carolina State University's department of Civil, Construction, and Environmental Engineering as a Master's student and chose to continue towards a PhD. in the same area. He spends much of his time conducting measurements of vehicle emissions and writing software to conduct quality assurance on the data from these measurements.

In his spare time, Gurdas likes to get behind the lens and capture the world as he sees it. He also writes a blog where he shares those experiences that deeply influence him. Gurdas enjoys driving, especially if the road is unknown and there is music to accompany. Gurdas finds humor to be healing and love to be eternal. In 2010 he met and subsequently got engaged to a wonderful woman. He hopes to soon start a family and continue to learn ever more from new responsibilities.

## ACKNOWLEDGEMENTS

At the very outset, I express my sincere thanks to Dr. Christopher Frey for his kind guidance and brilliant intellectual leadership and for patiently bearing with my many shortcomings. I then thank my committee members, Dr. John Baugh for insights on algorithmic efficiency and the occasional haiku and Dr. Joseph DeCarolis for sharing his expertise on energy modeling and motivating me on days when solutions were not coming forth.

Next, I remember friends and colleagues who with their love and understanding made this journey satisfying and pleasurable. It may not be possible to name all of them here, but you know who you are.

I then pay gratitude to my parents who even from thousands of miles away continue to be my pillars of love and truth. What would I be without you?

Finally, I acknowledge the assistance of clerical staff, lab managers, and other faculty at North Carolina State University, who in their own unique ways helped me.

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## 1. Introduction

Use of on-board portable emission measurements system (PEMS) for in-use real-world vehicle emissions measurement has gained importance in recent years. The EPA has conducted several studies (Hart *et al.*; 2002) on systems and methods for on-board analysis and has used results from various studies in the development of its latest vehicle emission inventory model, Mobile Vehicle Emission Modeling System (MOVES) (Hart *et al.*; 2002, Baldauf *et al.*; 2001). On-board systems allow for developing emission inventory for real-world driving cycles from emission data collected on a second-to-second basis. Some of the commercially available PEMS systems with second-by-second emission measurement capabilities are Clean Air Technologies Inc (CATI), Sensors Inc, and Horiba Inc. In this paper the key research questions addressed are: (1) What are the sources of errors (if any) in second-by-second real-world on-road vehicle emission and energy use data; (2) What quality assurance procedure can be used to minimize the effect of these errors on results; and (3) What is the effect of quality assurance procedure on modal fuel use and emission rates estimated from such data?

## 2. Motivation

### 2.1. Data Sample Sizes

In-use real-world should typically be conducted for four or more hours per vehicle for data sufficiency (giveref). Typical measurement conducted by various research groups involve five or more hours of driving for Light Duty Gasoline Vehicles (LDGVs) and up to eight hours of driving plus cargo loading-unloading (at warehouses visited during the test) time for combination trucks. Thus, the total data collected is between 18000 to 30000 seconds. In a study of excavators, data collection duration for the tests was typically 24,000 seconds and one test had 54,000 seconds (Abolhasani 2008). In another study of cement mixer trucks, measurement durations of 28,000 seconds are reported (Frey and Kim 2009).

### 2.2. Number Of Parameters

In this section the parameters recorded by commercially available PEMS systems such as Axion and Montana (CATI, Buffalo, NY), Semtech-D (from Sensors Inc., Saline, MI), and Horiba OBS-2000 (Horiba Inc) are described. All subsequent sections use CATI systems as examples.

The Semtech-D (from Sensors Inc., Saline, MI) PEMS for diesel vehicles measures CO, $CO_2$ using NDIR spectroscopy, NO and $NO_2$ using dual channel Non-dispersive Ultra-Violet (NDUV) resonant absorption spectroscopy, HCs using a heated Flame Ionization Detector (FID), $O_2$ using an electrochemical sensor, and vehicle engine parameters using a OBD, and vehicle location data using a GPS (Dearth *et al.*; 2005). The Semtech-G PEMS for gasoline vehicles is similar to Semtech-D except that it has a single channel NDUV that measures only NO (Gierczak *et al.*; 2006, Hart *et al.*; 2002). The latest generation Semtech-DS uses the same type of sensors as the Semtech-D (Johnson *et al.*; 2009).

The Horiba OBS-2000 measures CO and $CO_2$ concentration using a NDIR analyzer, HC concentration is measured by a FID analyzer, $NO_x$ concentration is measured by a Chemiluminescence Detector (CLD), exhaust flow measured by Pitot flow meter, ECU data monitored using Dearborn Instruments module, and has standard inputs to measure GPS signals (longitude, latitude, altitude, and velocity), exhaust temperature, exhaust pressure, ambient temperature, atmospheric pressure, and ambient humidity (Akard *et al.*; 2005, Horiba 2010).

The OEM-2100 Montana and OEM-2100AX Axion from CATI have two identical parallel operation 5-gas analyzers to measure exhaust gas concentrations. The gas analyzers measure hydrocarbons (HCs), carbon monoxide (CO), and carbon dioxide ($CO_2$) using nondispersive infrared (NDIR), nitric oxide (NO) and oxygen ($O_2$) using electrochemical sensors, and particulate matter (PM) concentrations using light scattering (Frey and Kim 2009, CATI

2007, CATI 2008, Vojtisek-Lom and Allsop 2001). This dual analyzer in parallel arrangement is provided because the gas analyzers need to "zero" periodically during a test. When a gas analyzer is zeroing, it is using ambient air as a reference to recalibrate itself. Both benches zero at pre-set intervals (such as every 10 minutes) but never together. When both analyzers are measuring, the PEMS computes the average of readings from both analyzers to estimate mass emission rate and fuel use rate. When one analyzer is zeroing, the PEMS uses readings from the non-zeroing analyzer to calculate mass emission rate and fuel use rate.

Depending on vehicle type and test configuration, measurements also involve : (a) an On-Board Diagnostic (OBD) scan tool or engine sensor array; and (b) a Global Position System (GPS) unit. The OBD scan tool is a hardware and software system that connects to the OBD-II port (found on most LDGVs manufactured since 1996) on one end and a recording computer on the other end. The OBD scan tool is used to read Electronic Control Unit (ECU) data such as engine RPM, Manifold Absolute Pressure (MAP), Intake Air Temperature (IAT), mass air flow rate, fuel use rate, and vehicle speed. When testing a vehicle that does not have an OBD port or a compatible OBD scan tool is not available, an engine sensor array is used to record RPM and IAT and a pressure sensor is used to measure MAP. The sensor array box receives analog signals from RPM and IAT sensors and converts them to digital signals that can be read by the PEMS. The MAP pressure sensor is directly connection to the PEMS. Both Montana and Axion have a GPS sensor connection and record GPS X and Y (latitude and longitude) coordinates. Additionally, stand alone GPS units can be used to get more accurate X and Y coordinates and measure additional parameters such as altitude (based on barometric pressure) which can be used to derive road grade.

For each second of data recorded there are at least 20 parameters including PEMS Timestamp, concentration of exhaust gases ($NO_x$, HC, CO, $CO_2$, and $O_2$) from each of the two identical gas benches (two benches operating in parallel to ensure when one of them is zeroing the other is measuring), Particulate Matter (PM) concentration, OBD Timestamp, Engine RPM, MAP, IAT, Vehicle Speed, GPS Timestamp, GPS X and Y coordinates, and

Elevation. Thus, a data file with 30000 seconds of measurement constitutes more than 600,000 measurement values.

### 2.3. Synchronization

The mass emission rate and fuel use rate for each second is calculated based on second-by-second data recorded by PEMS, OBD, and GPS. The measured parameters (from PEMS, OBD, and GPS) that go into calculations should be for the same instance of measurement. This can be a challenge because the internal clocks of these instruments, that write timestamps in the data file, are independent and not synchronized with each other. A brief overview of the key equations and calculation steps is given here to illustrate how data from PEMS, OBD, and GPS are used.

PEMS measurements of the exhaust gas composition are used to get dry basis mole fractions of pollutants.

$$y_i = \frac{[Y_{i,\,ppm}]}{10^6}$$ **Equation 1**

$$y_i = \frac{[Y_{i,\,\%}]}{100}$$ **Equation 2**

Where:

$[Y_{i,ppm}]$ = the concentration of measured specie $i$ in ppm, $i$ = NO and HC
$[Y_{i,\%}]$ = the concentration of measured specie $i$ in %, $i$ = CO, $CO_2$, and $O_2$

Intake air molecular flow rate, $M_{air}$, is estimated as per “speed-density” method (Vojtisek-Lom 1998). This method uses engine speed, intake air density, and the ideal gas law under constant engine volumetric efficiency, and engine parameters measured by OBD or engine sensor array. When multiplied with molecular weight of air it gives intake air mass flow rate,

$$m_{air}.M_{air} = \frac{P_{MAP,a}V_{engine}\left(\frac{S_{engine}}{30N_s}\right)}{R(T_{intake}+273.15)}\eta_{engine}$$ **Equation 3**

$$P_{MAP,a} = P_{MAP} - \frac{P_B}{C_{engine}}$$ **Equation 4**

Where:

$C_{engine}$ = engine compression ratio (~ 9.5 for light duty vehicle)

$N_s$ = number of strokes of engine (2 or 4)

$P_{MAP,a}$ = adjusted manifold absolute pressure (kpa)

$P_{MAP}$ = manifold absolute pressure (MAP, kpa)

$P_B$ = barometric pressure (kpa)

$R$ = universal gas constant (8.314 Jmol-1K-1)

$S_{engine}$ = engine speed (RPM, rpm)

$V_{engine}$ = engine displacement (L)

$T_{intake}$ = intake air temperature (IAT, ºC)

$\eta_{engine}$ = engine volumetric efficiency (~ 0.85 for light duty vehicle)

$$m_{air} = M_{air}MW_{air}$$ **Equation 5**

The dry basis molecular exhaust flow rate, $M_e$, is computed using combustor mass balance equations. The simplified equation for exhaust flow uses intake air molecular flow rate and the dry basis mole fractions of measured species in the exhaust.

$$M_e = \frac{2y_{O2,in}M_{air}}{(2y_{CO2} + y_{CO} + 2y_{O2,out} + y_{NO} - 0.5my_{HC}) + (y_{CO2} + y_{CO} + \mathrm{n}y_{HC})(0.5x - z)}$$ **Equation 6**

Pollutant mass emission rates, $m_i$, and fuel use rate, $m_f$, can be derived from dry basis mole fractions of pollutants and exhaust flow rate as per:

$$m_i = M_e y_i MW_i$$ **Equation 7**

$$m_f = M_e \left(y_{CO2} + y_{CO} + ny_{HC}\right) MW_{fuel}$$ **Equation 8**

where,

$m_i$ = the mass per time for specie $i$, $i$ = NO, HC, CO, $CO_2$, and fuel.
$MW_i$ = the molecular weight for specie $i$ = NO, HC, CO, $CO_2$, and fuel.

Air to Fuel ratio (AFR) is calculated as the ratio of intake air mass flow rate over fuel mass flow rate.

$$AFR = \frac{m_{air}}{m_f}$$ **Equation 9**

When intake air mass flow rate is available from OBD it is preferred over the value calculated as per speed-density method. When exhaust molecular flow rate is available, again, the measured value is substituted in place of the computed value.

A step-by-step derivation of key equations is given in Appendix A. The mass emission rates and fuel use rate are compared using a VSP (Vehicle Specific Power) modal model or MAP modal model. A VSP based model was first introduced in Jiménez-Palacios's Ph.D. thesis (Jiménez-Palacios 1999). VSP for LDGV is calculated as:

$$VSP = v*[1.1a + 9.81(\sin(\arctan(r))) + 0.132] + 0.000302v^3$$ **Equation 10**

Where,

VSP = Vehicle Specific Power, kw/ton ($m^2/s^3$)

v = vehicle speed, m/s

a = vehicle acceleration, $m/s^2$

r = road grade, %

Both VSP (Jiménez-Palacios 1999) and MAP are good indicators of engine load which in turn is a good measure of fuel consumption. VSP provides a method to categorize and explain the variability in fuel use and tailpipe emissions (Frey *et al.*; 2002a).VSP accounts for power demand, rolling resistance, road grade, and aerodynamic drag, and can be estimated based upon second-by- second speed (from OBD or GPS), acceleration, and road grade from GPS (Frey *et al.*; 2002a).

In order to handle the large amount of data and parameters and multiple timestamps generated by PEMS, OBD, and GPS, a computer-based quality assurance method is needed.

### 2.4. Need For Rapid Onsite QA

Rapid on-site quality assurance is important to capture and correct systemic failures in sensors or measurement setup. Examples of such failures could be a sensor that is biased high or low, air leak in the sampling line, or loss of signal for intermittent periods. Rapid on-site quality assurance will help to quickly identify problems so that it is possible they can be fixed. In turn, accumulation of errors over multiple tests in sequence can be avoided by quickly diagnosing and correcting problems as they occur.

Other examples of test setups that require rapid onsite QA are:

- Time sensitive series of tests that are needed for comparisons, to make sure baseline data are valid before proceeding with comparative tests. Such as tests to compare fuel alternatives (Petroleum Diesel vs. B20 Diesel) or effect of Fuel additives.

- Optimization tests such as engine performance versus emissions optimization tests. In these tests, one or more input parameters is varied (e.g. for locomotive engine tested on a dynamometer - fuel, airbox pressure, fuel injector type and/or timing, presence of heat shields, and configuration of cooler water) and the resulting engine power output and emissions are measured. Given the high cost of such tests, it is important that the data be quality assured and results be available shortly after the test is completed to ensure a decision can be made about the next optimization step.

Finally, a standardized ready-to-use computer based quality assurance method allows researchers to focus on data analysis and interpretation, and also to train new researchers with respect to QA procedure.

## 3. Data Quality And Error Identification

Data quality issues and errors typically observed in second-by-second data from PEMS are identical and described in the following paragraphs.

**Data Sampling Frequency:** When measuring emissions for real-world driving it is important to have data at a resolution that can capture driving transients, such as acceleration on a ramp, effects of stop and go traffic, and change in road grade. These influence engine power demand and in turn emissions from the vehicle. With current technology, the instruments deployed for in-use measurements - PEMS, GPS, and OBD – are capable of recording at approximately 1 Hz. A first step in developing a combined database from PEMS, GPS, and OBD data is to make sure all data are converted to the same reporting frequency. A description of PEMS, GPS, and OBD data reporting frequency is given here.

*PEMS and GPS:* Both PEMS and GPS generally provide second-by-second (1 Hz) data output with very few instances of missing seconds. On an average, both PEMS and GPS reported 1-2 instances of missing seconds for every 10-15 vehicles tested. Both PEMS and GPS record data with integer timestamps.

*OBD:* Scan tools used to read OBD ports often display three problems: (1) recording frequency is sensitive to number of parameters being recorded; (2) speed of laptop computer running the scan tool; and (3) Recording is at variable frequency, approximately equal to 1 Hz, which produces data rows with timestamps of 3.4, 4.4, 5.6, 7.8, and so on. In one example, recording speeds of approximately 1 Hz are achieved when recording up to 6 parameters but as more parameters are added the recording speed falls to 0.5 Hz or lower.

Some OBD devices report a separate time stamp for each data point for each parameter (or a group of parameters). In one example, an ECU data logger (Kvaser Memorator) for a Plug-in Hybrid Electric Vehicle (PHEV) produced a file with 270,000 rows of data representing test duration of 20,045 seconds. As an example, the log file had some of the parameters recorded with timestamp 1175.638, another group of parameters were recorded in the following row with the same timestamp as previous row (that is 1175.638) then other groups recorded with timestamps of 1175.639, 1175.647, and 1175.647.

Moreover, missing seconds are possible due to temporary loss of communication within an instrument or between the recording instrument and a data source (for example, OBD scan tool recording data from the OBD port). Thus there is a need to convert data to a 1 Hz basis in order to combine with PEMS and GPS data.

**Data Synchronization:** After the data from PEMS, GPS, and OBD is converted to 1 Hz it needs to be synchronized, or time-aligned, for calculation of mass based emission rates, fuel use rate, and VSP modal results. Misaligned timestamps can be caused because : (1) instruments each have their own independent internal clocks; and (2) a physical process is varying gas travel time in vehicle exhaust pipe and measurement system gas sampling line. Time misalignment due to varying gas travel time in exhaust and sampling line has been discussed by Weilenmann *et al.*; 2003, Konstantas and Stamatelos 2004, Hawley *et al.*; 2004, Ropkins *et al.*; 2007, Frey *et al.*; 2008.

A brief discussion on other errors related to second-by-second (s-b-s or 1Hz) data from PEMS, OBD, and engine sensor array is given below. For a detailed discussion of these errors refer Frey *et al.*; 2008, Frey and Kim 2005, Frey *et al.*; 2003, Frey *et al.*; 2002b.

**Engine Speed (RPM) Error:** The RPM lower limit and upper limit for a vehicle model or type is generally known and is used to evaluate the validity of RPM measurement. A RPM reading below the idling RPM can be used as lower limit and the upper limit can be estimated from manufacturer specifications or from the maximum on the dashboard tachometer (if available). For 4-stroke gasoline and diesel on-road vehicles a valid RPM range of 500 rpm to 4000 rpm is typical. For large 2-stroke diesel locomotive prime mover engine the range could be 300 rpm to 1000 rpm. For PHEVs the range typical range is similar to gasoline cars with the exception that when the vehicle is idling, the engine can shut off and RPM can fall to zero. An error in RPM reading is defined as a value below the RPM lower limit, above the RPM upper limit, or missing. The error second of data is deleted if RPM is being used to calculate intake molecular air flow rate (as per speed-density method), which in turn is used to calculate exhaust flow rate and subsequently pollutant mass emission rate.

**IAT Error:** The intake air temperature is a slow changing variable and based on previous field data a change in IAT greater than $\pm 1^{o}$C between two consecutive seconds (t and t+1) is considered to be an error. Thus, the data at time t+1 are marked as bad. Additionally, missing IAT values are marked as error. The error timestamps are deleted if IAT is being used to calculate intake molecular flow rate (as per speed-density method) and in turn exhaust flow rate and pollutant mass emission rate.

**MAP Error:** For cases where MAP value is missing for up to 3 consecutive seconds, an absolute relative difference (ARD) is calculated using the valid MAP values occurring immediately before and after the missing MAP values. If the ARD is within 5%, the missing MAP value is calculated using the two MAP values immediately preceding and following the missing value. If MAP value is missing for 4 or more seconds and MAP is being used to calculate intake molecular flow rate (as per speed-density method) then the timestamps are marked as error and removed from the error free QAed database.

**Zeroing Error:** For the period when a gas analyzer is zeroing, plus the 10 seconds immediately before and after the zeroing period, the mass emission rates are calculated using emission concentration readings from the non-zeroing gas analyzer. This is done because for the bench that is zeroing the preceding and following seconds contain a mix of exhaust sample and ambient air.

**Gas Analyzer Freezing Error:** A gas analyzer is marked with freezing error if the reported concentration measurement, for each of the measured pollutants, from the gas analyzer is same over two consecutive seconds but one or more of the engine parameters (RPM, IAT, MAP) for the two seconds.

**Negative Concentration Error:** The PEMS can sometimes report negative pollutant concentrations. This usually happens when the real concentration of the pollutant is low and not statistically significantly different from zero. Sensor precision is used to infer what negative values will be considered as zero. For example, the precision of the CATI NO sensor is 25 ppm. Since the lowest feasible value for concentration is 0 ppm, the NO sensor may read that as -25 ppm. If NO for any gas analyzer is reported between 0 and -25 ppm, it is replaced with a value of 0 ppm. If NO is reported below -25 ppm, then the reading is marked as an error and not used to calculate mass emission rates.

**Inter-Analyzer Discrepancy (IAD) Error:** In PEMS having two identical gas analyzers, the absolute value of the difference in the instantaneous readings of the two analyzers, for a given pollutant, is the IAD. The maximum acceptable difference (MAD) between the readings of the two gas analyzers, for a given pollutant, is equal to twice the precision of the pollutant sensor. This is because the acceptable measured concentration values from the two sensors are maximally separated when one sensor is reading pollutant concentration as (True Value + Precision) and other sensor is reading (True Value – Precision). A difference in the reading of the two gas analyzers greater than the MAD is reported as an IAD error. When IAD ≤ MAD, the average of the reading of two gas analyzers is used. When IAD > MAD, and both analyzers report values greater than detection limit, the number of consecutive seconds of measurement with IAD > MAD is counted. If count is less than or equal to 15 then average of two analyzers is used else the analyzer data is deleted for the said seconds. When IAD > MAD and one analyzer is above detection limit and other is below detection limit, the value of the analyzer above detection limit is used. When IAD > MAD and both analyzers are below detection limit, then an average is taken of both analyzers.

**Air Leakage:** Any leak in the exhaust sampling line upstream of the gas analyzers would result in excess air, lower CO, $CO_2$, NO, and HC mole fractions, and increase of $O_2$ and $N_2$

mole fractions. Air leakage does not affect the mass emission rates for the pollutants because the decrease in pollutant mole fractions is balanced by the increase in dry exhaust molecular flow rate which is calculated from the intake air flow rate (Frey *et al.*; 2008). The ratio of intake air mass flow rate to fuel use rate, known as AFR (g-air/g-fuel), is used to test for air leakage. An acceptable AFR can be set based on field data. For example, for construction vehicles 99.9% of the s-b-s field data has AFR value within the range 25 to 150 g-air/g-fuel (Frey *et al.*; 2008). When AFR is within acceptable range the AFR value is used. When AFR value is outside of acceptable range the random measurement error in the pollutant concentration may result in large uncertainty in the mass emission rate. In such a scenario the concentration reading is compared to the sensor precision. If pollutant concentrations are above the precision then the second of data is used, otherwise the second of data is deleted.

Errors related to data from GPS are described below.

**VSP Modal Binning Error:** Second by second GPS elevation data (based on barometric pressure) can be used to calculate road grade which in turn is used to calculate VSP. Thus, incorrect road grade estimates can affect the VSP based modal model results.

As an example, the specifications for the GPSMAP 76CSx are : GPS latitude and longitude accuracy < 10 m, DGPS accuracy (Differential GPS) = 3-5 m, Velocity accuracy = 0.05 m/sec steady state, Altimeter accuracy = +- 10 feet (Garmin 2009).

Road grade is estimated as:

$$RG_t = \frac{\Delta E_{t,t-1}}{d_{t,t-1}} * 100 \qquad \textbf{Equation 11}$$

Where,

$RG_t$ = road grade at time t (in %)

$\Delta E_{t,t-1}$ = change in elevation from time t-1 to time t (m)

$D_{t,t-1}$ = distance travelled from time t-1 to time t (m)

Field tests show GPS elevation data and X-Y coordinate data have significant precision related noise and using Equation 10 at a 1Hz resolution can result in spurious estimates of very large road grades (such as ±70% in some cases). Real road grades are typically between ±10%. A moving window averaging technique could be applied to elevation data to smooth out some of the noise but it does not solve the issue of occurrence of impossible range road grades. Moreover, the same averaging technique cannot be applied to X-Y coordinate data if the vehicle is moving.

Further, Light Detection and Ranging (LIDAR) data may not be available for a given geographic area/test route. Road grade from Geographic Information System (GIS) may not be reliable depending on how such data were obtained. In view of these limitations, it is important to have a method to get good road grade estimates using on-board GPS elevation data.

# 4. Methodology

## 4.1. Sensitivity Analysis

Knowledge of sensitivity of outputs to change in inputs is important to the QA method because input parameters that can change rapidly and have significant impact on results will need to undergo tighter QA criteria while parameters that have less significant impact on end result can do with more relaxed QA criteria. The QA criteria strength is important because tighter criteria will remove an error or missing second of measurement more often than relaxed criteria.

Sensitivity analysis was conducted for a 15 liter heavy duty diesel (HDD) combination truck and a 2.2 liter light duty gasoline (LDG) car to measure the percent change in fuel use (g/s), pollutant mass emissions rate for $NO_x$, HC, CO, $CO_2$, $O_2$ (each g/s), intake air mass flow rate (g/s), and dry exhaust mass flow rate (g/s) for a ±10% change in exhaust gas concentrations ($NO_x$, HC, CO, $CO_2$, $O_2$) and engine data (RPM, IAT, MAP). A typical second of data (base case) was picked from actual real-world in-use emissions measurement database and the parameter under test was varied by ±10% with subsequent recalculation of output results. **Table 1** gives the base case and typical range of values for the input parameters. Since the resulting fuel use and mass emission rates for each second are based on empirical calculations that use input data for only that second, the sensitivity of outputs to inputs calculated using one second can be safely assumed to be the typical sensitivity.

**Table 1.** Sensitivity Analysis - Base Case and Typical Range for Selected Input Parameters

| | **RPM** | **IAT ($^o$C)** | **MAP (kPa)** | **$NO_x$ (ppm)** | **HC (ppm)** | **CO (%)** | **$CO_2$ (%)** | **$O_2$ (%)** |
|---|---|---|---|---|---|---|---|---|
| | 15.0 liter HDD Truck | | | | | | | |
| **Base Case** | 1656 | 54 | 265 | 134 | 9 | 0.045 | 7.12 | 12.8 |
| **Typical Range** | 670- | 30-80 | 98-300 | 10-200 | 5-45 | 0-0.08 | 0.5-9.0 | 10-19 |
| | 2.2 liter LDG Car | | | | | | | |
| **Base Case** | 2068 | 46 | 83 | 290 | 32 | 0.059 | 14.11 | 0.23 |
| **Typical Range** | 700- | 37-60 | 15-90 | 10-400 | 2-50 | 0-0.3 | 8-14.5 | 0.02-1.0 |

### 4.2. Synchronization

Of the two data sets that need to be synchronized one is labeled "master" and the other is labeled "slave". If PEMS data is one of the two datasets involved in synchronization then it is considered as master and the OBD or GPS datasets are considered slave. If the OBD dataset is being synchronized with GPS then OBD is master and GPS is slave. The choice of master and slave is a matter of convention and a different choice would not affect the final result as long as a consistent scheme of selecting master and slave is made. Frequently used master-slave synchronization pairs are given in Table 2.

**Table 2.** Frequently used dataset/parameter pairs to synchronize datasets

| Master Parameter (Source) | Slave Parameter (Source) |
|---|---|
| $CO_2$ (PEMS) | RPM (OBD) |
| CO (PEMS) | RPM (OBD) |
| $NO_x$ (PEMS) | RPM (OBD) |
| Vehicle Speed (PEMS) | Vehicle Speed (OBD) |
| Vehicle Speed (PEMS) | Vehicle Speed (GPS) |
| Vehicle Speed (OBD) | Vehicle Speed (GPS) |

These pairs of parameters are used for synchronization because their time series shows correlated trends. For example, a large change in engine RPM over a short period of time (such as during sudden acceleration or deceleration) is often accompanied by noticeable change (having same trend) in emissions concentration of $CO_2$, CO, and $NO_x$. To assist in synchronization, a throttle snap is built into the test procedure where the driver floors the gas pedal (and thus spikes the RPM and exhaust emissions) while the vehicle is parked. This is done at the start and end of a test route or when the vehicle is ready to start driving after a long period of idling such as loading/unloading for combination trucks. The master parameter (from the master database) and the slave parameter (from the slave database) are plotted on a common time-axis and sections of the test with high rate of change in the master and/or slave parameter are marked out. Timestamp of the slave parameter is adjusted until the instance of start of rise (or fall) in the master parameter coincides with the start of rise (or fall) of the slave parameter. Other sections of test data having similar characteristic steep rise or fall are checked to make sure that the time adjustment is applicable throughout the dataset.

As a confirmation of the visual technique of synchronization, any appropriate pair of master-slave time series data arrays, when correctly synchronized, will return a high Pearson Coefficient of Correlation(PCC) (Kubelt and Bonnel 2007).

The PCC, denoted as *r*, for a master-slave data array pair is given as:

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$ **Equation 12**

Where,

r = Pearson's Coefficient of Correlation

X = Master data array with n elements

$\bar{X}$ = Mean of X

Y = Slave data array with n elements

$\bar{Y}$ = Mean of Y

### 4.3. Intake Air Temperature

The algorithm for marking IAT errors was updated to more than a mere comparison of a pair of consecutive values since that simple algorithm results in false positives. For example, consider three consecutive IAT values (in $^oC$) of …, 60, 71, 61, … where the 71 $^oC$ is an error value. If the algorithm is set to delete the former of the pair, it would delete 60 $^oC$ appearing before the 71 $^oC$ which is incorrect. If the algorithm is set to delete the latter of a pair and the data were … 60, 71, 71, 61 … it would correctly delete the first 71 $^oC$ value but keep the second 71 $^oC$ value and instead delete the valid 61 $^oC$ value. Errors in IAT values are uncommon but when they do occur, each instance is typically 1 to 4 consecutive seconds long. The new algorithm, when it encounters an error value, retains the last good value and makes an extended comparison till the next good value is encountered or 5 seconds have elapsed, whichever is earlier. IAT is a slow moving variable and the sensitivity of fuel use and exhaust emission mass rates to IAT is less than 2% to a change of 10% in IAT value. Thus, to prevent loss of data due to IAT error, it is safe to impute missing or error IAT values up to 5 consecutive seconds which is implemented in the updated algorithm.

### 4.4. Road Grade Estimation

When using a VSP based modal model for fuel use and pollutant mass emission rates, road grade will influence the modal results. For real-world in-use driving tests, road grade is calculated from coordinate information and elevation data recorded by GPS unit. Second by second road grade calculated as the change in elevation per second over the distance travelled in that second is noisy and leads to spurious road grade numbers characterized by : (1) rapidly varying road grade even while driving over roads known to have little grade variation and (2) road grades frequently lying beyond the typical range of ±10%. To prevent VSP results getting biased due to noisy and incorrect road grade, the road grade is calculated as the slope of the least square fit line for a set of consecutive seconds during which the vehicle has travelled a specified distance, which is called here as $RG_{step}$. Values of 0.1 mile, 0.05 mile and 0.25 mile have been used for $RG_{step}$ and from preliminary review of road grade data calculated for a series of real world driving tests, 0.1 mile is found to produce best approximation, though this is part of an ongoing study and final results may alter this selection.

## 5. Results

### 5.1. Sensitivity Analysis

For HDD, a ±10% change in RPM and MAP results in about 10% change of same polarity in fuel use, mass emission rates, intake air rate, and dry exhaust air rate. A ±10% change in vol% $CO_2$ produces about 5.5% change of same polarity in fuel use and $CO_2$ mass emission rate, about 4.5% change of reverse polarity in $NO_x$, HC, and CO mass emission rates, a 4.0% change of reverse polarity in exhaust air flow rate. A ±10% change in vol% $O_2$ results in about 5.5% change of reverse polarity in all output parameters except intake air which is unaffected. A 10% change in IAT produces about 1.6% change of reverse polarity in all output parameters. A ±10% change in exhaust volume fractions of $NO_x$, HC, and CO has no effect on any output parameters except an almost equivalent change in their own mass emission flow rate. The sensitivity of HDD fuel use to change in input parameters in shown in Figure 1 and graphs for effect on other parameters is included in the appendix.

For LDG, a % change in RPM, MAP, and $NO_x$, HC, and CO has similar effect on output parameters as with HDD. A ±10% change in vol% $CO_2$ has negligible effect on fuel use rate and $CO_2$ mass flow rate but a almost 10% change of reverse polarity in $NO_x$, HC, and CO mass emission rates and exhaust air flow rate. A ±10% change on vol% $O_2$ has negligible effect on all parameters. The sensitivity of LDG fuel use to change in input parameters in shown in Figure 2 and graphs for effect on other parameters is included in the appendix.

In summary, in general, the output parameters are most sensitive to changes in RPM and MAP followed by $CO_2$ and $O_2$ and finally to a lesser degree IAT. Thus, from a QA criteria strength perspective, if the RPM value is missing for more than one second it is advised to delete the second rather than impute the missing RPM value. On the other hand, if a couple of IAT values are missing or error they can be safely imputed using linear interpolation.

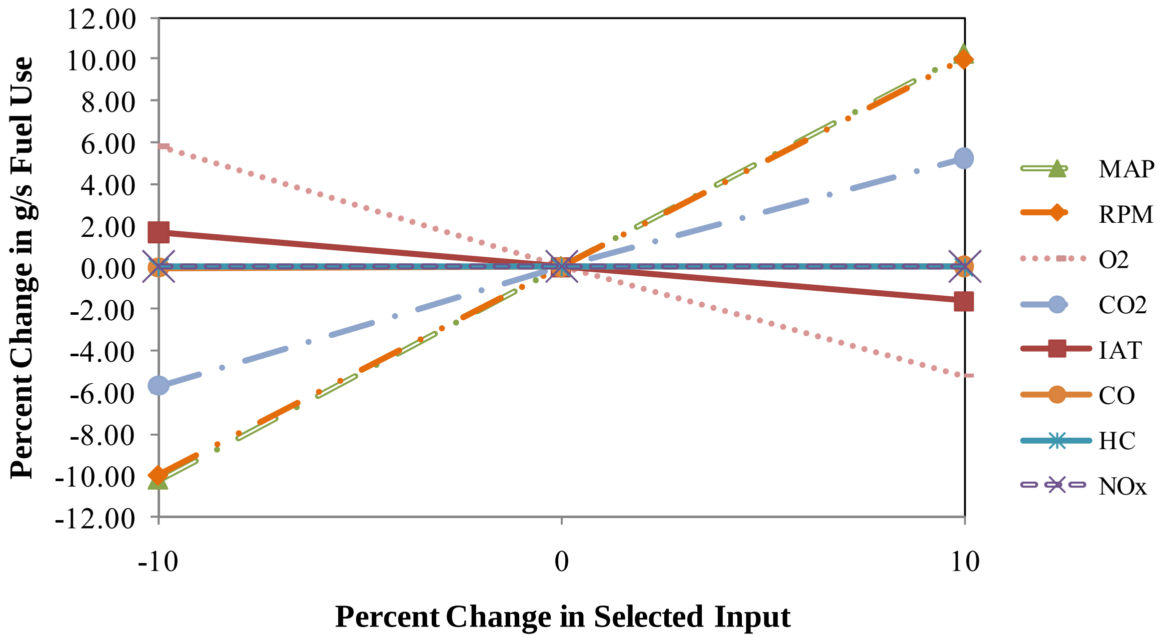



**Figure 1.** Sensitivity of g/s Fuel Use to Input Parameters for Heavy Duty Diesel Vehicle

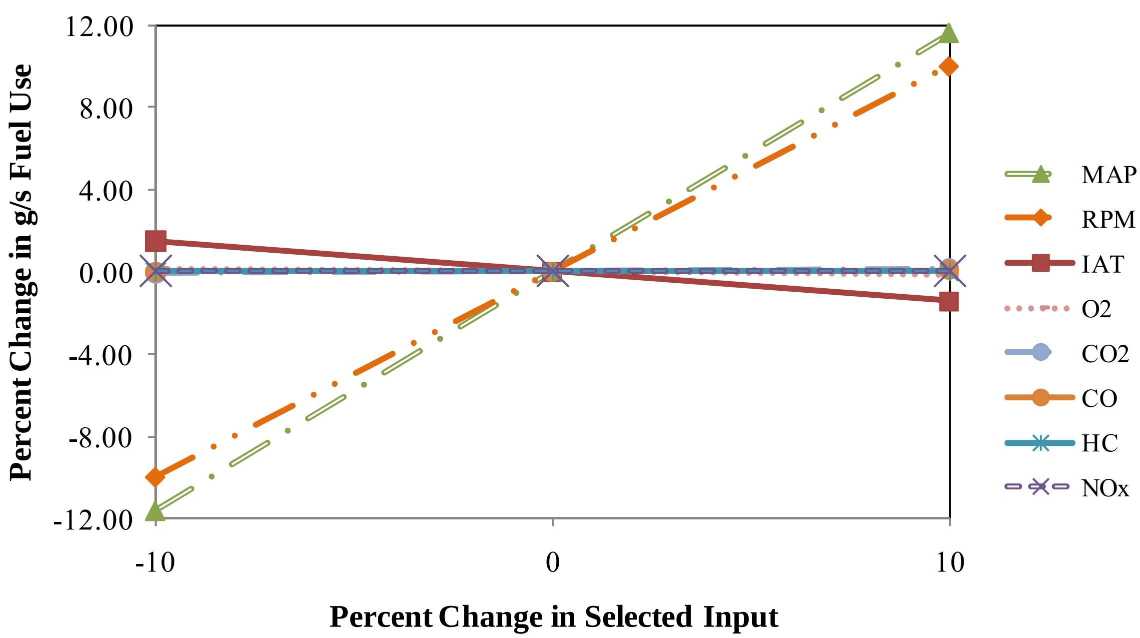



**Figure 2.** Sensitivity of g/s Fuel Use to Input Parameters for Light Duty Gasoline Vehicle

### 5.2. Synchronization

For LDGV, the recommended pairs for synchronizing PEMS and OBD data are CO-RPM and $NO_x$-RPM, both of which produce prominent and sharp PCC peak. Generally, PCC values are in the vicinity of 0.3 and 0.6 for CO-RPM pair and $NO_x$-RPM pair respectively. For HDDV, the recommended pair is $CO_2$-RPM which produces PCC values in the vicinity of 0.5. Other options are $O_2$-RPM and $NO_x$-RPM which typically produce -0.4 and 0.4 PCC values respectively. For any vehicle type, when using the same parameter type pairs, such as vehicle speed from OBD and vehicle speed from GPS or $NO_x$ from gas analyzer 1 and 2, PCC values are typically close to 0.9 to 1.0.

The PEMS and OBD databases for a real-world in-use emissions testing of a Honda Accord (1997 model, 2.2 liter engine, 130HP) is conducted using $NO_x$ from PEMS as master parameter and RPM from OBD as slave parameter. Figure 3 and Figure 4 show before and after synchronization time series plots. Figure 5 and Figure 6 show PCC plots before and after synchronization. Here, RPM timestamp is adjusted by -5 seconds for the two datasets to be synchronized. Correct synchronization results in PCC peak occurring at 0 mark on the x-axis which signifies the slave timestamp need not be further adjusted.

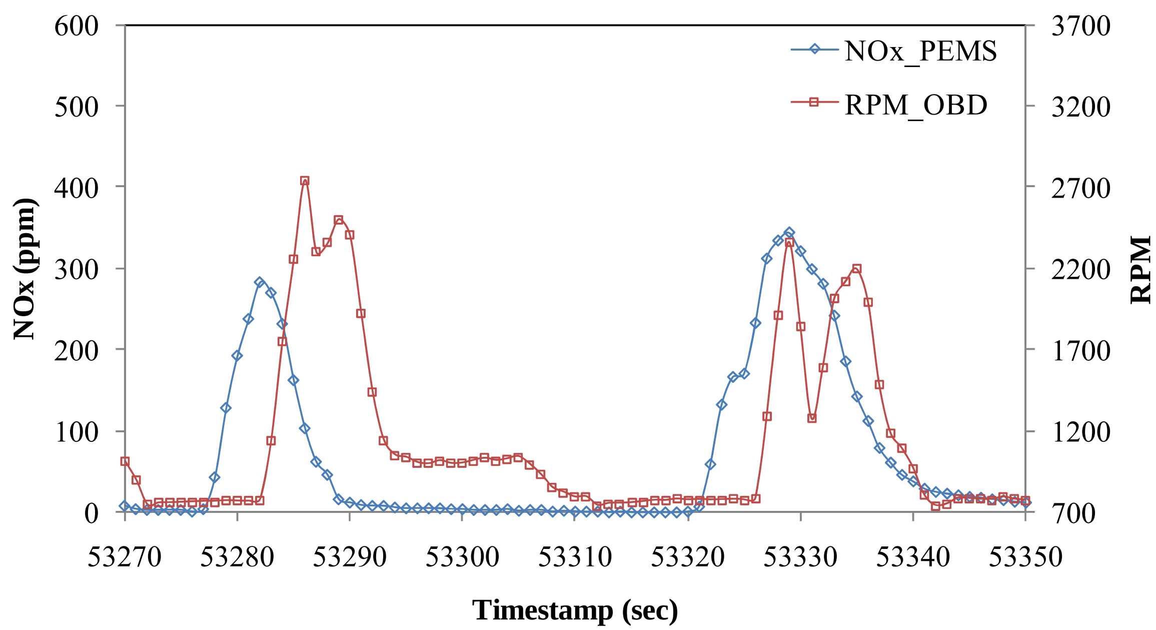



**Figure 3.** $NO_x$ from PEMS and RPM from OBD before synchronization

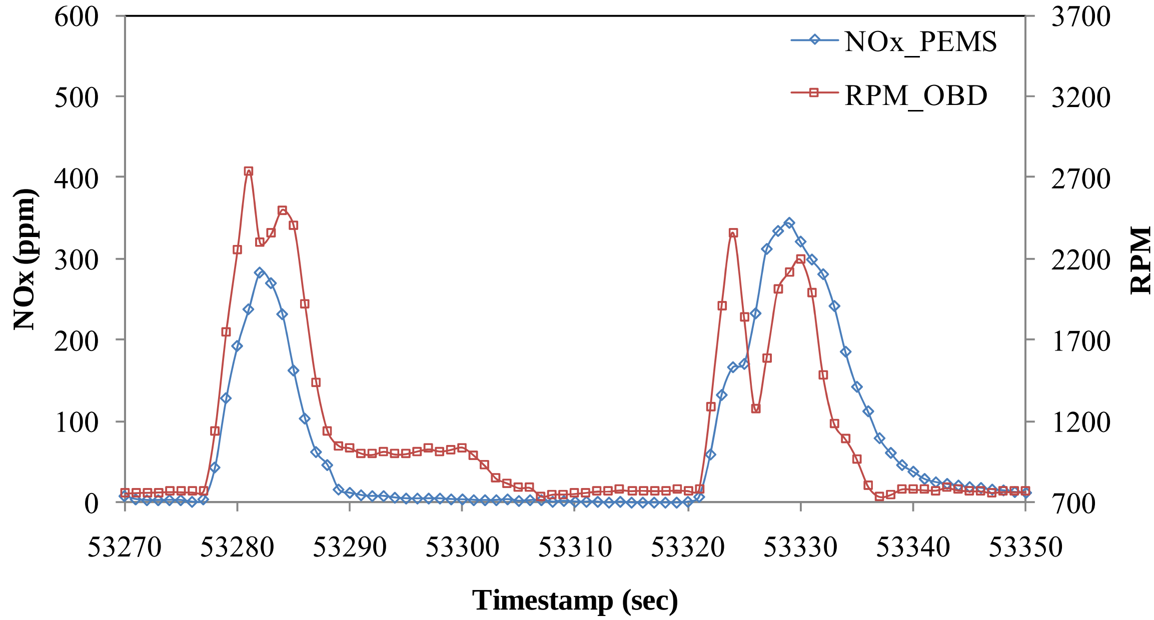



**Figure 4.** $NO_x$ from PEMS and RPM from OBD after synchronization

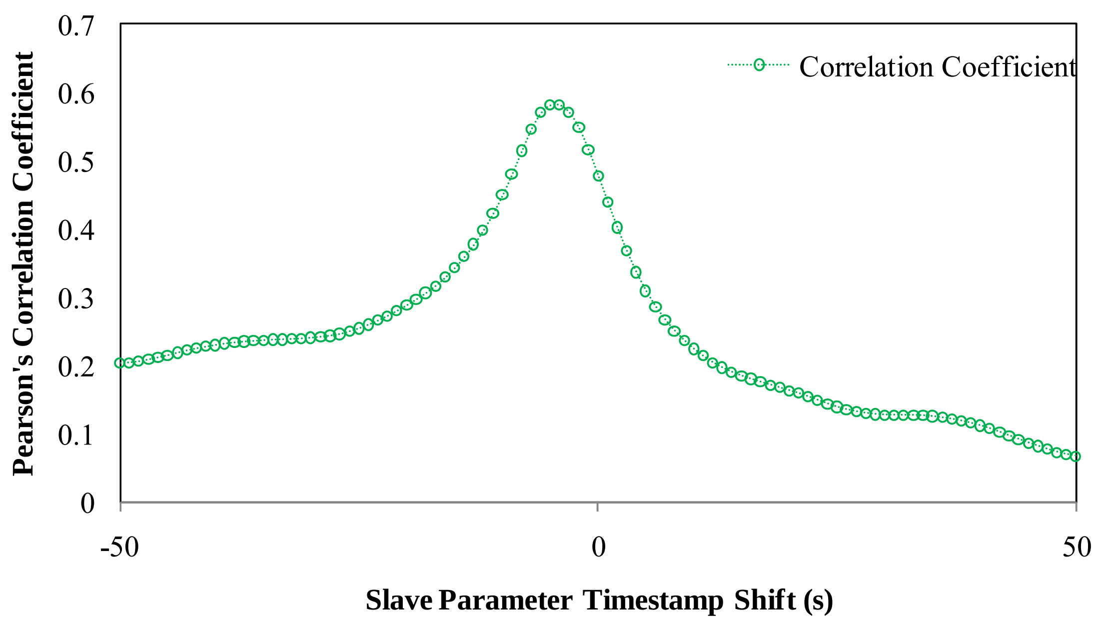



**Figure 5.** Correlation between $NO_x$-PEMS and RPM-OBD before synchronization

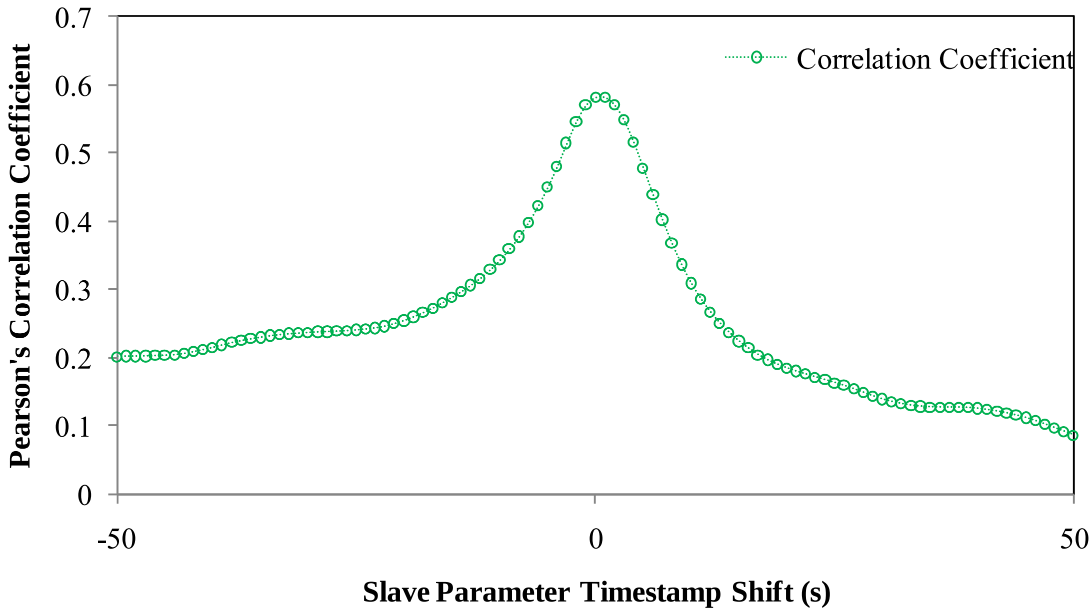



**Figure 6.** Correlation between $NO_x$-PEMS and RPM-OBD after synchronization

In another example, the OBD and GPS used while testing a Pontiac Grandprix (1999 model, 3.1 liter engine, 160 HP) are synchronized using vehicle speed from OBD as master and vehicle speed calculated from GPS coordinate information as slave. The GPS timestamp is advanced by 3 seconds to achieve synchronized datasets. Figure 7 and Figure 8 show before and after synchronization time series plots. Figure 9 and Figure 10 show PCC plots before and after synchronization.

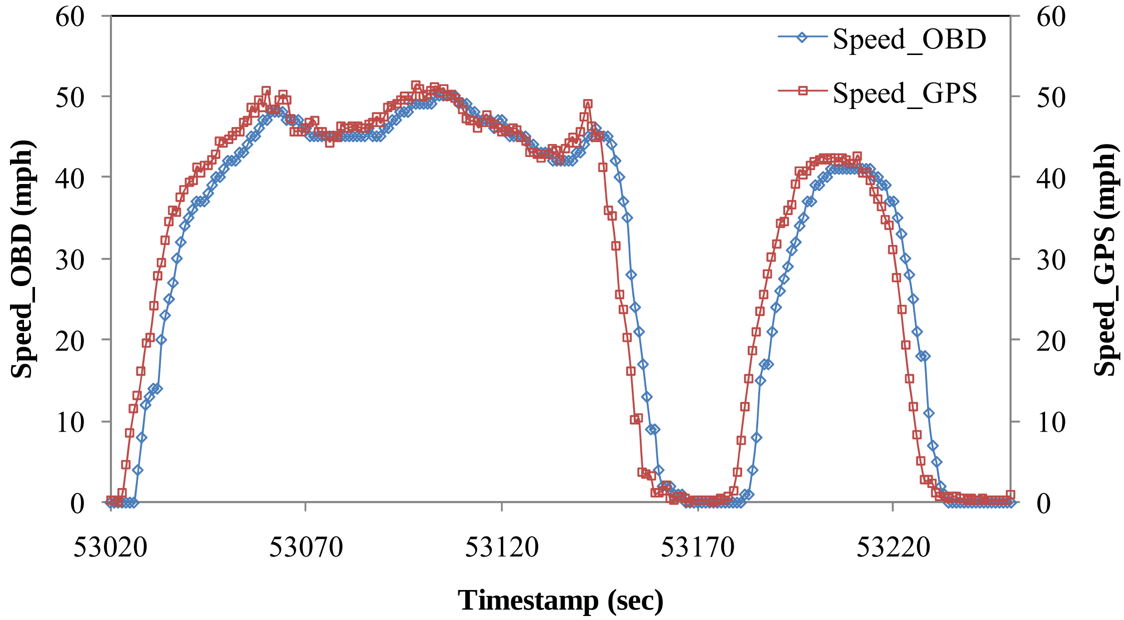



**Figure 7.** Vehicle Speed from OBD and Vehicle Speed from GPS before synchronization

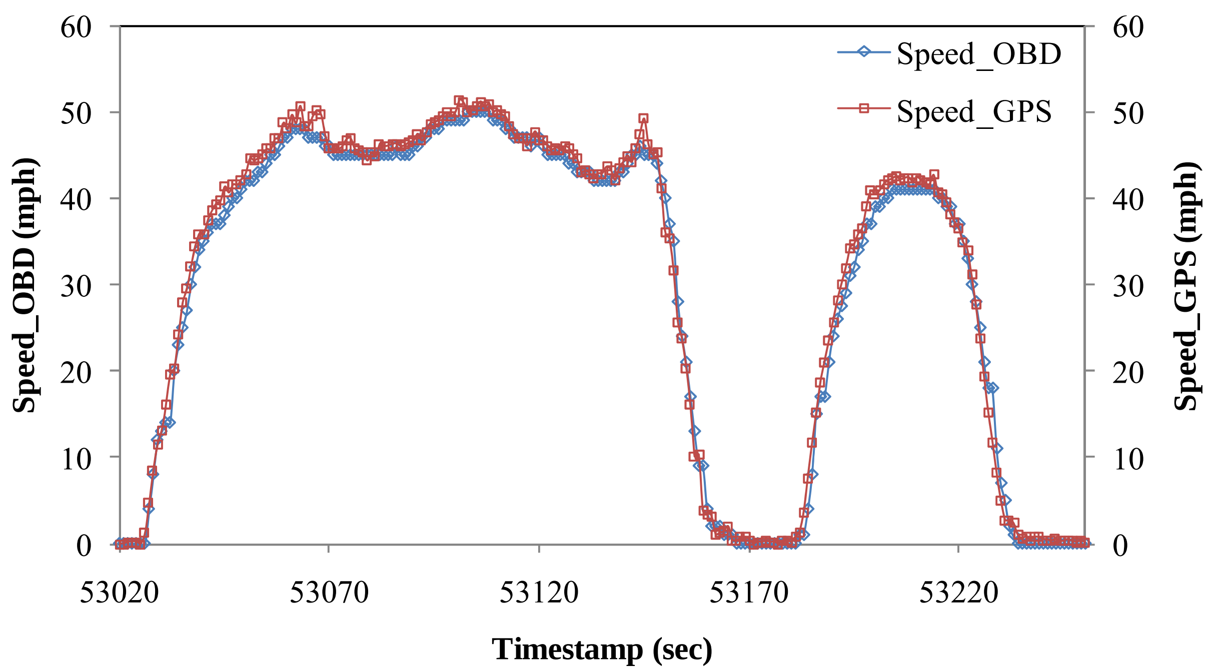



**Figure 8.** Vehicle Speed from OBD and Vehicle Speed from GPS after synchronization

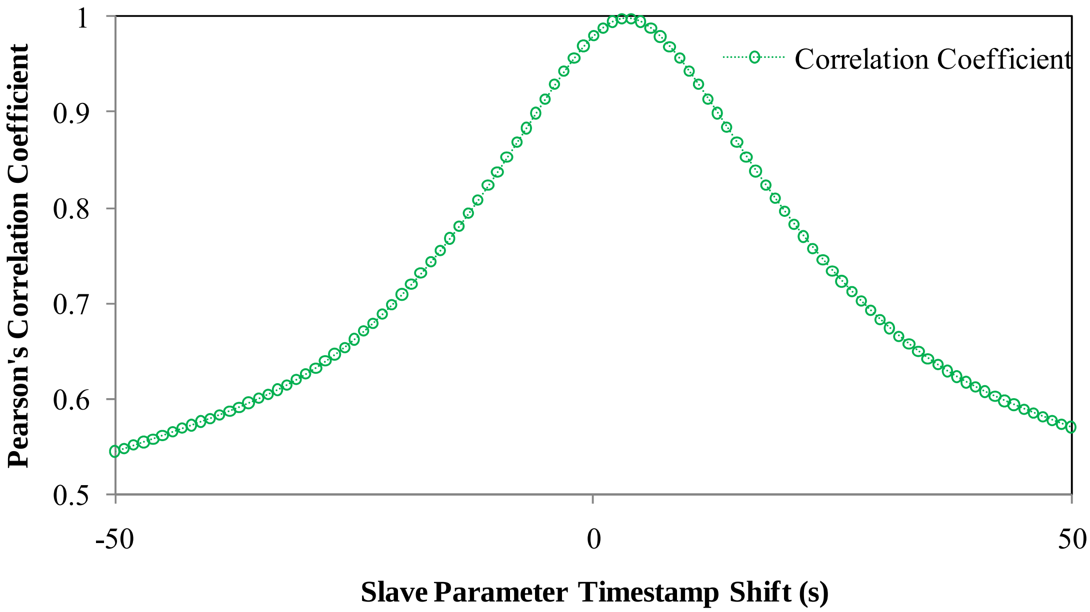



**Figure 9.** Coefficient of correlation for vehicle speed from OBD and GPS before synchronization

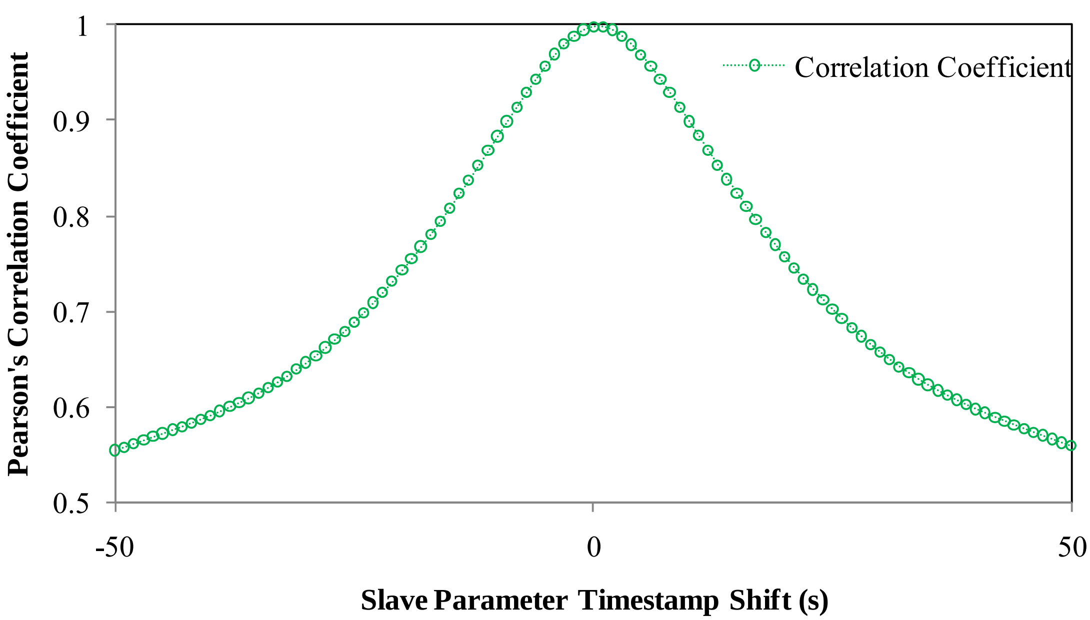



**Figure 10.** Coefficient of correlation for vehicle speed from OBD and GPS after synchronization

### Effect of Synchronization on VSP and MAP Modal Model Results

Sensitivity analysis of VSP and MAP modal model results with respect to synchronization was conducted using real-world in-use emissions measurement of a 1997 make, 2.2 liter, 130HP Honda Accord with 228,000 miles on the odometer. Starting with second by second data (approx. 12550 seconds), the datasets for PEMS, OBD, and GPS are synchronized using the visual and PCC technique explained previously. This is the base case and subsequent cases are created by shifting either OBD or GPS data by 5 or 10 seconds. VSP based results for fuel use and pollutant mass emission rates are generated for both OBD and GPS data shifts while MAP based results for fuel use and pollutant mass emission rates are generated for only OBD data shifts (since GPS data does not influence MAP based results).

VSP based fuel use, VSP based $NO_x$ mass emissions rate, and MAP based $NO_x$ mass emissions rate are significantly affected when OBD data is out of sync with PEMS and GPS data.

**Results for VSP and MAP based fuel use:** For OBD data out of sync by +5 seconds, fuel use rate increased by 12.6% for VSP mode 1 and 6.1%, 5.5%, and 6.1% for VSP modes 2, 3, and 4 respectively. For the same case, fuel use rate decreased by 3% and 4.5% for VSP modes 11 and 13. A shift of +10 seconds to OBD data resulted in fuel use numbers for VSP modes 1, 2, 3, and 4 increasing by 32.6%, 8.9%, 8.6%, and 13.6% respectively. At the same time fuel use rates decreased by more than 6% for VSP modes 10, 11, and 12 and more than 16% for VSP modes 13 and 14. Results for VSP based fuel use when the OBD data is shifted are shown in Figure 11. MAP based fuel use results show lower sensitivity to OBD data shift. When the OBD data is shifted by +5 seconds, fuel use for normalized MAP mode 0.1 decreased by 4.7% and increased by 7.5% for the same mode when the data is shifted by +10 seconds. When GPS data is shifted by 10 seconds, fuel use increased by 26.3%, 10.8%, and 9.4% for VSP modes 1, 2, and 4.

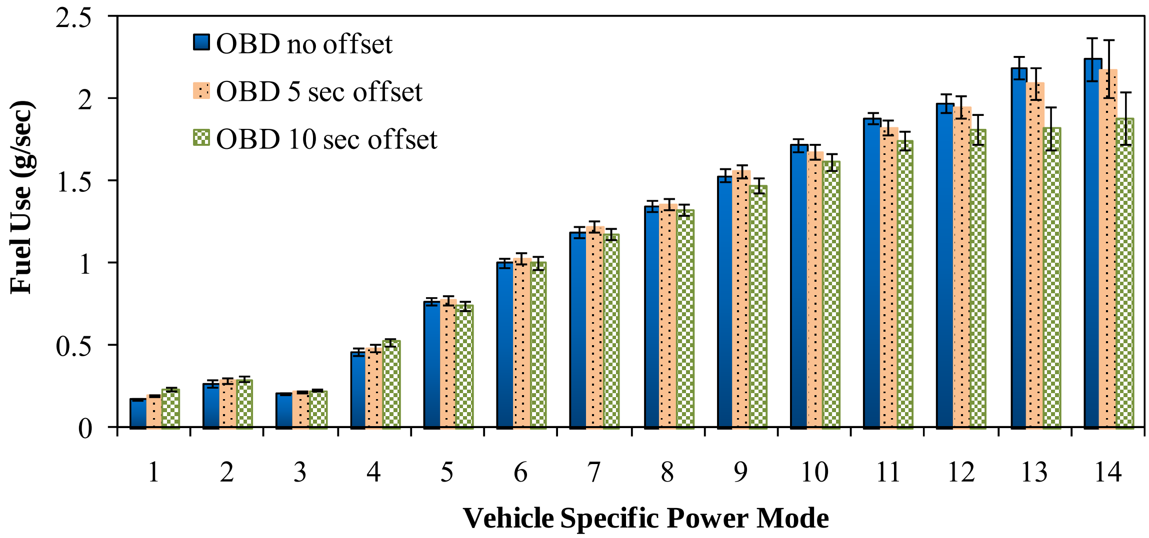



**Figure 11.** Effect of shifting OBD Data on VSP based Fuel Use Rate

**Results for VSP and MAP based $NO_x$ emissions rate:** When OBD data is shifted by +5 seconds, VSP based $NO_x$ emissions rate increased by 15.7%, 10.4%, and 77.3% for modes 1, 2, and 3 respectively and decreased by 18.3% for mode 13. A +10 second shift to OBD data resulted in $NO_x$ emissions rate increasing by 48.9% and 126.4% for VSP modes 1 and 3. At the same time $NO_x$ emissions rate decreased by 22% to 48% for modes 9 to 14. Results for $NO_x$ emissions rate when OBD data is shifted are shown in Figure 12. A shift of +5 seconds to OBD data decreased the $NO_x$ emissions rate by 13.6% for MAP mode 0.1 and increased the emissions rate by 16.6% for MAP mode 0.3. For a +10 second shift to OBD data, $NO_x$ emissions rate 26.3% and 49.3% for MAP modes 0.2 and 0.3 and decreased by 24.8%, 38%, and 29.1% for MAP modes 0.8, 0.9, and 1. A shift of +10 seconds to GPS data increased $NO_x$ emissions rate by 32.1% and 26.6% for VSP modes 1 and 4.

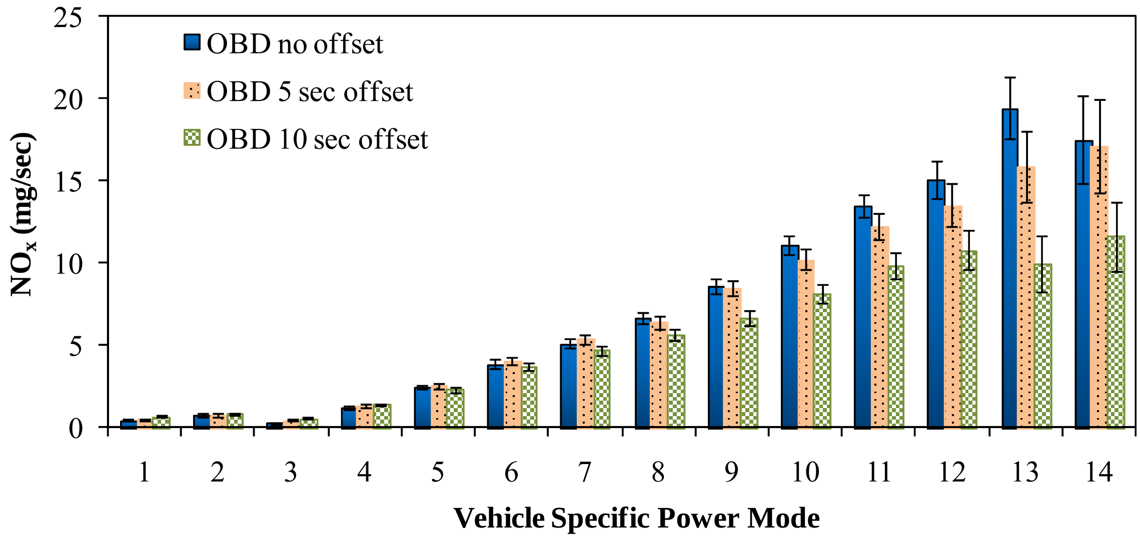



**Figure 12.** Effect of shifting OBD data on VSP based $NO_x$ Emissions Rate

### 5.3. Intake Air Temperature

In a field test of a 15 liter HDDV combination truck, the sensor array connected to the PEMS experienced communication problems that resulted in data having spurious IAT values. The updated IAT algorithm was able to recognize a total of 605 seconds of erroneous IAT data (out of total test duration of 29254 seconds) out of which 560 seconds were correctly interpolated. The previous algorithm had marked 1031 seconds as error many of which were false positives and did not use interpolation to save any seconds from being deleted. Figure 13 shows a section of the test with error IAT values and subsequently interpolated IAT values.

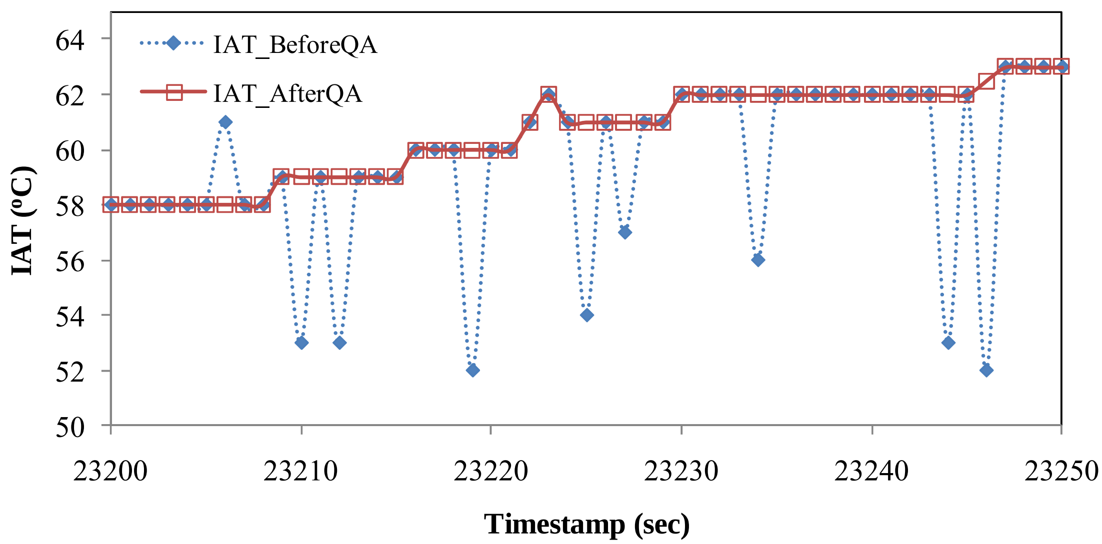



**Figure 13.** Test data with error IAT readings corrected by the IAT algorithm

### 5.4. Road Grade Estimation

Road grade, calculated using GPS data from real-world in-use emissions testing of a LDGV, with $RG_{step}$ values of 0.1 mile, 0.05 mile, and 0.25 mile is shown in Figure 14. A smaller $RG_{step}$ is better able to capture the change in road grade while a larger $RG_{step}$ is more immune to noise in elevation and position data. Road grades calculated using $RG_{step}$ = 0.05 mile have higher rate of change than actual and more seconds have values outside of the ±10% range (which is the typical range for city and highway roads). $RG_{step}$ value of 0.25 mile result in loss of resolution of actual road grade variation, especially for hilly road sections.

In the field test the GPS unit recorded a total of 14623 seconds of data. Road grade calculated with $RG_{step}$ of 0.1 mile resulted in 0.34% seconds falling outside of ±10% range. Similarly, for $RG_{step}$ values of 0.01 mile and 0.25 mile, 0.56% and 0% seconds had values outside of ±10% range. However, road grade calculated as change in elevation per second over distance travelled per second produced 22% seconds with road grade outside of ±10% range.

A cumulative frequency of the road grades using different $RG_{step}$ values for the complete test duration is shown in Figure 15.

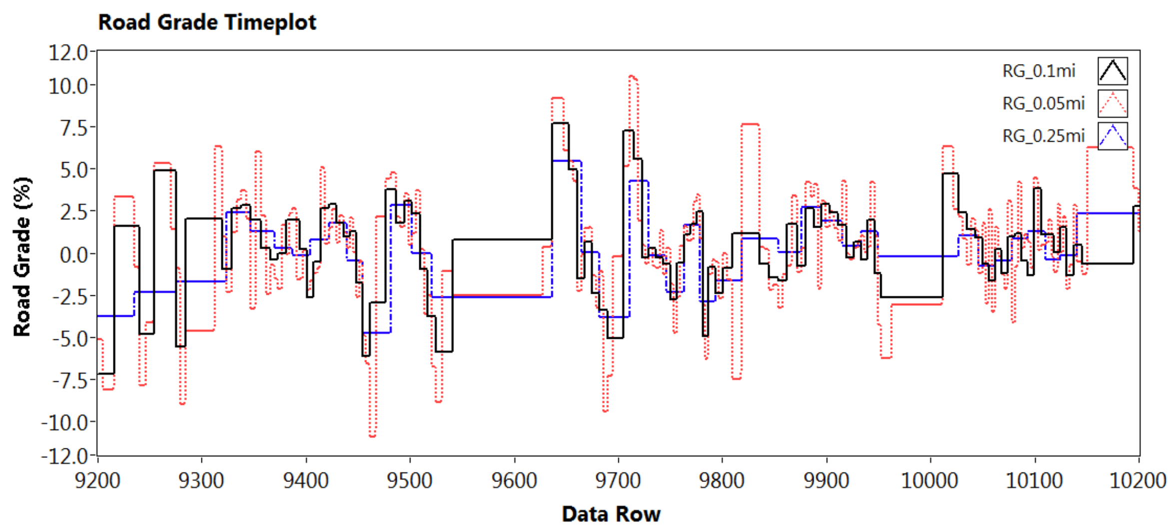



**Figure 14.** Comparison of road grades for $RG_{step}$ values of 0.1 mile, 0.05 mile, and 0.25 mile

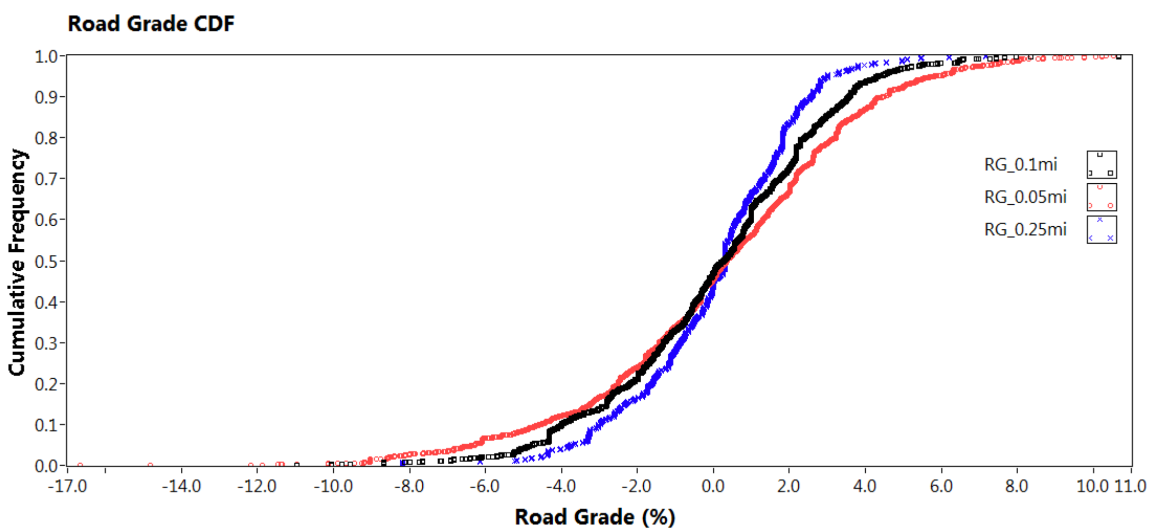



**Figure 15.** CDF for roadgrades calculated using $RG_{step}$ values of 0.1, 0.05, and 0.25 mile

**Effect of $RG_{step}$ on VSP Modal Results**

The effect of choice of $RG_{step}$ value on VSP based modal model fuel use and pollutant emissions rate is evaluated. Results with $RG_{step}$ = 0.1 mile is taken as basis for comparison of results with $RG_{step}$ values of 0.05 mile and 0.25 mile. $RG_{step}$ did not significantly impact VSP based fuel use, CO, and $CO_2$ emission rates. For both fuel use and $CO_2$ emissions rate the highest impacts were 6.3% increase for VSP mode 1 when $RG_{step}$ = 0.05 mile and a 4% increase for VSP mode 9 when $RG_{step}$ = 0.25 mile. For CO emissions rate were generally affect by less 5% except for a 24% jump for VSP mode 1 when $RG_{step}$ =0.25 mile. $NO_x$ emissions rate increased by 13.8% and 16.4% for VSP mode 1 and 3 when $RG_{step}$ = 0.05 and decreased by 11% for the same road grade criteria. With $RG_{step}$ = 0.25 mile $NO_x$ emissions rate saw a 2% to 10% increase for VSP modes 1 to 10 and dropped by 16% for VSP mode 14. HC emissions rate increased by 11% for VSP mode 1 and 12 with $RG_{step}$ = 0.05 mile. An increase of 33%, 18%, and 16% in HC emissions rate was observed for VSP modes 1, 4, and 12 when $RG_{step}$ =0.25 mile. VSP based results for $NO_x$ and HC emissions rate is shown in Figure 16 and Figure 17.

In general, road grades calculated using the $RG_{step}$ scheme provide numbers that are within known extremes. An $RG_{step}$ value within a reasonable range (0.05 mile to 0.25 mile) does not significantly affect the VSP based results. This may change if the test route involves larger percentage of hills, in which case a smaller $RG_{step}$ value may produce more accurate results.

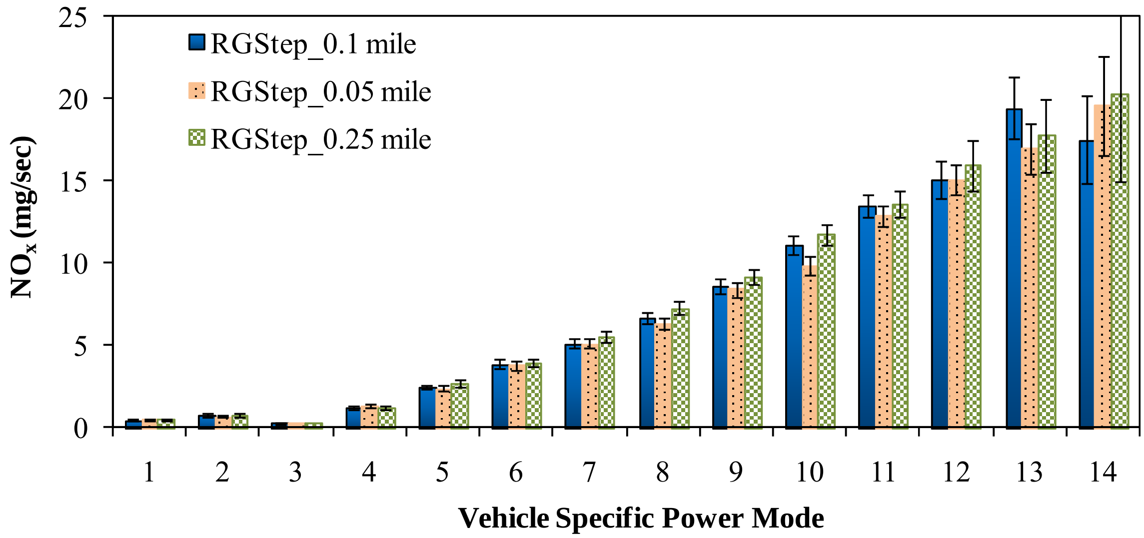



**Figure 16.** Effect of $RG_{step}$ criteria on VSP based $NO_x$ Emissions Rate

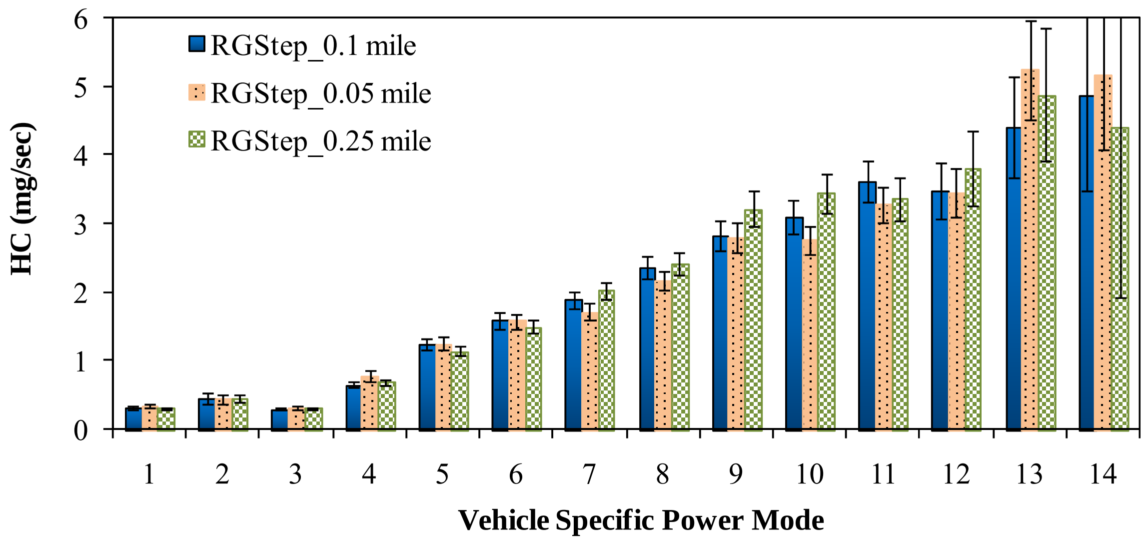



**Figure 17.** Effect of $RG_{step}$ criteria on VSP based HC Emissions Rate

## 6. Conclusions

Second-by-second emissions rate calculated using the speed-density method is highly sensitive to MAP and RPM values. The use of proper installation, calibration, and verification of these two parameters is important to the accuracy of final mass per time fuel use and emissions rate. Synchronization of multiple data stream from independently functioning instruments is another important step in quality assurance. Pearson's Correlation Coefficient can be used to approximate the correct synchronization setting. However, it is not always accurate and the visual technique of matching rising or falling slopes is to be used as the ultimate check.

Improperly synchronized OBD and GPS datasets, with respect to PEMS dataset, can affect VSP based fuel use rate and NOx mass per time emissions rate by 33% and 49%. MAP based fuel use rate show lesser sensitivity to time misalignment but even then the modal fuel use rates can be affected by up to 26%. In all cases, there is substantial reduction in the highest modal rates and less variability when comparing highest to lowest modal rates.

The use of a least square fit line approach provides road grade estimates that are more robust, as compared to a simple second by second gradient calculation, to elevation data noise and overall the estimates are consistently within actual road grade range. The VSP modal results are not significantly sensitive to road grade estimates estimated using this approach which further highlights the usefulness of this technique.

# Chapter 2 Methods for Field Comparison of Alternative Fuels

## 1.0 Introduction

The purpose of this study is to apply a methodology for real-world evaluation of a fuel additive in order to assess the change in fuel economy and emissions before and after the additive is used. The methodology features the use of portable emission measurement systems (PEMS) for the purpose of quantifying the activity, fuel use, and emissions of vehicles during actual duty cycles. A baseline test for B20 (20% Biodiesel, 80% Petroleum Diesel) was conducted without the Fuel additive for three tractor trailer trucks owned and operated by the North Carolina Department of Transportation (NCDOT). A second test was conducted to measure the fuel economy and emissions with the additive.

North Carolina State University (NCSU) has been a pioneer in the development and application of procedures for real world data collection of in-use vehicles using Portable Emission Measurement Systems (PEMS). Beginning in 1999, NCSU has conducted field studies of the activity, fuel use, and emissions of light duty vehicles (Frey *et al.*, 2003). Beginning in 2004, NCSU conducted field studies on comparison of B20 versus petroleum diesel for heavy duty diesel vehicles, including dump trucks (Frey and Kim, 2006). Since 2005, NCSU has been conducting field studies on nonroad vehicles, including bulldozers, backhoes, front end loaders, motor graders, excavators, off-road dump trucks, and skid steer loaders (Frey *et al.*, 2008a; Frey *et al.*, 2008b). NCSU has provided technical assistance on several other projects, including assessment of activity, fuel use, and emissions of vehicles on dirt versus paved roads, assessment of light duty diesel vehicle emissions in England, and assessment of the effect of a Fuel additive on fuel use and emissions (in progress).

## 2.0 Background

Commonly used methods for measuring vehicle energy use and emissions include engine dynamometers, chassis dynamometers, tunnel studies, remote sensing, and on-board measurement. Available data regarding heavy-duty vehicle emissions is typically from engine dynamometer measurements. These data are reported in units of g/bhp-hr, which are not directly relevant to in-use emissions estimation. Furthermore, many engine dynamometer test cycles are based upon steady-state modal tests that are not likely to be representative of real world emissions. Although there are also transient engine dynamometer tests, it is not likely that any particular standardized test cycle will be representative of operation of a particular type of vehicle and real world duty cycle.

Chassis dynamometer tests provide emissions data in units that are more amenable to the development of emission inventories, such as grams of pollutant emitted per mile of vehicle travel. This emission factor can be multiplied by estimates or measurements of vehicle miles traveled to arrive at an inventory. These tests are expensive and the number of heavy duty dynamometer facilities is limited. The applicability of chassis dynamometer test results to real world emissions is limited by the potential lack of representativeness of standard test cycles.

Tunnel studies are based upon measurements for a specific link of roadway and thus are not representative of an entire duty cycle. Tunnel studies are limited in their ability to discriminate among specific vehicle types.

Remote sensing can be used to measure emissions from any vehicle that passes through the infrared and, if available, ultraviolet beams that are used to measure pollutant concentrations. Each measurement is only a snap shot at a particular location, and thus cannot characterize an entire duty cycle.

On-board emissions measurement systems offer the advantage of being able to capture real world emissions during an entire duty cycle. In particular, Portable Emissions Measurement Systems (PEMS) that are more easily installed in multiple vehicles than complex on-board systems, are selected for use in this study.

# 3.0 Technical Approach

The general technical approach for this project involved four major components: (1) the Portable Emission Measurement System (PEMS) instrumentation; (2) preparation for field data collection; (3) field data collection; and (4) quality assurance and quality control. Each of these components of the technical approach is described.

## 3.1 Portable Emission Measurement System

The OEM-2100 Montana system is comprised of two parallel five-gas analyzers, a PM measurement system, an engine sensor array, a global position system (GPS), and an on-board computer. The two parallel gas analyzers simultaneously measure the volume percentage of carbon monoxide (CO), carbon dioxide ($CO_2$), hydrocarbons (HC), nitrogen oxide (NO), and oxygen ($O_2$) in the vehicle exhaust. The PM measurement capability includes a laser light scattering detector and a sample conditioning system. A temporarily mounted sensor array is used to measure Manifold Absolute Pressure (MAP), intake air temperature, and engine RPM in order to estimate air and fuel use. A GPS system measures vehicle position. The on-board computer synchronizes the incoming emissions, engine, and GPS data. Intake airflow, exhaust flow, and mass emissions are estimated using a method reported by Vojtisek-Lom and Cobb (1997).

The gases and pollutants measured include $O_2$, HC, CO, $CO_2$, NO, and PM using the following detection methods:

- HC, CO and $CO_2$ using non-dispersive infrared (NDIR). The accuracy for CO and $CO_2$ are excellent. The accuracy of the HC measurement depends on type of fuel used.

- NO measured using electrochemical cell. On most vehicles with Tier 2 or older engines, $NO_x$ is comprised of approximately 95 volume percent NO.
- PM is measured using light scattering, with measurement ranging from ambient levels to low double digits opacity.

The Montana System is designed to measure emissions during the actual use of the vehicle or equipment in its regular daily operation. The complete system comes in two weatherproof plastic cases, one of which contains the monitoring system itself, and the other of which contains sample inlet and exhaust lines, tie-down straps, AC adapter, power and data cables, various electronic engine sensor connectors, and other parts. The monitoring system weighs approximately 35 *lbs*. The system typically runs off of the 12V DC vehicle electrical system, using the cigarette lighter outlet. The power consumption is 5-8 Amps at 13.8 V DC. The components of the sensor array, including the MAP sensor, engine RPM sensor, and IAT sensor, are briefly described.

#### *3.1.1 Manifold Air Boost Pressure Sensor*

In order to measure MAP, a pressure sensor is installed on the engine. For most heavy duty diesel engines, there is a port on the engine after the turbocharger. For example, Figure 1 depicts the location of an existing port on the intake air manifold of a Cummins ISX-500 engine. In a regular engine performance check, this port is used for performance testing of the turbocharger. An existing bolt is removed and a barb fitting is screwed into the port. Plastic tubing is used to connect the MAP sensor to the barb fitting. The MAP sensor is attached to a convenient location in the engine, away from a hot surface, using plastic ties. The MAP sensor provides manifold air pressure data for the computer of the main unit through a cable that connects the sensor to the MAP port located in the back of the main unit.

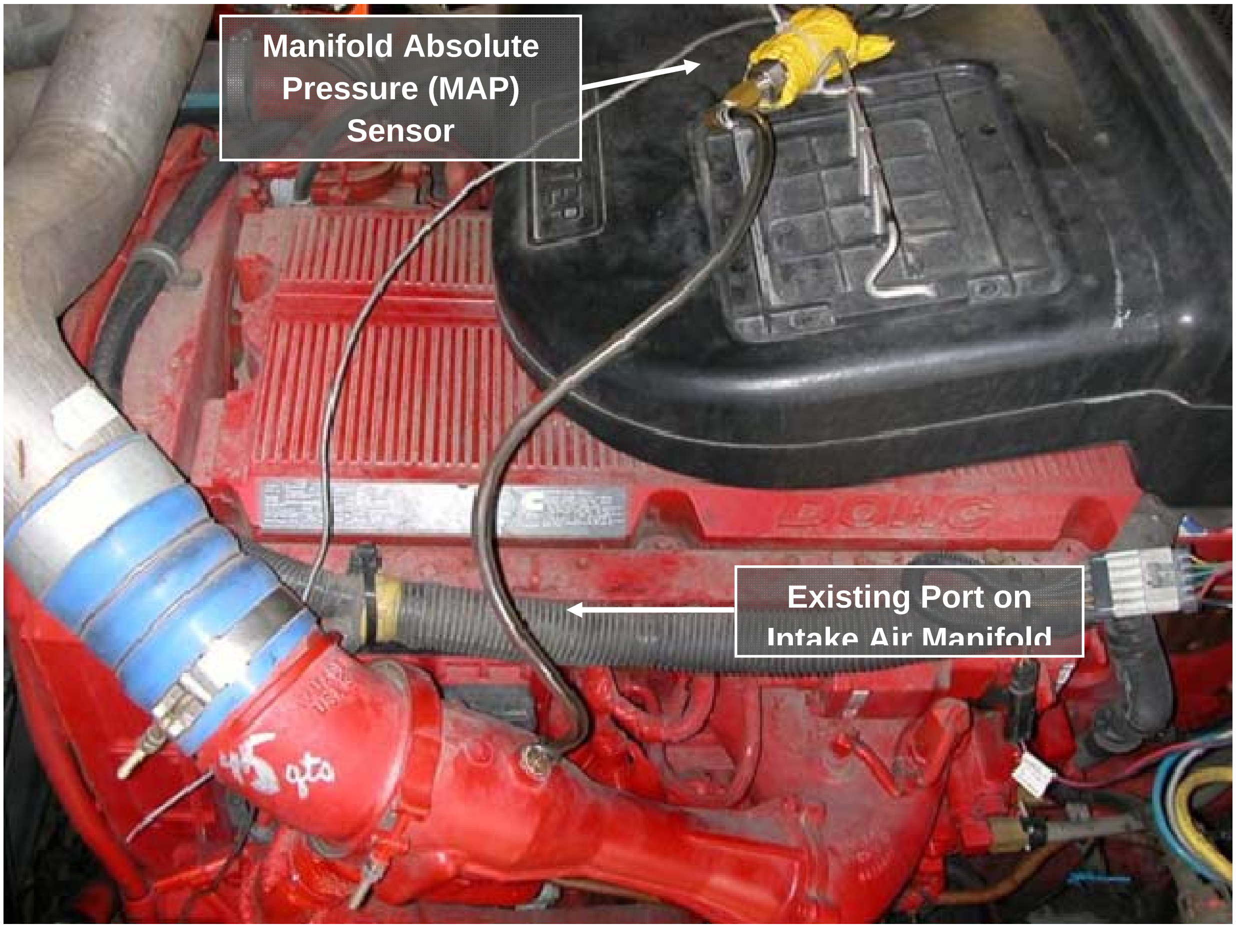



**Figure 18. Placement of the Manifold Absolute Pressure Sensor on a Cummins ISX-500 Engine (Truck 215-6415).**

### *3.1.2 Engine Speed Sensor*

The engine speed sensor is an optical sensor used in combination with reflective tape to measure the time interval of revolutions of a pulley that rotates at the same speed as the engine crankshaft. The engine speed sensor has a strong magnet to attach easily on metal materials. The reflective tape must be installed on a pulley that is connected to the crankshaft. The placement of the reflective tape and the optical sensor for a Cummins ISX-500 engine is shown in Figure 2. Some of the key factors in placement of the sensor include: (1) avoid proximity to the engine cooling fan and other moving components; (2) place the sensor in a location where the magnet can securely affix the sensor to a surface; and (3) place the sensor so that its cable can reach the sensor array box, which is located in the driver cabin. The signal from the RPM sensor is transmitted by cable to a sensor array box, which in turn transmits the signal by a second cable to the main unit of the Montana system.

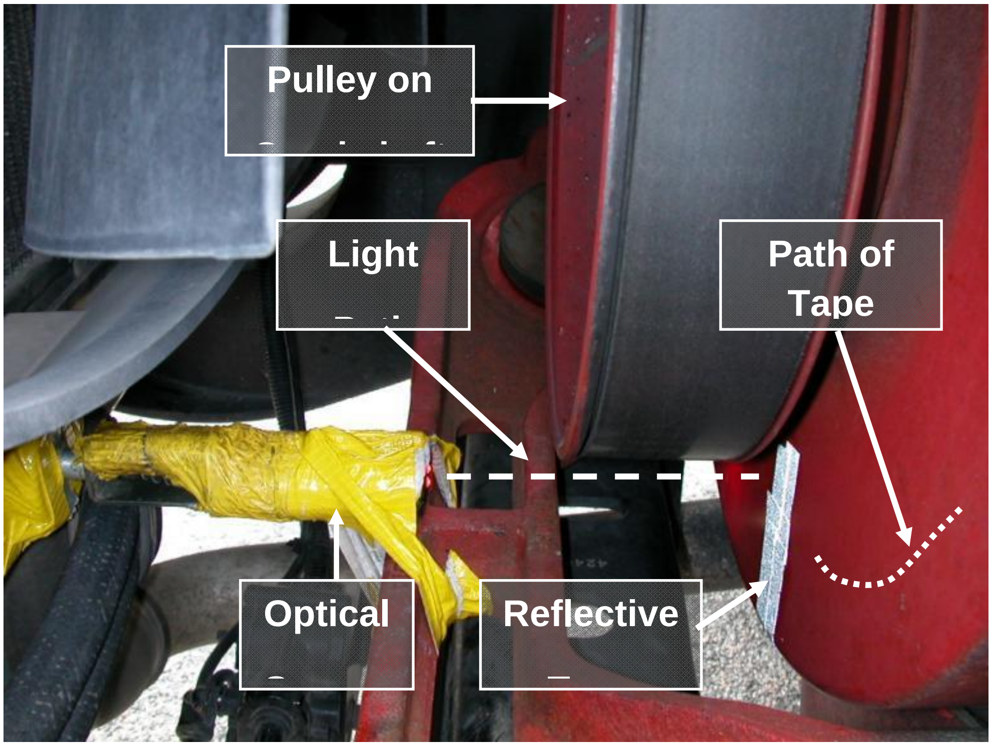



**Figure 19. Placement of Optical Engine RPM Sensor and Reflective Tape on ISX-500 Engine (Truck 215-6415)**

### *3.1.3 Intake Air Temperature Sensor*

The engine intake air sensor is a thermocouple that is installed in the intake air flow path. Installation of the intake air temperature sensor is somewhat easy compared to the engine speed and MAP sensors. Using duct tape or a plastic tie, one can fix the intake air temperature sensor near the intake air flow where the MAP port is located.

### *3.1.4 Sensor Array Box*

The sensor array box provides signal conditioning and data acquisition for the intake air temperature and engine speed sensors. The temperature and speed signal data is collected by the sensor array box and converted from an analog to a digital RS-232 serial signal which is transmitted to the PEMS main unit. The sensor array box was placed in the driver cabin close to the PEMS main unit. The temperature and speed sensors which were in the engine compartment are connected to the sensor array box using appropriate cables.

### *3.1.5 Operating Software*

The Montana System includes a laptop computer that is used to collect and synchronize data obtained from the engine scanner, gas analyzers, and GPS system. Data from all three of these sources are reported on a second-by-second basis. The computer is controlled either by touching the screen or plugging in a keyboard. Upon startup, the computer queries the user regarding information about the test vehicle, fuel used, test characteristics, weather conditions, and operating information. Most of this information is for identification purposes. However, the fuel type and composition, engine displacement, sample delivery delays, unit configuration, intake air sensor configuration, and volumetric efficiency are critical inputs that affect the accuracy of the reported emission rates. The details of the definition and significance of each of these are detailed in the Operation Manual of the instrument (CATI, 2003).

The software provides a continuous display of data during normal operation, including gas analyzer data, engine scanner data, GPS data, and calculated quantities including the emission rate in units of mass per time. The following parameters are typically available on-screen on a second-by-second basis: engine rpm, MAP, concentrations of the measured pollutants, exhaust flow, fuel consumption, and mass flow rates of the measured pollutants.

### *3.1.6 Validation and Calibration*

The Montana System gas analyzer utilizes a two-point calibration system that includes "zero" calibration and "span" calibration.

Zero calibration is performed using ambient air at frequent intervals (every 5-15 minutes at power up, every 30 minutes once fully warmed up). Although zero-air stored in bottles or generated using an external zero-air generator can be used, it is believed that the ambient air pollutant levels are negligible compared to those found in undiluted exhaust; therefore, ambient air is viewed as sufficient for most conditions. For zero calibration purposes, it is assumed that ambient air contains 20.9 *vol*-% oxygen, and negligible NO, HC, or CO. $CO_2$ levels in ambient air are approximately 300-400 ppm, which are negligible compared to the typical levels of $CO_2$ in exhaust gases.

Span calibration is performed using a BAR-90 low concentration calibration gas mixture, which has a known gas composition. The calibration gas includes a mixture of known concentrations of $CO_2$, CO, NO, and hydrocarbons, with the balance being $N_2$. Span gas calibration is recommended once every three months. The gas analyzer NDIR subsystem used in the gas analyzers is very stable and tends not to drift significantly from their span calibrations.

Data from several laboratories using various vehicles and fuels suggests that when the Montana System is operated simultaneously with the laboratory system, the difference is typically less than 10% for aggregate mass $NO_x$ and $CO_2$. The accuracy of HC and CO measurements depends on the fuel used and on the emission levels (Vojtisek-Lom and Allsop, 2001).

### *3.1.7 System Setup and Operation*

The time to install the instrument on the study trucks is typically two hours. Figure 3 illustrates several aspects of the installation of the PEMS, using the example of truck 5715. In Figure 3, the portable instrument is shown, including its placement inside the vehicle and the connections for DC power, engine data, and exhaust sampling hoses. Figure 4 shows the use of a cigarette lighter port to draw the required DC power necessary to power the PEMS main unit, the placement of the GPS antenna on the roof, and setup of the exhaust sampling lines from the truck exhaust pipe to the passenger cabin. Figure 5 displays the routing of sampling hoses to the instrument via the passenger window, the MAP sensor, and the engine RPM sensor.

**Figure 20. Installation of the Portable Emissions Measurement System (PEMS) Main Unit in a Truck 215-5715:**

*(a) the portable unit on a passenger seat (front-view); (b) the portable unit on a passenger seat (rear-view); (c) routing exhaust hoses from PEMS through the window.*

**Figure 21. Installation of the Portable Emissions Measurement system (PEMS) Power Cable, GPS Receiver, and Exhaust Sampling Lines in a Truck 215-5715:**

*(a) accessing power from the vehicle's cigarette lighter; (b) GPS receiver on the roof of the test vehicle; (c) sampling exhaust gases using a probe secured with a hose clamp.*

**Figure 22. Installation of the Portable Emissions Measurement System (PEMS) Sampling Hoses and Engine Sensors in a Truck 215-5715:**

*(a) routing sampling hoses through the window, secured with ties (front-view); (b) Installation of MAP sensor; (c) Installation of RPM sensor.*

After completing all installation steps, the instrument needs to warm up for approximately 45 minutes. This time period is recommended in order to ensure consistency of measurements made by the instrument (CATI, 2003).

During testing, periodic checks of the system status are recommended. For example, the security of all connections with the vehicle should be evaluated. This can be done by determining whether engine data is updated on the instrument display in an appropriate manner, whether the gas concentrations are reasonable, and whether the instrument is receiving power. If any of the data relating to gas concentration and/or engine parameter is "frozen" or missing, then it will be necessary to reboot the PEMS main unit. If the $CO_2$ gas concentration is very low, then there could be a leakage in the sampling line and therefore inspection and repositioning of the sampling line may be indicated.

### 3.2 Preparation for Field Data Collection

Preparations for field data collection include three major components: (1) verification of the status of the PEMS and that all necessary parts and consumables are available; (2) laboratory calibration of the PEMS; (3) completion of a field study design; and (4) coordination with the vehicle owner/operator regarding scheduling of the test and access to the vehicle.

As part of preparation, NCSU ensured that the PEMS had appropriate electrochemical sensors for NO and $O_2$, and that all consumables/replacement parts were replaced, such as filters in the sampling line. NCSU conducted a calibration of the PEMS using a standard calibration gas.

Field study design includes specifying which vehicles are to be tested, when they are to be tested, what fuel will be used, what type of duty cycle will be performed, and who will operate the vehicle. As part of this project, NCDOT allowed NCSU to access selected vehicles for testing. Three vehicles were tested. Each vehicle was tested during one day when operated on B20 biodiesel without the Fuel additive, and a repeat test was made on another day when operated on B20 biodiesel with the Fuel additive (B20FA). NCDOT obtained the fuel and fueled the vehicles.

NCDOT provided a driver/operator for each vehicle. NCSU instrumented each vehicle and used the instrument to observe the vehicle during normal activity.

### 3.3 Field Data Collection Procedure

NCSU used the OEM-2100 Montana system PEMS for data collection. This PEMS and the key aspects of instrumenting a vehicle are described in the text below. Figure 6 provides an example of a check list that is used during pre-installation and on test day.

Field data collection includes the following main steps: (1) pre-installation; (2) final installation; (3) data collection; and (4) decommissioning.

**Pre-installation** was performed the morning or afternoon before a scheduled test. This step involves installing on the vehicle the exhaust gas sampling lines, power cable, and engine data sensor array. Exhaust gas sampling lines have a probe that is inserted into the tailpipe. The probe is secured to the tailpipe using a hose clamp. The sampling line is secured to various points on the chassis of the vehicle using plastic ties. The sampling line is routed through the passenger side window of the truck cab so that it can be connected to the Montana main unit. Likewise, a power cable is routed from the cigarette lighter port. An engine sensor array was used to measure manifold absolute pressure (MAP), engine revolutions per minute (RPM), and intake air temperature (IAT). MAP, RPM, and IAT are used, in combination with the measured exhaust gas composition, to estimate the fuel and air flow through the engine. The engine sensor array includes an MAP sensor that is connected to an existing port on the intake air manifold of the engine. The RPM sensor is based on an optical device that detects the reflection of light from reflective tape that is placed on a pulley wheel that rotates at the same RPM as the engine. IAT is measured with a thermocouple. The amount of time for pre-installation was approximately two hours per vehicle.

**Final installation** was performed in the morning prior to field data collection. The Montana system was secured in the cab of the vehicle and was connected to the exhaust sample lines, engine data cables, and power cable. In addition, a GPS receiver was deployed. As part of final installation, the Montana system main unit was warmed up for about 45 minutes. The research assistant entered data into the Montana system regarding vehicle characteristics and fuel type.

**Data collection** involved continuously recording, on a second-by-second basis, exhaust gas concentration, engine, and GPS data. The research assistant followed the test vehicle in a pick-up truck and periodically checked on the status of the PEMS during a break in work activity, in order to determine quickly if any problems arose during data collection that could be corrected. For example, sometimes there can be a loss of signal that can be corrected by checking connections in a cable. Sometimes the gas analyzers "freeze" (they fail to continuously update) which can be corrected by rebooting the gas analyzer. However, these problems did not occur during the testing.

**Decommissioning** occurs after the end of the test period. During decommissioning, the NCSU research assistant discontinued data collection, copied data that have been collected, powered down the Montana system, and removed the exhaust sample lines, power cable, data cable, and GPS receiver and cable.

The use of the PEMS did not involve any modification to the vehicle.

PRE-INSTALLATION

- Check if filter in gas sampling line needs to be replaced
- Install sampling (Gas and PM) probes into vehicle exhaust and connect other end (with sampling bowls) to Montana
- Install exhaust (3) lines and zeroing (1) line and connect to Montana
- Install Montana GPS unit on roof. Connect to Montana data port and DC power port on 3-way splitter
- Install Garmin GPS (3) antenna on roof and connect to respective handset
- Install RPM sensor and connect wire to sensor array box
- Install Temperature sensor and connect wire to sensor array box
- Install MAP sensor and connect wire to Montana
- Connect sensor array box to Montana
- Connect 3-way power splitter to vehicle DC power port (cigarette lighter port)
- Connect Montana power to 3-way splitter
- Check MAP, RPM, Temperature values
- Check Gas concentrations and PM level
- Check GPS fix (might not work indoors)

TEST DAY

- Warm-up Montana for at least 45 minutes
- Turn on Garmin GPS (3)
- Install Montana in vehicle seat, insert bottom padding if required
- Connect power cable (Montana to DC splitter)
- Connect MAP cable to Montana
- Connect Sensor Array cable to Montana
- Connect Gas and PM sampling lines to Montana
- Connect exhaust lines (3) and zeroing line (1) to Montana
- Connect Montana GPS to data port and power port
- Secure sampling lines so that they do not interfere with gear shift
- Check MAP, RPM, Temperature values
- Check Gas concentrations and PM level
- Check Montana GPS fix
- Take Odometer reading ____________________ (miles)

**Figure 23. Example of a Check-List for Installation of the Montana System on a Vehicle**

## 3.4 Quality Assurance and Quality Control

For quality assurance purposes, the combined data set for a vehicle run is screened to check for errors or possible problems. If errors are identified, they are either corrected or the data set is not used for data analysis. First, the types of errors typically encountered are described followed by a discussion of methods for making corrections.

The predominant types of errors or problems include:

### *Engine Data Errors*

On occasion, communication between the vehicle's onboard computer and the engine scanner may be lost, leading to loss of data. Sometimes the loss of connection is because of a physical loss of electrical contact, while in other cases it appears to be a malfunction of the vehicle's on-board diagnostic system. This rarely happens. However, when it happens, this error can be solved easily by rebooting the system in the field. After rebooting, the computer begins logging a new data file automatically. Thus, when this is noticed in the field, this error can be addressed. Loss of engine data is also obvious from the data file, since the missing data are evident and any calculations of emission rates are clearly invalid. The following types of engine errors are included in the quality assurance procedure:

(1) Unusual Engine RPM

Engine RPM typically varies from not less than 600 RPM during idling to about 3,000 RPM during most kinds of vehicle operation. As a conservative estimate, the bounds for possible engine RPM were set as greater than or equal to 600 RPM and less than or equal to 10,000 RPM (Qiao *et al*., 2005). Thus, if engine RPM is less than 600 or greater than 10,000 RPM, those data need to be removed for the further data analysis. However, this problem did not occur in any of the data collected in our previous work for NCDOT. This error occurred only briefly during one test.

(2) Engine RPM Freezing

"Freezing" refers to situations in which a value that is expected to change dynamically on a second-by-second basis remains constant over an unacceptably or implausibly long period of time. Engine RPM tends to fluctuate on a second-by-second basis even if the engine is running at approximately constant RPM. Therefore, we performed a check to identify situations in which engine RPM remained constant for more than three seconds. This problem occurs only in situations where the engine scanner became physically disconnected from the data logging computer. This type of error is rare and did not occur during these tests.

***Gas Analyzer Errors***

The Montana system has two gas analyzers, which are referred to as "benches." Most of the time, both benches are in use. Occasionally, one bench is taken off-line for "zeroing." Therefore, most of the time, the emissions measurements from each of the two benches can be compared to evaluate the consistency between the two. If both benches are producing consistent measurements, then the measurements from both are averaged to arrive at a single estimate on a second-by-second basis of the emissions of each pollutant.

When the relative error in the emissions measurement between both benches is within five percent, and if no other errors are detected, then an average value is calculated based upon both of the benches.

However, if the relative error exceeds five percent, then further assessment of data quality is indicated. A discrepancy in measurements might be due to any of the following: (a) a leakage in the sample line leading to one bench; (b) overheating of one of the benches; or (c) problems with the sampling pump for one of the benches, leading to inadequate flow. If one of these problems is identified for one of the benches, then only data obtained from the other bench was used for emissions estimation. When problems are identified in the field, then attempts are made to resolve the problems in the field. For example, if a leak or overheating problem is detected during data collection, then the problem is fixed and testing resumes.

Data recorded during the period when a leak or overheating event occurred are not included in any further analyses. However, no gas analyzer errors were detected in these tests.

### *Zeroing Procedure*

For data quality control and assurance purpose, each gas analyzer bench is zeroed alternatively every 15 minutes. While zeroing, the gas analyzer will intake ambient air instead of tailpipe emissions. After zeroing is finished, a solenoid valve changes the intake from ambient air to the tailpipe. There is a period of transition when this occurs. In particular, the oxygen sensor needs several seconds to respond the switching of gases, since there is a large change in oxygen concentration when this switch occurs. To allow adequate time for a complete purging of the previous gas source from the system, a time delay of 10 seconds is assumed. Thus, for 10 seconds before zeroing begins, the time period of zeroing, and 10 seconds after zeroing ends, data for the bench involved in zeroing are excluded from calculations of emission rates, and the emission rates are estimated based only upon the other bench.

### *Negative Emissions Values*

Because of random measurement errors, on occasion some of the measured concentrations will have negative values that are not statistically different from zero or a small positive value. Diesel vehicles typically produce HC emissions less than gasoline vehicles do (Durbin *et al.*, 2000). Thus, it is frequently the case that HC emission measurements are very low and not substantially different from zero. Negative values of emissions estimates were assumed to be zero and were replaced with a numerical value of zero. There were no negative values observed in these tests that were significantly different from zero.

### *Air Leakage*

Air Leakage quality procedure is used to eliminate some of the data which affected by the problem of ambient air infiltration into the exhaust gas sampling stream. This infiltration could occur anywhere in the exhaust gas flow path between vehicle exhaust pipe and gas analyzers. Air Leakage is decided based on value of Air to Fuel Ratio (AFR), which is the mass-basis ratio of intake air to fuel consumption. A data second having AFR greater than the threshold value of AFR and one or more gas concentration lower than PEMS's precision level is eliminated.

***Invalid Data***

Sometimes the PEMS would not record valid concentration data for the gases and/or valid RPM value. In such instances the value for the parameter (gas concentration or RPM) is recorded as zero, and the corresponding column for validity is marked as “NO” by the PEMS. These seconds of data are marked as “invalid” by the QA procedure. This error is sparse, and since the basic data is missing the QA procedure deletes the said second of data.

***Loss of Power to Instrument***

A loss of power to the instrument resulted in a complete loss of data collection during the time period when power was not available. However, the system saves data up to the point at which the power loss occurs. A typical cause of power loss for manual transmission vehicles is stalling of the engine due to a problem shifting. Such problems typically occur when going from idle into first gear, or for the lower gears. After a loss of power, the instrument needs to be rebooted, which takes approximately five to ten minutes. During the power loss and rebooting, no data can be collected.

NCSU has developed a series of Macros in Visual Basic, in conjunction with MS Excel. Raw data from the Montana system is processed via these macros to identify data quality problems. Where possible, such problems are corrected. If correction is not possible, then the errant data are omitted from the final database used for analysis.

## 4.0 Results

The results include the field data collection schedule, vehicle characteristics and test conditions, quality assurance, and detailed characterization of each vehicle.

## 4.1 Scheduling of Field Data Collection

Field data collection occurred during a period from June 9, 2009 to August 11, 2009, as summarized in Table 1. The baseline tests with B20 for each vehicle were conducted in quick succession and all three trucks were tested within the second and third week of June 2009. A period of approximately one month occurred between the initial baseline test for B20 and the comparison test with the Fuel additive. This time period was used to "break-in" and "condition" the vehicle with the Fuel additive. Usage of the Fuel additive began immediately after the baseline test was completed. Each truck was run through two tankfulls of B20 with Fuel additive before it was tested for B20 with Fuel additive. Also, the fuel filters were replaced a day before the test with Fuel additive.

**Table 3. Data Collection Schedule**

| Phase | Test Fuel | Period | | Vehicle | | |
|---|---|---|---|---|---|---|
| | | Start | End | **215-5715** | **215-6415** | **215-6667** |
| I | B20, No Additive (B20) | 06/09/2009 | 06/16/2009 | 06/10/2009 | 06/09/2009 | 06/16/2009 |
| II | B20 with Fuel additive (B20FA) | 07/08/2009 | 08/11/2009 | 07/08/2009 | 07/14/2009 | 08/11/2009 |

B20: 20% Biodiesel, 80% Petroleum Diesel

## 4.2 Vehicle Characteristics and Test Conditions

An example of a tested vehicle is shown in Figure 7. The detailed characteristics of each tested vehicle as well as the conditions of the 6 tests for each vehicle are given in Table 2. The vehicles tested included one 1999 model International 2574 6x4 tractor with a Cummins ISM-370 10.8 liter 6-cylinder 370-hp engine, one 2004 International 9400I 6x4 tractor with a Cummins ISX-500 15.0-liter 6-cylinder 500-hp engine, and one 2007 International 9200I 6x4 tractor with a Cummins ISX-500 15.0 liter 6 cylinder 500 hp engine with diesel particulate filter (DPF). All three trucks pulled 48 foot long trailers. The "unloaded" weight of each truck was approximately 34,000 to 37,000 lbs. The loaded weight was approximately 37,000 to 43,000 lbs. The vehicles carried miscellaneous cargos of parts and materials for delivery to NCDOT Division field sites at various locations in the state.


**Figure 24. NCDOT Combination Trucks: Examples of the loading, unloading activities, and the fueling of B20 for instrumented trucks**

It was discovered during the second run with Fuel additive for Truck 5715 that the exhaust pipe had ruptured as a result of rust, as shown in Figure 8.

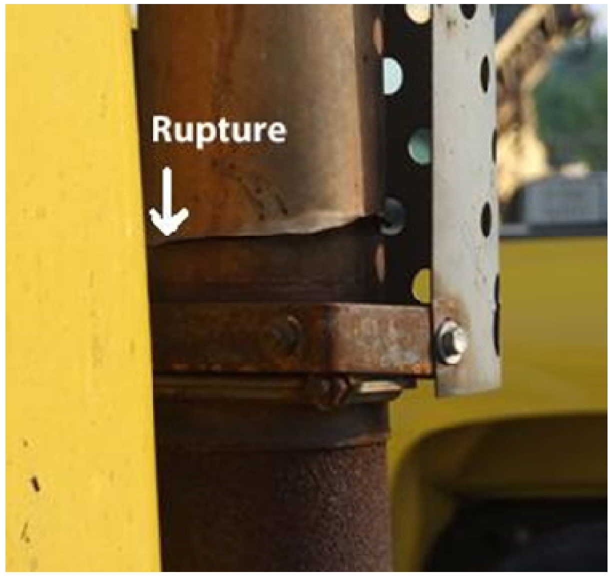



**Figure 25. Ruptured Tailpipe of Truck 5715 from the B20FA run on July 8, 2009**

The exhaust pipe may have been perforated by rust prior to the rupture. This likely lead to the introduction of ambient air into the tailpipe upstream of the exhaust sample probe. Therefore, during the baseline test and part of the Fuel additive test, there was likely to have been excess ambient air introduced to the sample line. Dilution of the exhaust sample with ambient air does not affect the estimate of gram per gallon emission rates for NO, CO, or HC. These estimates depend only on the relative ratios of NO, CO, HC, and $CO_2$ in the exhaust. The relative ratios among these components do not change because of dilution. Hence, comparisons can still be made on a g/gallon basis. However, the dilution affects the mass per time and mass per distance emission rates, since these are calculated based on the air-to-fuel ratio estimated from the exhaust composition. The dilution of the exhaust gas with ambient air leads to an increase in the apparent air-to-fuel ratio. This in turn affects the calculation of g/sec and g/mile emission rates. Thus, although these rates are reported, they are footnoted as not being reliable because the amount of dilution is not known. Furthermore, the estimated fuel flow rate (g/sec) for this truck calculated from PEMS data is low because of the dilution.  In sum, the reliable results for truck 5715 are for the g/gallon results for NO, CO, and HC.  These numbers are not affected by dilution of the exhaust.

**Table 4. Data Collection Field Log**

| *Chassis* | | *Engine* | | *Trailer* | |
|---|---|---|---|---|---|
| ID | **215-5715** | Year | 1999 | ID | 016-1287 |
| License # | PM 1645 | Make | Cummins | Model | GWR 65000 |
| Type | Combination Trailer | Engine | ISM-370 | Length | 48 *feet* |
| Year | 1999 | Displacement | 10.8 liter | Tire | 295/75/R22 5G |
| Make | International | # of | 6 | | |
| Model | 2574  6X4 | # of Gears | 13 | | |
| GVW | 53,220 *lbs.* | HP @ RPM | 370 hp@ 2100 | | |
| # of Axles | 5 Axles with 18 | | | | |
| *Test Condition* | | | | | |
| B20 | | | B20 and Fuel additive[a] | | |
| Test Date | June 10, 2009 | | Test Date | July 08, 2009 | |
| Truck (measured) | Unloaded | Loaded | Truck Weight (measured) | Unloaded | Loaded |
| | 33,300 *lbs.* | 42,060 *lbs.* | | 34,080 *lbs.* | 36,860 *lbs.* |
| Cargo | Replacement Parts | | Cargo | Replacement Parts | |

[a] Tail pipe rupture estimated to have occurred about 30 miles prior to NCDOT unit at Castle Hayne (travelling from Raleigh). The rupture was fixed at the Castle Hayne stop and test data after that point (which is about 50% of total test data for this run) can be considered to be free of tail pipe dilution due to rupture.

| *Chassis* | | *Engine* | | *Trailer* | |
|---|---|---|---|---|---|
| ID | **215-6415** | Year | 2004 | ID | 016-1286 |
| License # | PM 1073 | Make | Cummins | Model | GWR 65000 |
| Type | Combination | Engine | ISX-500 | Length | 48 *feet* |
| Year | 2004 | Displacement | 15.0 liter | Tire | 295/75/R22 5G |
| Make | International | # of | 6 | | |
| Model | 9400I  6X4 | # of Gears | 13 | | |
| GVW | 54,000 *lbs.* | HP @ RPM | 500 hp@ 2100 | | |
| # of Axles | 5 Axles with 18 | | | | |
| *Test Condition* | | | | | |
| B20 | | | B20 and Fuel additive | | |
| Test Date | June 09, 2009 | | Test Date | July 14, 2009 | |
| Truck (measured) | Unloaded | Loaded | Truck Weight (measured) | Unloaded | Loaded |
| | 34,940 *lbs.* | 40,520 *lbs.* | | 34,360 *lbs.* | 40,460 *lbs.* |
| Cargo | Replacement Parts | | Cargo | Replacement Parts | |

*Continued on next page.*

**Table 4. Continued**

| *Chassis* | | *Engine* | | *Trailer* | |
|---|---|---|---|---|---|
| ID | **215-6667** | Year | 2007 | ID | 016-1286 |
| License # | PK 8854 | Make | Cummins | Model | GWR 65000 |
| Type | Combination | Engine | ISX-500 | Length | 48 *feet* |
| Year | 2007 | Displacement | 15.0 liter | Tire | 295/75/R22 5G |
| Make | International | # of | 6 | | |
| Model | 9200I | # of Gears | 13 | | |
| GVW | 54,000 *lbs.* | HP @ RPM | 500 hp@ 2000 | | |
| # of Axles | 5 Axles with 18 | | | | |

| *Test Condition* | | | | | |
|---|---|---|---|---|---|
| B20 | | | B20 and Fuel additive | | |
| Test Date | June 16, 2009 | | Test Date | August 11, 2009 | |
| Truck | Unloaded | Loaded | Truck Weight | Unloaded | Loaded |
| (measured) | 36,700 *lbs.* | 42,600 *lbs.* | (measured) | 36,300 *lbs.* | 40,760 *lbs.* |
| Cargo | Replacement Parts | | Cargo | Replacement Parts | |

## 4.3 Sites and Truck Routes

Selection of sites and routes for on-board data collection was determined by the normal work requirements of NCDOT. According to the NCDOT work schedule, I440, I40, US64, US70, US421 and US301 were traveled more than other roads. I440 is the beltline of Raleigh-Cary area. I440 was driven for every truck route to leave or return to NCDOT Division 5 maintenance yard at Raleigh. I40 and US421 were driven to visit the NCDOT at North Wilkesboro and Winston-Salem. I40, US117, and US421were traveled to visit the NCDOT at Castle Hayne, Burgaw, and Clinton.

**Table 5. Summary of Data Collection Routes**

| Run[1] | Key Destinations | Key Routes | Distance | Duration |
|---|---|---|---|---|
| 5715_B20 | Castle Hayne, Burgaw, | I40, US117, US421 | 269 | 22875 |
| 5715_B20FA | Castle Hayne, Burgaw, | I40, US117, US421 | 270 | 24581 |
| 6415_B20 | North Wilkesboro, | I40 , US421 | 323 | 25833 |
| 6415_B20FA | North Wilkesboro, | I40, US421 | 320 | 26936 |
| 6667_B20 | North Wilkesboro, | I40, US421 | 328 | 26512 |
| 6667_B20FA | North Wilkesboro, | I40, US421 | 316 | 29254 |

[1] All run start and stop at Raleigh
[2] Based on odometer reading
[3] Includes time spent in loading and unloading

Figure 9 displays a graphical summary of the two routes that were included in the field data collection effort for the three trucks that were tested on B20 with or without the Fuel additive. There are two routes in the Figure 9. In the morning, all three trucks start at the NCDOT Division 5 maintenance yard which is marked as Raleigh with a red dot in Figure 9. This yard is located at Blue Ridge and Trinity Roads in Raleigh, NC. The duty cycles of these vehicles typically included travel to NCDOT locations in Raleigh, North Wilkesboro, Winston-Salem, Castle Hayne, Burgaw, and Clinton, all of which are in North Carolina.

For truck 215-5715, B20 and B20FA runs, the travel loop was Raleigh→Castle Hayne→Burgaw→Clinton→Raleigh. For trucks 215-6415 and 215-6667, B20 and B20FA runs, the travel loop was Raleigh→North Wilkesboro→Winston-Salem→Raleigh.

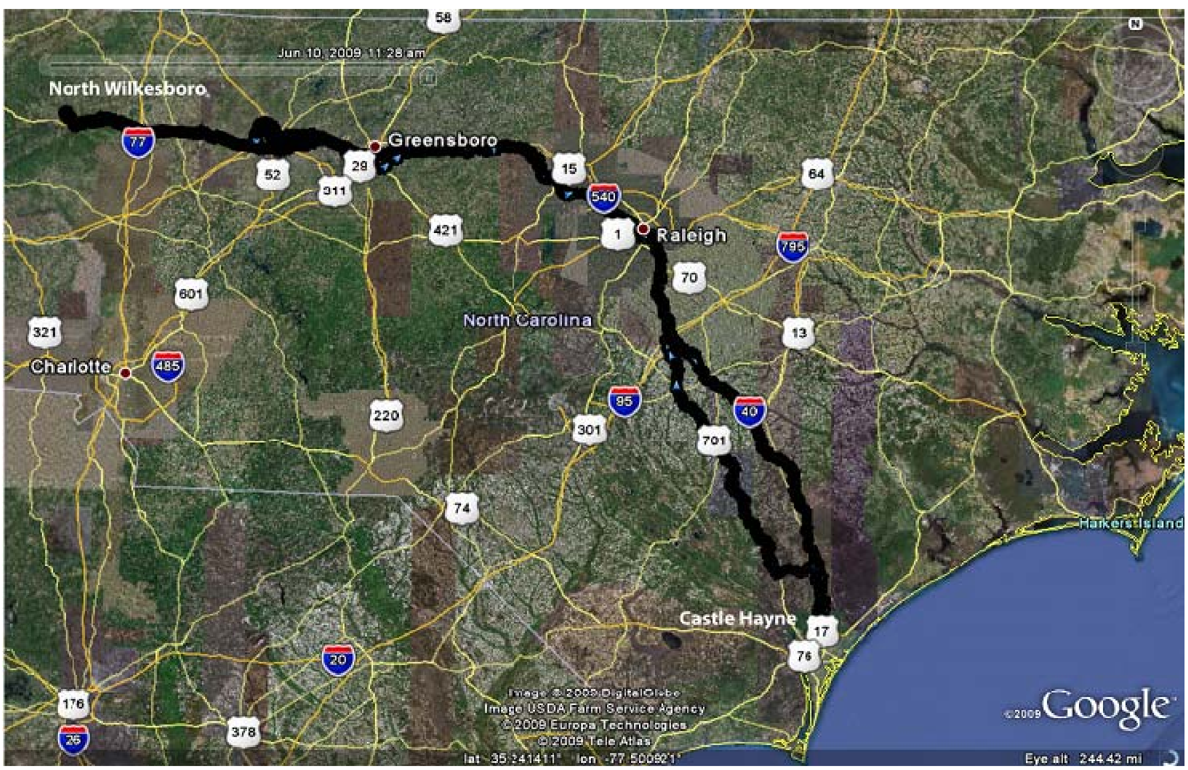



**Figure 26. Map of the Geographic Area of In-Use Field Measurements**

## 4.4 Real World Duty Cycle

The trucks were tested during real world duty cycles. In order to make comparisons between tests for each truck, a typical duty cycle was selected.

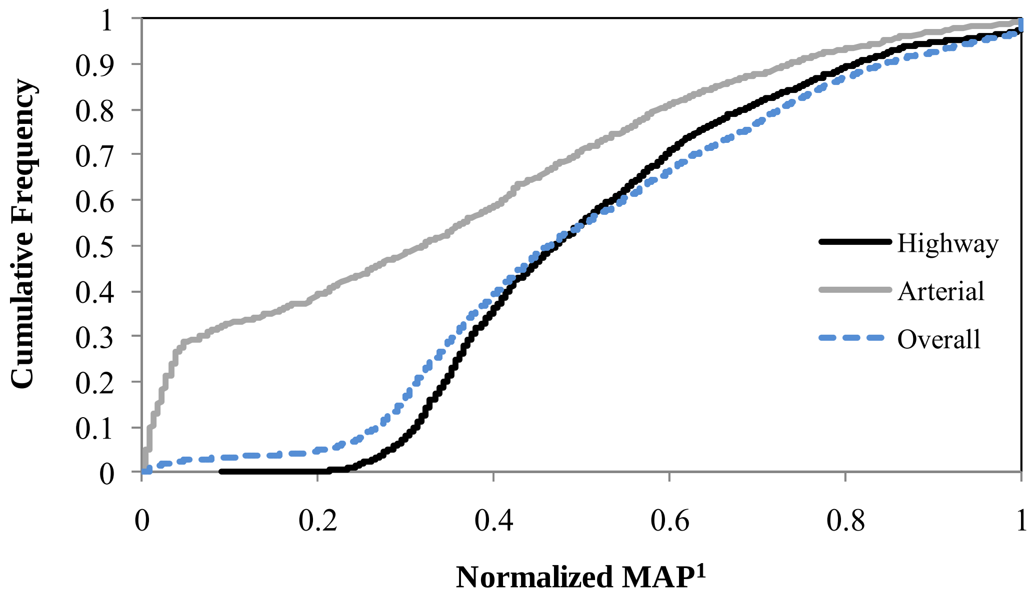
The duty cycle and its components are quantified in terms of frequency distributions of manifold absolute pressure (MAP) of the engine. MAP has been found in previous work to be highly correlated with fuel use and emissions of diesel engines, and is measured by the sensor array used with the Montana system. MAP takes into account all factors that cause load on the engine, such as vehicle speed, acceleration, road grade, and load. Thus, the frequency distribution of MAP for a component of a duty cycle is an empirical representation of the real world conditions that affected the engine. As shown in Figure 10, there are empirical frequency distributions of MAP for each component of the duty cycle as well as for the weighted combination of all components. The latter represents a complete "Overall duty cycle".

"Overall" Cycle represents the total round trip driven by Truck 6415 (B20 run). The time spent idling when the truck was being loaded and/or unloaded at a NCDOT unit is not included in the Overall cycle. Idling time at an intersection is included. "Highway" and "Arterial" are subsets of the "Overall" cycle. "Highway" is the highway only driving from Winston-Salem to Raleigh. "Arterial" is the arterial only non-highway driving from Winston-Salem to Raleigh. The "Overall" duty cycle is dominated by highway driving, which comprises 85 percent of the total seconds, with the remaining 15 percent coming from arterial driving.

**Table 6. Summary of Duty Cycle Time Fraction for MAP Modes**

| | Fraction of Time[1] | | |
|---|---|---|---|
| **Normalized MAP Mode** | **Highway** | **Arterial** | **Overall** |
| **0.1** | 0.000 | 0.309 | 0.030 |
| **0.2** | 0.001 | 0.063 | 0.012 |
| **0.3** | 0.049 | 0.099 | 0.082 |
| **0.4** | 0.267 | 0.098 | 0.234 |
| **0.5** | 0.211 | 0.125 | 0.172 |
| **0.6** | 0.158 | 0.108 | 0.120 |
| **0.7** | 0.122 | 0.074 | 0.111 |
| **0.8** | 0.080 | 0.055 | 0.105 |
| **0.9** | 0.060 | 0.039 | 0.060 |
| **1.0** | 0.053 | 0.030 | 0.074 |
| **Total Duration (sec)** | 5397 | 991 | 18410 |
| **Total Distance (miles)** | 97.47 | 6.69 | 303.23 |
| **Average Speed (mph)** | 55.84 | 31.19 | 51.46 |

[1] Sum of Fraction of Time for all MAP Modes may not add up to 1.000 because of rounding error.




[1] The Normalization of MAP is between 96 kPa and 306 kPa

| | Seconds | Min MAP | Max MAP | Avg. MAP |
|---|---|---|---|---|
| **Highway** | 5397 | 115 | 306 | 205 |
| **Arterial** | 991 | 97 | 306 | 166 |
| **Overall** | 18410 | 96 | 306 | 203 |

**Figure 27. Cumulative Frequency of Normalized Manifold Absolute Pressure for Each Duty Cycle**

### 4.5 Estimation of Fuel Use and Emission Rates for Baseline Test with B20

The average fuel use and emission rates, as well as total fuel use and emissions, were estimated for the typical duty cycle for each vehicle, in order to have a consistent basis for comparison.

Appendix A provides detail on time-based modal fuel use and emission rates for B20 with Fuel additive and B20 without additive for each of the three tested vehicles. For each vehicle, the range of variability in engine manifold absolute pressure (MAP) was normalized based on the minimum and maximum observed values of MAP, and divided into 10 ranges. These ranges are referred to as modes. An average fuel use or emission rates were estimated for each mode. As the value of MAP increases, the average fuel use or emission rate for the corresponding MAP-based mode increases monotonically. An example can be seen for Truck No. 215-6415 in Figure A-3 of Appendix A. The frequency distribution of MAP for the typical duty cycle shown in Figure 10 was used to estimate the proportion of time spent in each of the 10 MAP-based modes. Weighted average fuel use and emission rates were estimated based on the typical duty cycle. The weighted average rate is multiplied by the total time spent in the duty cycle to arrive at an estimate of total fuel use and emissions for the duty cycle.

For key components of the duty cycle, an average mileage based fuel use and emission rate is estimated by dividing the total fuel use and emissions for the component or total cycle by the corresponding distance traveled for the component or the total cycle, respectively.

In addition, fuel-based emission factors can easily be estimated. These emission factors are on a gram of pollutant emitted per gallon of fuel consumed basis. The fuel-based emission factors are estimated based on a carbon mass balance for the fuel and the pollutants. The carbon in the fuel is emitted as $CO_2$, CO, hydrocarbons, and particulate matter. Typically, more than 99 percent of the carbon in the fuel is emitted as $CO_2$. The amount of CO and hydrocarbons emitted by diesel engines tends to be small because these engines operate with a fuel lean mix of air and fuel. Hence, there is sufficient oxygen available in the air and fuel mixture to promote a high proportion of complete oxidation of carbon in the fuel to $CO_2$. The amount of carbon in particulate matter is very small and does not significantly affect the carbon balance for purposes of estimating fuel-based emission factors.

For each vehicle, detailed results are provided for emission factors for each component of the duty cycle and for the overall duty cycle on a mass per time basis and a mass per gallon of fuel basis. Mileage based emission factors (mass per mile of vehicle travel) are provided for the components of the duty cycle and for the overall duty cycle. Fuel usage rates are reported on both a per time and per mile of vehicle travel basis.

### 4.6 Quality Assurance Results

The detailed results of quality assurance for each of the three tested vehicles and for each of the two tests of each vehicle are given in Table A-8 in Appendix A. The average rate of loss of data among all six tests was 11 percent. However, most of the loss of data is attributed to episodes of unusually high air-to-fuel ratios. Unusual RPM, Unusual IAT, Negative Concentration, and Invalid Data contributed to the remaining 1 percent. An average of approximately 26,000 seconds of data was collected for each vehicle; thus, on average, approximately 23,200 seconds of data were used for estimation of fuel use and emission rates for each vehicle.

As noted in Section 4.2, it was discovered during the test of Truck 5715 with additive that the exhaust pipe ruptured as a result of perforation from rust. The perforation had likely existed during the baseline test and continually increased, leading to a gradual increase in infiltration of ambient air into the exhaust pipe over the course of the baseline test and during the comparison test with additive up until the time that the rupture was discovered and corrected. Dilution of the exhaust sample with ambient air does not affect the fuel-based emission rates for NO, CO, or HC. Hence, a comparison is still made between the fuel with additive versus baseline fuel without additive for fuel-based emission factors. However, the dilution of exhaust with ambient air will lower the estimates of mass per time fuel flow rate and emission rates, and also will lead to underestimation of the mass per distance fuel flow and emission rates. Although these results are reported, they are footnoted to indicate that they are for informational purposes only and should not be used for comparison.

### 4.7 Results of Fuel use and Emission Rates for Each Tested Truck

Table 5 is a summary of the total fuel use and emissions for each of the three tested trucks based on the "Overall" real world duty cycle given in Figure 10.

For example, Truck No. 215-6415 consumed 194 kg of fuel and emitted 598 kg of $CO_2$, 1.82 kg of NO (reported as equivalent mass of $NO_2$), 30.6 g of particulate matter, 152 g of hydrocarbons, and 582 g of CO, when operating on baseline B20 without Fuel additive.

The HC and CO emission rates of diesel engines tend to be very low. Many of the measured concentrations of these two pollutants were below the detection limits of the gas analyzers, as documented in Tables A-1 through A-6 in the Appendix. Thus, comparisons of these emission rates for a given truck for with and without additive are typically inconclusive.

The last part of Table 3 shows the ratio of fuel use and emissions for B20 with Fuel additive versus baseline B20. On average, total fuel use and total $CO_2$ emission increased by 5 percent with the use of the Fuel additive. The PM emissions decreased by 2 percent. The NO emissions increased by 12 percent. The results for HC and CO are not conclusive, as discussed above.

**Table 7. Total Fuel Use and Emissions based on "Overall" Representative Real World Duty Cycle for Three B-20 Fueled Combination Trucks with and without Fuel additive**

| Fuel | Pollutant | "Overall" Representative Real-World Duty Cycle | | | |
|---|---|---|---|---|---|
| | | 215-5715[d] | 215-6415 | 215-6667 | Average |
| B20[a] | Fuel Use [Kg] | 139 | 194 | 205 | 200 |
| | NOx [g] | 4840 | 1820 | 1070 | 1450 |
| | HC [g][c] | 279 | 152 | 231 | 192 |
| | CO [g][c] | 279 | 582 | 31 | 307 |
| | CO2 [kg] | 430 | 598 | 636 | 617 |
| | PM[g] | 9.4 | 30.6 | 1.4 | 16 |
| B20FA[b] | Fuel Use [Kg] | 153 | 211 | 205 | 208 |
| | NOx [g] | 5160 | 2150 | 1120 | 1630 |
| | HC [g][c] | 293 | 157 | 384 | 271 |
| | CO [g][c] | 655 | 695 | 228 | 462 |
| | CO2 [kg] | 472 | 653 | 633 | 643 |
| | PM [g] | 12.6 | 30.2 | 1.3 | 15.8 |
| B20FA/B20 | Fuel Use | | 1.09 | 1.00 | 1.05 |
| | NOx | | 1.18 | 1.05 | 1.12 |
| | HC [c] | | 1.03 | 1.66 | 1.35 |
| | CO [c] | | 1.19 | 7.42 | 4.31 |
| | CO2 | | 1.09 | 1.00 | 1.05 |
| | PM | | 0.99 | 0.97 | 0.98 |

[a] 20% Biodiesel, 80% Petroleum Diesel
[b] 20% Biodiesel, 80% Petroleum Diesel with Fuel additive
[c] The concentrations of HC and CO are lower for some MAP ranges than the detection limits of PEMS as documented in Tables A-1 to A-6 of the Appendix.
[d] The estimated mass of fuel use and emissions for Truck 5715 are biased low because of perforation of the exhaust pipe by rust that was detected partway through the test with Fuel additive. The numbers reported for this truck are for informational purposes only. They are not included in the average results shown in the last

column. Because the amount of dilution likely differed when comparing the baseline test and the test with additive, ratios for 'with additive' to 'without additive' are not shown for this truck.

## 4.8 Results of Fuel use and Emission Rates for Each Tested Truck

Detailed results are given for time-based, fuel-based, and distance based for each of the three tested vehicles, as follows:

**Vehicle 215-5715:**

- Table 6: Time-based average fuel use and emission factors based on the real world typical duty cycles of Figure 10. The estimated mass of fuel use and emissions for Truck 5715 are biased low because of perforation of the exhaust pipe by rust that was detected partway through the test with Fuel additive. The numbers reported for this truck are for informational purposes only. Because the amount of dilution likely differed when comparing the baseline test and the test with additive, ratios of the mass per time rates for 'with additive' to 'without additive' are not shown for this truck.

- Table 7: Fuel-based emission factors based on the real world typical duty cycles of Figure 10. The fuel-based emission factors for NO, CO, and HC are not affected by the diluation of exhaust with ambient air because of perforation of the exhaust pipe with rust. Hence, ratios of these emission rates with additive to those without additive are shown. However, the PM emission rate is calculated in a different manner from those of the gases, and these results are affected by dilution of the exhaust with ambient air. Therefore, ratios are not shown for PM.

- Table 8: Travel distance-based average fuel use and emission factors based on the real world typical duty cycles of Figure 10. The distance-based rates are shown for informational purposes. These rates are biased low because of dilution of the exhaust with ambient air as a result of perforation of the exhaust pipe by rust. Therefore, ratios of the distance based rates with additive to without additive are not shown.

- Modal Emission Factors: Time-based modal fuel use and emission factors for B20 without and with Fuel additive are given in Figure A-1 of Appendix A. Fuel based emission factors for B20 without and with Fuel additive are given in Figure A-2 of Appendix A. The average exhaust gas concentrations for NO, HC, CO, $CO_2$, and $O_2$ for each MAP-based mode are given in Tables A-1 and A-2 of Appendix A for B20 without and with Fuel additive, respectively.

**Vehicle 215-6415:**

- Table 9: Time-based average fuel use and emission factors based on the real world typical duty cycles of Figure 10.

- Table 10: Fuel-based emission factors based on the real world typical duty cycles of Figure 10.

- Table 11: Travel distance-based average fuel use and emission factors based on the real world typical duty cycles of Figure 10.

- Modal Emission Factors: Time-based modal fuel use and emission factors for fuel without and with additive are given in Figure A-3 of Appendix A. Fuel based emission factors for the B20 without and with Fuel additive are given in Figure A-4 of Appendix A. The average exhaust gas concentrations for NO, HC, CO, $CO_2$, and $O_2$ for each MAP-based mode are given in Tables A-3 and A-4 of Appendix A for B20 without and with Fuel additive, respectively.

**Vehicle 215-6667:**

- Table 12: Time-based average fuel use and emission factors based on the real world typical duty cycles of Figure 10.

- Table 13: Fuel-based emission factors based on the real world typical duty cycles of Figure 10.

- Table 14: Travel distance-based average fuel use and emission factors based on the real world typical duty cycles of Figure 10.

- Modal Emission Factors: Time-based modal fuel use and emission factors for fuel without and with additive are given in Figure A-5 of Appendix A. Fuel based emission factors for the B20 without and with Fuel additive are given in Figure A-6 of Appendix A. The average exhaust gas concentrations for NO, HC, CO, $CO_2$, and $O_2$ for each MAP-based mode are given in Tables A-5 and A-6 of Appendix A for B20 without and with Fuel additive, respectively.

**Table 8. Time-Based Average Fuel Use and Emission Factors based on Representative Real-World Duty Cycles for the Combination Truck 215-5715[d]**

| Fuel | Pollutant | Representative Real-World Duty | | |
|---|---|---|---|---|
| | | Highway | Arterial | Overall |
| B20[a] | Fuel Use [g/s] | 7.69 | 5.05 | 7.55 |
| | NOx [mg/s] | 270 | 176 | 263 |
| | HC [mg/s] [c] | 15 | 11 | 15 |
| | CO [mg/s] [c] | 15 | 13 | 15 |
| | $CO_2$ [g/s] | 23.7 | 15.6 | 23.3 |
| | PM [mg/s] | 0.50 | 0.35 | 0.51 |
| B20FA[b] | Fuel Use [g/s] | 8.48 | 5.52 | 8.31 |
| | NOx [mg/s] | 288 | 189 | 281 |
| | HC [mg/s] [c] | 16 | 12 | 16 |
| | CO [mg/s] [c] | 36 | 27 | 36 |
| | $CO_2$ [g/s] | 26.2 | 17.0 | 25.7 |
| | PM [mg/s] | 0.68 | 0.46 | 0.68 |

[a] 20% Biodiesel, 80% Petroleum Diesel
[b] 20% Biodiesel, 80% Petroleum Diesel with Fuel additive
[c] The concentrations of HC and CO are lower for some MAP ranges than the detection limits of PEMS, as documented in Tables A-1 and A-2.
[d] The estimated mass of fuel use and emissions for Truck 5715 are biased low because of perforation of the exhaust pipe by rust that was detected partway through the test with Fuel additive. The numbers reported for this truck are for informational purposes only. Because the amount of dilution likely differed when comparing the baseline test and the test with additive, ratios of the mass per time rates for 'with additive' to 'without additive' are not shown for this truck.

**Table 9. Fuel-Based Emission Factors based on Representative Real-World Duty Cycles for the Combination Truck 215-5715[d]**

| Fuel | Pollutant | Representative Real-World Duty | | |
|---|---|---|---|---|
| | | Highway | Arterial | Overall |
| B20[a] | NOx [g/gal] | 113 | 113 | 112 |
| | HC [g/gal] [c] | 6.44 | 6.98 | 6.46 |
| | CO [g/gal] [c] | 6.3 | 8.1 | 6.5 |
| | PM [g/gal] | 0.21 | 0.22 | 0.22 |
| B20FA[b] | NOx [g/gal] | 110 | 110 | 109 |
| | HC [g/gal] [c] | 6.10 | 6.89 | 6.17 |
| | CO [g/gal] [c] | 13.6 | 15.7 | 13.8 |
| | PM [g/gal] | 0.26 | 0.27 | 0.26 |
| B20FA/B20 | NOx | 0.97 | 0.98 | 0.97 |
| | HC [c] | 0.95 | 0.99 | 0.95 |
| | CO [c] | 2.16 | 1.94 | 2.14 |
| | PM | 1.22 | 1.21 | 1.22 |

[a] 20% Biodiesel, 80% Petroleum Diesel
[b] 20% Biodiesel, 80% Petroleum Diesel with Fuel additive
[c] The concentrations of HC and CO are lower for some MAP ranges than the detection limits of PEMS, as documented in Tables A-1 and A-2.
[d] The fuel-based emission factors for NO, CO, and HC are not affected by the diluation of exhaust with ambient air because of perforation of the exhaust pipe with rust. Hence, ratios of these emission rates with additive to those without additive are shown. However, the PM emission rate is calculated in a different manner from those of the gases, and these results are affected by dilution of the exhaust with ambient air. Therefore, ratios are not shown for PM.

**Table 10. Travel Distance-Based Average Fuel Use and Emission Factors based on Representative Real-World Duty Cycles for the Combination Truck 215-5715[d]**

| Fuel | Pollutant | Representative Real-World Duty | | |
|---|---|---|---|---|
| | | Highway | Arterial | Overall |
| B20[a] | Fuel [g/mile] | 426 | 747 | 459 |
| | NOx [g/mile] | 15.0 | 26.1 | 16.0 |
| | HC [g/mile] [c] | 0.85 | 1.62 | 0.92 |
| | CO [g/mile] [c] | 0.83 | 1.88 | 0.92 |
| | $CO_2$ [g/mile] | 1310 | 2310 | 1420 |
| | PM [g/mile] | 0.03 | 0.05 | 0.03 |
| B20FA[b] | Fuel [g/mile] | 469 | 817 | 505 |
| | NOx [g/mile] | 16.0 | 28.0 | 17.0 |
| | HC [g/mile] [c] | 0.89 | 1.75 | 0.97 |
| | CO [g/mile] [c] | 1.98 | 3.99 | 2.16 |
| | $CO_2$ [g/mile] | 1450 | 2520 | 1560 |
| | PM [g/mile] | 0.04 | 0.07 | 0.04 |

[a] 20% Biodiesel, 80% Petroleum Diesel
[b] 20% Biodiesel, 80% Petroleum Diesel with Fuel additive
[c] The concentrations of HC and CO are lower for some MAP ranges than the detection limits of PEMS, as documented in Tables A-1 and A-2.
[d] The fuel-based emission factors for NO, CO, and HC are not affected by the diluation of exhaust with ambient air because of perforation of the exhaust pipe with rust. Hence, ratios of these emission rates with additive to those without additive are shown. However, the PM emission rate is calculated in a different manner from those of the gases, and these results are affected by dilution of the exhaust with ambient air. Therefore, ratios are not shown for PM.

**Table 11. Time-Based Average Fuel Use and Emission Factors based on Representative Real-World Duty Cycles for the Combination Truck 215-6415**

| Fuel | Pollutant | Representative Real-World Duty | | |
|---|---|---|---|---|
| | | Highway | Arterial | Overall |
| B20[a] | Fuel Use [g/s] | 10.6 | 6.98 | 10.5 |
| | NOx [mg/s] | 99 | 68 | 99 |
| | HC [mg/s] [c] | 8 | 7 | 8 |
| | CO [mg/s] [c] | 32 | 26 | 32 |
| | $CO_2$ [g/s] | 32.9 | 21.6 | 32.5 |
| | PM [mg/s] | 1.66 | 1.09 | 1.66 |
| B20FA[b] | Fuel Use [g/s] | 11.6 | 7.53 | 11.5 |
| | NOx [mg/s] | 118 | 83 | 117 |
| | HC [mg/s] [c] | 9 | 7 | 9 |
| | CO [mg/s] [c] | 38 | 29 | 38 |
| | $CO_2$ [g/s] | 35.8 | 23.3 | 35.5 |
| | PM [mg/s] | 1.65 | 1.08 | 1.64 |
| B20FA/B20 | Fuel Use | 1.09 | 1.08 | 1.09 |
| | NOx | 1.18 | 1.23 | 1.18 |
| | HC [c] | 1.03 | 1.01 | 1.03 |
| | CO [c] | 1.20 | 1.12 | 1.19 |
| | $CO_2$ | 1.09 | 1.08 | 1.09 |
| | PM | 0.99 | 0.99 | 0.99 |

[a] 20% Biodiesel, 80% Petroleum Diesel
[b] 20% Biodiesel, 80% Petroleum Diesel with Fuel additive
[c] The concentrations of HC and CO are lower for some MAP ranges than the detection limits of PEMS, as documented in Tables A-3 and A-4.

**Table 12. Fuel-Based Emission Factors based on Representative Real-World Duty Cycles for the Combination Truck 215-6415**

| Fuel | Pollutant | Representative Real-World Duty | | |
|---|---|---|---|---|
| | | Highway | Arterial | Overall |
| B20[a] | NOx [g/gal] | 30 | 31 | 30 |
| | HC [g/gal] [c] | 3 | 3 | 3 |
| | CO [g/gal] [c] | 10 | 12 | 10 |
| | PM [g/gal] | 0.50 | 0.50 | 0.51 |
| B20FA[b] | NOx [g/gal] | 33 | 36 | 33 |
| | HC [g/gal] [c] | 2 | 3 | 2 |
| | CO [g/gal] [c] | 11 | 13 | 11 |
| | PM [g/gal] | 0.46 | 0.46 | 0.46 |
| B20FA/B20 | NOx | 1.08 | 1.14 | 1.08 |
| | HC [c] | 0.95 | 0.93 | 0.94 |
| | CO [c] | 1.10 | 1.04 | 1.09 |
| | PM | 0.91 | 0.92 | 0.90 |

[a] 20% Biodiesel, 80% Petroleum Diesel
[b] 20% Biodiesel, 80% Petroleum Diesel with Fuel additive
[c] The concentrations of HC and CO are lower for some MAP ranges than the detection limits of PEMS, as documented in Tables A-3 and A-4.

**Table 13. Travel Distance-Based Average Fuel Use and Emission Factors based on Representative Real-World Duty Cycles for the Combination Truck 215-6415**

| Fuel | Pollutant | Representative Real-World Duty | | |
|---|---|---|---|---|
| | | Highway | Arterial | Overall |
| B20[a] | Fuel [g/mile] | 588 | 1034 | 638 |
| | NOx [g/mile] | 5.5 | 10.0 | 6.0 |
| | HC [g/mile] [c] | .5 | 1 | .5 |
| | CO [g/mile] [c] | 2 | 4 | 2 |
| | $CO_2$ [g/mile] | 1820 | 3190 | 1970 |
| | PM [g/mile] | 0.09 | 0.16 | 0.10 |
| B20FA[b] | Fuel [g/mile] | 642 | 1115 | 697 |
| | NOx [g/mile] | 6.5 | 12.3 | 7.1 |
| | HC [g/mile] [c] | .5 | 1 | .5 |
| | CO [g/mile] [c] | 2 | 4 | 2 |
| | $CO_2$ [g/mile] | 1990 | 3440 | 2150 |
| | PM [g/mile] | 0.09 | 0.16 | 0.10 |
| B20FA/B20 | Fuel | 1.09 | 1.08 | 1.09 |
| | NOx | 1.18 | 1.23 | 1.18 |
| | HC [c] | 1.03 | 1.01 | 1.03 |
| | CO [c] | 1.20 | 1.12 | 1.19 |
| | $CO_2$ | 1.09 | 1.08 | 1.09 |
| | PM | 0.99 | 0.99 | 0.99 |

[a] 20% Biodiesel, 80% Petroleum Diesel
[b] 20% Biodiesel, 80% Petroleum Diesel with Fuel additive
[c] The concentrations of HC and CO are lower for some MAP ranges than the detection limits of PEMS, as documented in Tables A-3 and A-4.

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**Table 14. Time-Based Average Fuel Use and Emission Factors based on Representative Real-World Duty Cycles for the Combination Truck 215-6667**

| Fuel | Pollutant | Representative Real-World Duty | | |
|---|---|---|---|---|
| | | Highway | Arterial | Overall |
| B20[a] | Fuel Use [g/s] | 11.3 | 7.68 | 11.2 |
| | NOx [mg/s] | 59 | 40 | 58 |
| | HC [mg/s] [c] | 13 | 9 | 13 |
| | CO [mg/s] [c] | 1 | 5 | 2 |
| | $CO_2$ [g/s] | 34.9 | 23.8 | 34.5 |
| | PM [mg/s] | 0.08 | 0.06 | 0.07 |
| B20FA[b] | Fuel Use [g/s] | 11.2 | 7.72 | 11.1 |
| | NOx [mg/s] | 62 | 42 | 61 |
| | HC [mg/s] [c] | 21 | 16 | 21 |
| | CO [mg/s] [c] | 12 | 16 | 12 |
| | $CO_2$ [g/s] | 34.7 | 23.9 | 34.4 |
| | PM [mg/s] | 0.07 | 0.05 | 0.07 |
| B20FA/B20 | Fuel Use | 1.00 | 1.01 | 1.00 |
| | NOx | 1.05 | 1.05 | 1.05 |
| | HC [c] | 1.66 | 1.71 | 1.66 |
| | CO [c] | 8.70 | 3.47 | 7.42 |
| | $CO_2$ | 1.00 | 1.00 | 1.00 |
| | PM | 0.98 | 0.96 | 0.97 |

[a] 20% Biodiesel, 80% Petroleum Diesel

[b] 20% Biodiesel, 80% Petroleum Diesel with Fuel additive

[c] The concentrations of HC and CO are lower for some MAP ranges than the detection limits of PEMS, as documented in Tables A-5 and A-6.

**Table 15. Fuel-Based Emission Factors based on Representative Real-World Duty Cycles for the Combination Truck 215-6667**

| Fuel | Pollutant | Representative Real-World Duty | | |
|---|---|---|---|---|
| | | Highway | Arterial | Overall |
| B20[a] | NOx [g/gal] | 17 | 17 | 17 |
| | HC [g/gal] [c] | 4 | 4 | 4 |
| | CO [g/gal] [c] | 0.4 | 2 | 0.5 |
| | PM [g/gal] | 0.02 | 0.02 | 0.02 |
| B20FA[b] | NOx [g/gal] | 18 | 18 | 18 |
| | HC [g/gal] [c] | 6 | 7 | 6 |
| | CO [g/gal] [c] | 3 | 7 | 4 |
| | PM [g/gal] | 0.02 | 0.02 | 0.02 |
| B20FA/B20 | NOx | 1.06 | 1.05 | 1.05 |
| | HC [c] | 1.67 | 1.70 | 1.67 |
| | CO [c] | 8.73 | 3.45 | 7.44 |
| | PM | 0.98 | 0.95 | 0.98 |

[a] 20% Biodiesel, 80% Petroleum Diesel
[b] 20% Biodiesel, 80% Petroleum Diesel with Fuel additive
[c] The concentrations of HC and CO are lower for some MAP ranges than the detection limits of PEMS, as documented in Tables A-5 and A-6.

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**Table 16. Travel Distance-Based Average Fuel Use and Emission Factors based on Representative Real-World Duty Cycles for the Combination Truck 215-6667**

| Fuel | Pollutant | Representative Real-World Duty | | |
|---|---|---|---|---|
| | | Highway | Arterial | Overall |
| B20[a] | Fuel [g/mile] | 625 | 1140 | 677 |
| | NOx [g/mile] | 3.3 | 6.0 | 3.5 |
| | HC [g/mile] [c] | 0.7 | 1 | 0.8 |
| | CO [g/mile] [c] | 0.08 | 0.7 | 0.1 |
| | $CO_2$ [g/mile] | 1930 | 3520 | 2100 |
| | PM [g/mile] | 0.00 | 0.01 | 0.00 |
| B20FA[b] | Fuel [g/mile] | 622 | 1140 | 675 |
| | NOx [g/mile] | 3.4 | 6.3 | 3.7 |
| | HC [g/mile] [c] | 1 | 2 | 1 |
| | CO [g/mile] [c] | 0.7 | 2 | 0.8 |
| | $CO_2$ [g/mile] | 1920 | 3530 | 2090 |
| | PM [g/mile] | 0.00 | 0.01 | 0.00 |
| B20FA/B20 | Fuel | 1.00 | 1.01 | 1.00 |
| | NOx | 1.05 | 1.05 | 1.05 |
| | HC [c] | 1.66 | 1.71 | 1.66 |
| | CO [c] | 8.70 | 3.47 | 7.42 |
| | $CO_2$ | 1.00 | 1.00 | 1.00 |
| | PM | 0.98 | 0.96 | 0.97 |

[a] 20% Biodiesel, 80% Petroleum Diesel
[b] 20% Biodiesel, 80% Petroleum Diesel with Fuel additive
[c] The concentrations of HC and CO are lower for some MAP ranges than the detection limits of PEMS, as documented in Tables A-5 and A-6.

For example, as shown in Table 9 for Vehicle 215-6415, the time-based average fuel use rate for B20 without additive varies from 7.0 g/sec for travel on arterial duty cycle to 10.6 g/sec for travel on highway duty cycle, with an average of 10.5 g/sec for overall duty cycle. The variability in fuel use rate among different components of the duty cycle indicates the variation in engine load among these components.

While operating on B20 without additive, the average time-based NO emission rate for Vehicle 215-6415 varies from 68 mg/sec for travel on arterial duty cycle to 99 mg/sec for travel on highway duty cycle, representing an increase of about 50%, with an average of 99 mg/sec for overall duty cycle.

The ratios of the fuel use and emission rates for the highway, arterial and overall duty cycles are given in the bottom section of Table 9, based on comparison of fuel with additive to fuel without additive. The values shown here for the overall duty cycle are also reported in Table 3. In general, there were similar results for the ratio with to without additive for fuel use and emissions when comparing the duty cycles.

The fuel-based emission factors for Vehicle 215-6415 are given in Table 10. There is less variability in the fuel-based emission factors when comparing different components of the duty cycle, versus the results for the time-based emission factors. For example, whereas the time-based NO emission factor varied by a factor of about 50 percent from the lowest to highest value among the three duty cycles, the fuel-based emission factor varies by less than 5 percent among these cycles. Thus, fuel-based emission factors tend to be less sensitive to engine load than time-based emission factors. The comparison for additive versus without is less sensitive for NO, HC, and CO for the fuel-based emission rates than for the time-based emission rates, in that there is less variability in these ratios in the former case.

The travel distance-based emission factors for Vehicle 215-6415 are given in Table 11. The mileage based fuel use and emission rates are higher for the arterial cycle than for the highway cycle, whereas the converse is the case for the time-based fuel use and emission rates. However, the ratios of fuel use and emission rates with to without additive are the same regardless of whether they are estimated from time- or mileage-based emission factors, since the estimates are based on the same set of duty cycles that are given in Figure 10.

Similar results are given for the other two vehicles, as described previously. For example, for Vehicle 215-6667, as shown in Table 12, there is no difference in fuel use and $CO_2$ emission rate, a 5 percent increase in NO emission rate, and a 3 percent decrease in PM emission rate, based on the overall duty cycle. Differences in HC and CO are not significant because many measurements were below the detection limits for these pollutants.

The ratios of emissions with versus without additive based on the fuel-based emission factors differ somewhat from those obtained from the time or distance-based emission factors. The fuel-based $NO_x$ emission rate was 3 percent lower for Truck 5715 with the additive versus without, whereas it was 8 and 5 percent higher for Trucks 6415 and 6667, respectively. The PM emission rate was lower for the latter two trucks by 2 to 10 percent, but higher for Truck 5714 by 22 percent. The results for HC and CO are inconclusive, for reasons previously stated.

The fuel use for the three trucks was assessed in two ways. One was based on recording the actual amount of fuel required to refuel the truck after completing a test. The other was an estimate based on the second-by-second PEMS data. The estimate is made by considering the exhaust composition, which is used to infer the air-to-fuel ratio, and the mass throughput of air to the engine, which is calculated based on engine RPM, MAP, and IAT. Detailed results of these comparisons are given in the Appendix. The PEMS estimate of fuel consumption agrees well with the actual amount of fuel that was added to the tank for three of the tests. For one test, NCDOT did not record the actual amount of fuel added after the test; therefore, no comparison of estimated versus actual fuel use is possible. For Truck 5715, as previously explained, the conditions of the test do not permit an accurate estimate of the fuel consumption. As shown in Figure A-7 in the Appendix, the PEMS estimate of fuel consumed for this truck is biased low because of the effect of air leakage in the tailpipe due to the ruptured exhaust pipe, which leads to an over-estimate of the air-to-fuel ratio. In turn, this leads to an underestimate of the amount of fuel consumed.

Fuel use during an actual duty cycle is sensitive to the distribution of time that the engine is subject to different loads. Engine load is represented by MAP. The frequency distributions of MAP for each truck, comparing the tests with and without the additive, are given in the Appendix in Figures A-8 to A-10. For example, Figure A-9 is for Truck 6415. Although there are some minor differences in the distribution of MAP for each test, the average MAP was nearly identical, at 176 to 177 kPa, and the variability in MAP was very similar, with a standard deviation of 60 to 65 kPa and a range of 96 to 306 kPa. Likewise, for the other two trucks, the average, standard deviation, and range of values of MAP were similar for both tests. Hence, we do not suspect that there was enough variability in the activity patterns of the duty cycles to lead to substantial differences in results when making comparisons of fuel consumption with versus without the additive. Similarly, we compared the distribution of time for vehicle speed, as given in Figures A-11 to A-13 of the Appendix. For Truck 5715, the average speed for each test ranged from 39 to 42 mph, with a standard deviation of 27 to 28 mph. For Truck 6415, the average speed was 43 to 45 mph with a standard deviation of 28 to 30 mph. For Truck 6667, the average speed was 39 to 44 mph, with a standard deviation of 27 to 31 mph. Thus, the operating conditions of the tests with additive were very similar to the operating conditions of the test without additive.

## 5.0 Conclusions

The purpose of this study is to compare fuel use and emissions with an additive to without an additive for B20-fueled tractor trailer trucks.

Data were collected for real-world duty cycles for each of three trucks. Each truck operated on the same route for a day of testing without additive and a later day of testing with additive. The activity patterns of each test for a given truck were very similar, based on comparisons of frequency distributions of engine load, quantified based on MAP, and of vehicle speed. However, in order to reduce the effect of inherent variability in operating conditions when comparing the two tests, comparisons were made by first creating modal rates of fuel use and emissions with respect to ten ranges of increasing MAP, and then weighting the modal rates using a common set of three duty cycles. The three duty cycles represent arterials, highways, and an overall mix of arterials and highways.

The trucks had only modest loads during each test, which were delivered from Raleigh to specific destinations along the route. The loads varied from approximately 3,000 to 8,000 lbs, compared to an unloaded weight of approximately 33,000 to 36,000 lbs, depending on the truck. Since the loads are modest compared to the overall weight of the truck, and since the loads and mileage associated with delivering the loads were similar for tests with and without additive, these are not likely to affect the comparisons.

There was a problem with Truck 5715 in that the exhaust pipe ruptured partway into the test with additive, leading to a discovery that it likely had a crack that grew in size during the course of operations up until that time and dating probably to before the baseline test. The crack meant that ambient air was drawn into the exhaust pipe, which lead to biasing the concentration measurements downward. This does not affect estimation of fuel-based emission rates, which are based on molar ratios of pollutants in the exhaust and fuel properties, but it does bias estimates of mass per time and mass per distance fuel use and emission rates for this truck. Therefore, only fuel-based emission rates for Truck 5715 were used as a basis for comparing performance with the additive to without the additive.

For fuel economy (miles per gallon), or fuel consumption rate (g/sec or g/mile), comparisons could be made for Trucks 6415 and 6667 based on estimates from the PEMS data. Comparisons could be made based on the actual amount of fuel added to the truck after a test for Trucks 5715 and 6667. Based on the PEMS data for Trucks 6415 and 6667, there is no observable evidence of a beneficial effect of the additive in terms of reducing fuel consumption.

With respect to emission rates, there is some variability in results among the three trucks. For example, based on fuel-based emission factors, one of the trucks had lower $NO_x$ emissions with the additive, while the other two had slightly higher $NO_x$ emissions. Two of the three trucks had slightly lower PM emission rates. The results for HC and CO are generally inconclusive. Diesel engines typically have low emission rates of HC and CO, because they operate with excess air which promotes efficient combustion. Many of the measurements of HC and CO concentrations were below the detection limit of the gas analyzers. Thus, the average emission rates are subject to substantial uncertainty, which leads to inconclusive comparisons.

Despite some of the challenges encountered, particularly with Truck 5715, the data that were used for analysis underwent a rigorous quality assurance screening process. Therefore, the data that were used as the basis for comparisons are deemed to be valid. Overall, the results do not imply any supportable conclusion for either beneficial or adverse effects of the tested additive.

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# APPENDIX

## Appendix A : Detailed Emission Factor Results for Individual Tested Vehicles

This appendix contains the following results for each of the three tested vehicles:

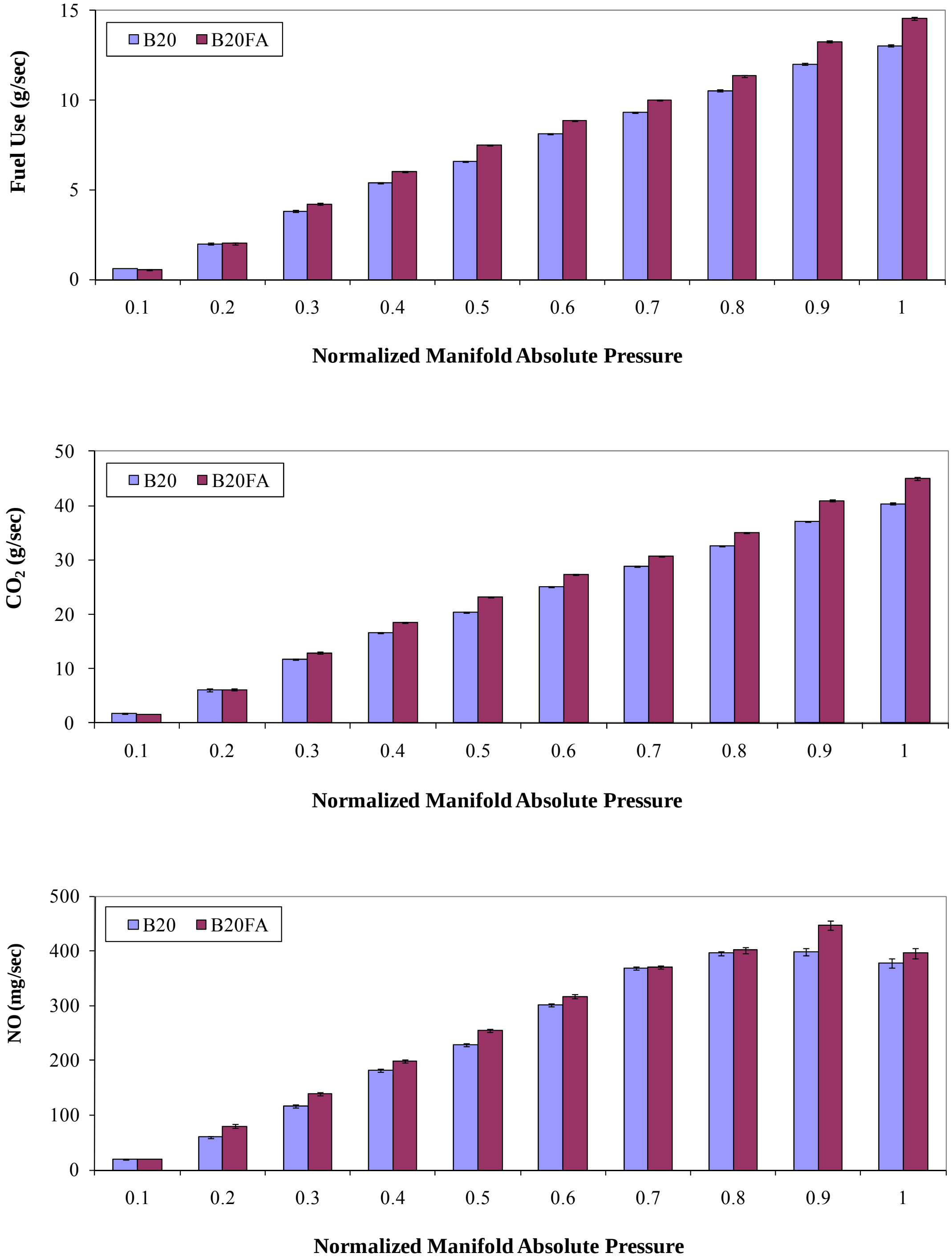
- Time-based modal fuel use rate and emission factors with respect to normalized Manifold Absolute Pressure (MAP) for B20 with and without the Fuel additive.
- Fuel-based modal emission factors with respect to normalized Manifold Absolute Pressure (MAP) for B20 with and without the Fuel additive.

In addition, there are several tables that summarize the mean exhaust gas concentrations for each vehicle and fuel that was tested. The purpose of these tables is to identify situations in which the mean pollutant concentration was at or below the gas analyzer detection limit, in order to provide insight regarding data quality.

A comparison is given between the measured and actual fuel use for each of the 6 tests. This comparison illustrates that there is excellent agreement between the fuel use measured based on the portable emission measurement system and the actual amount of fuel consumed as determined by the amount of fuel that was put into the fuel tank after each day of testing.

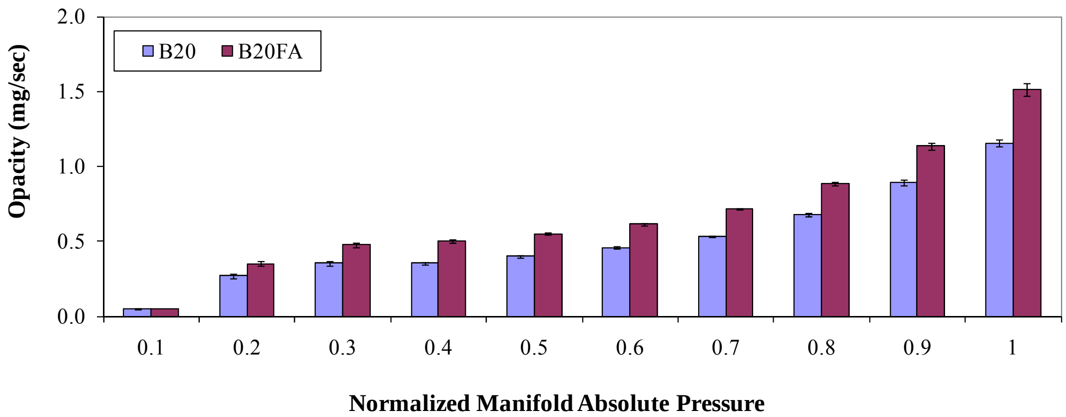
A summary is given of the total sample size of the data sets for each tested vehicle and fuel. There were approximately 7,500 to 24,000 seconds of data for most of the tests.

A summary is given of the overall rate of loss of data because of data quality issues. On average, 10% of the data were lost or excluded because of data quality issues. RPM error occurred for the test of truck 215-6415 with B20 in the rainy day. Except this RPM error, on average, only 6.0% of data were lost or excluded because of data quality issues. Without considering this RPM error, the most frequent causes of data loss were RPM error and analyzer “freezing”.

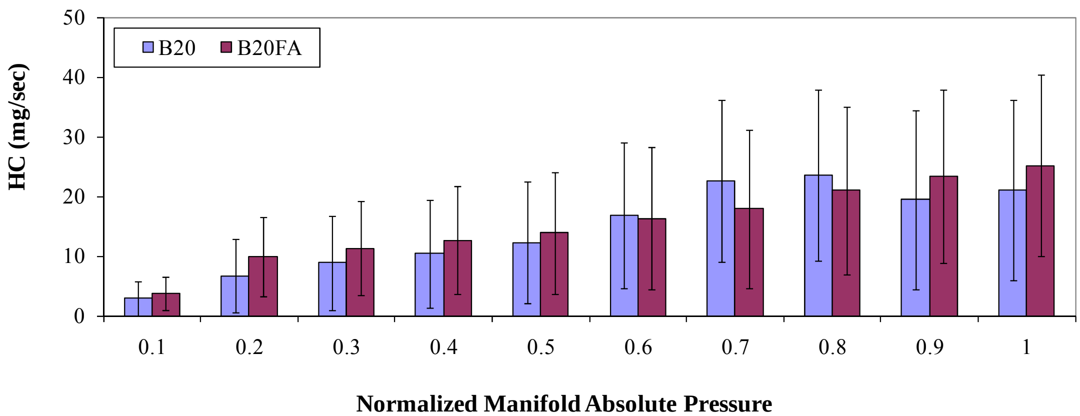



B20 = 20% Biodiesel, 80% Petroleum Diesel. B20FA = B20 with Fuel additive

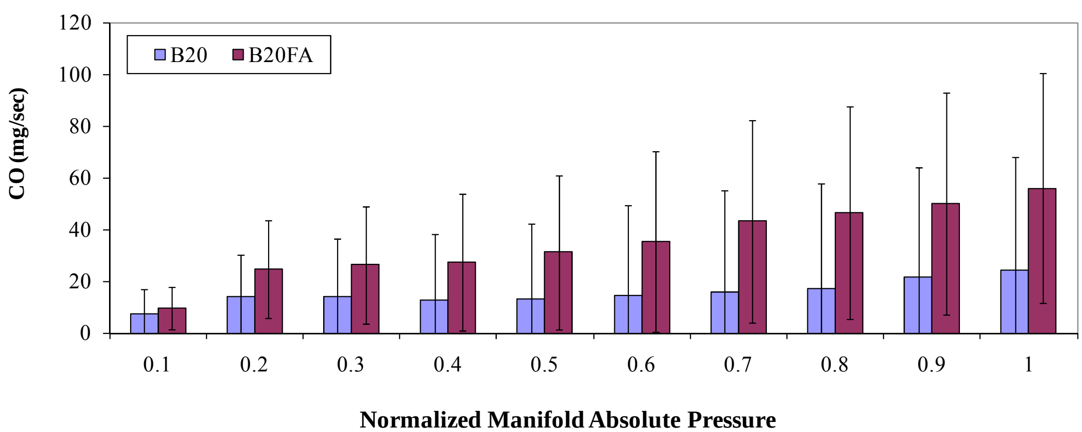
**Figure A-1. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Combination Truck 215-5715**



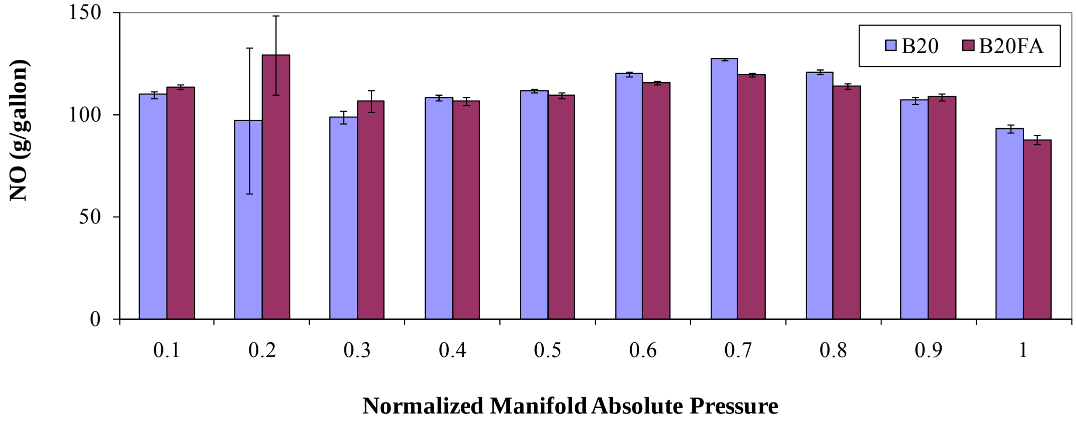
B20
B20FA
Opacity (mg/sec)
2.0
1.5
1.0
0.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure

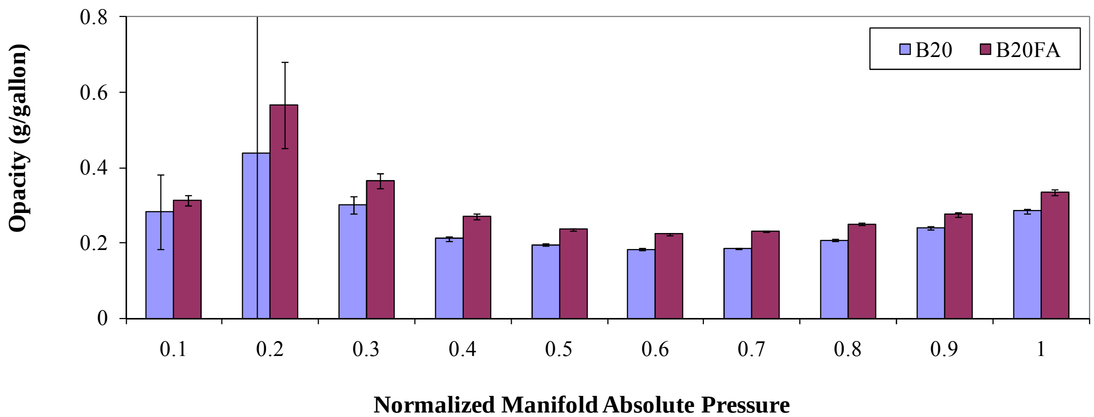



B20
B20FA
HC (mg/sec)
50
40
30
20
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure

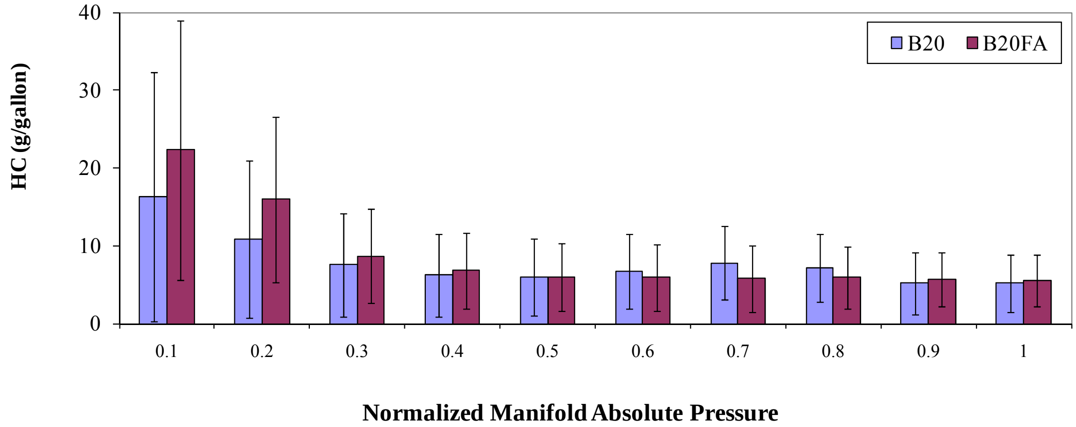
B20
B20FA
CO (mg/sec)
120
100
80
60
40
20
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure



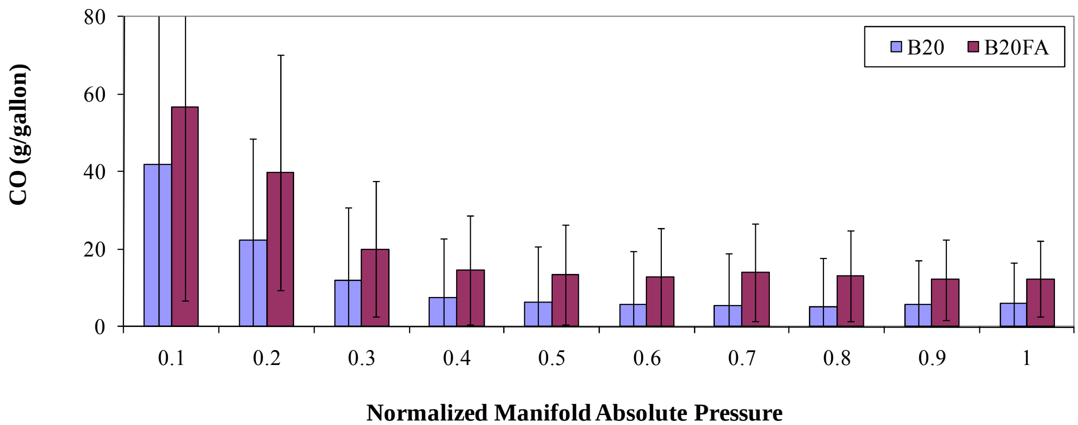




B20 = 20% Biodiesel, 80% Petroleum Diesel. B20FA = B20 with Fuel additive.

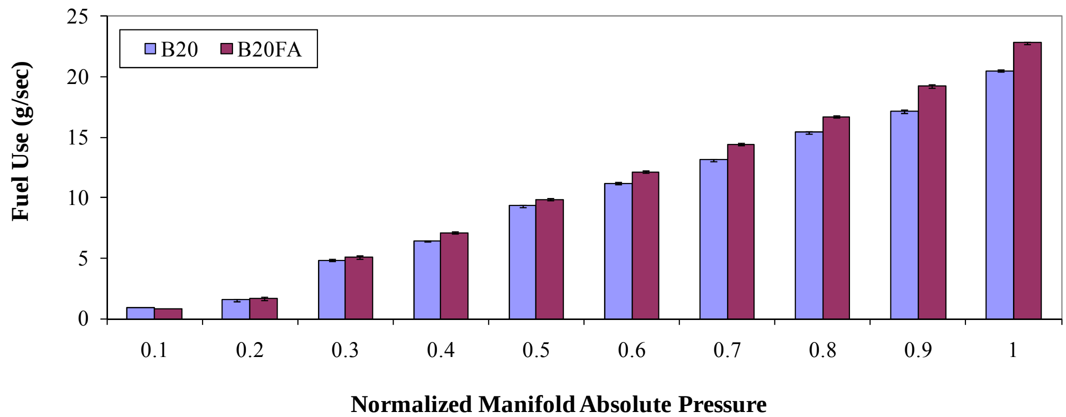
**Figure A-2. Emission Rates of Each Pollutant on a Per Fuel Basis for Engine-Based Modes for Combination Truck 215-5715**

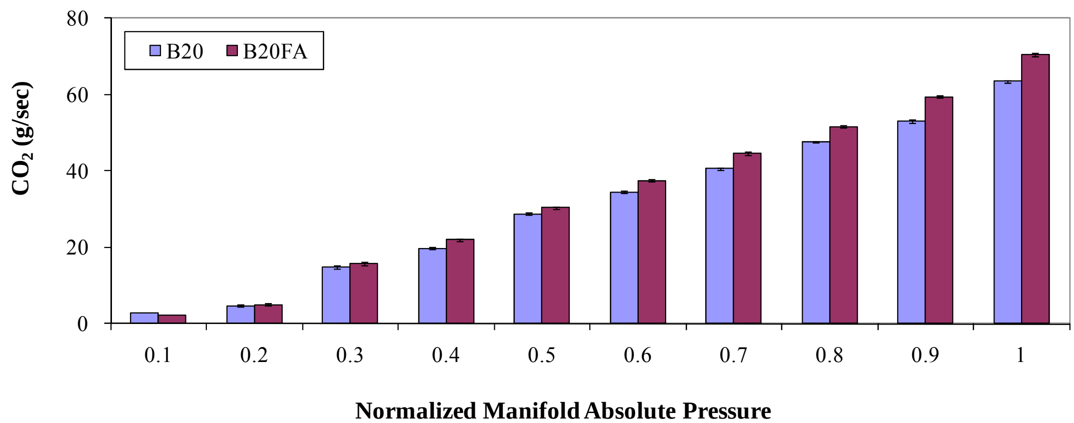


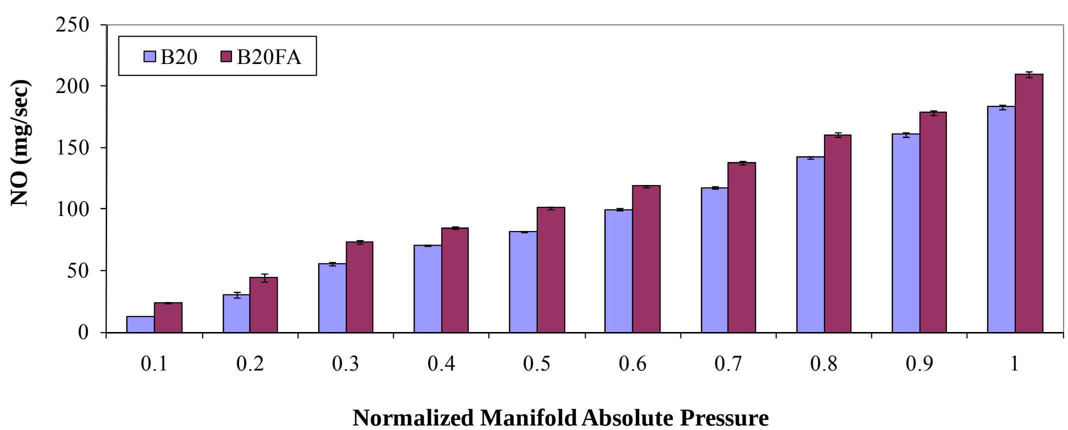
HC (g/gallon)
40
30
20
10
0
B20
B20FA
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure

CO (g/gallon)
80
60
40
20
0
B20
B20FA
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure

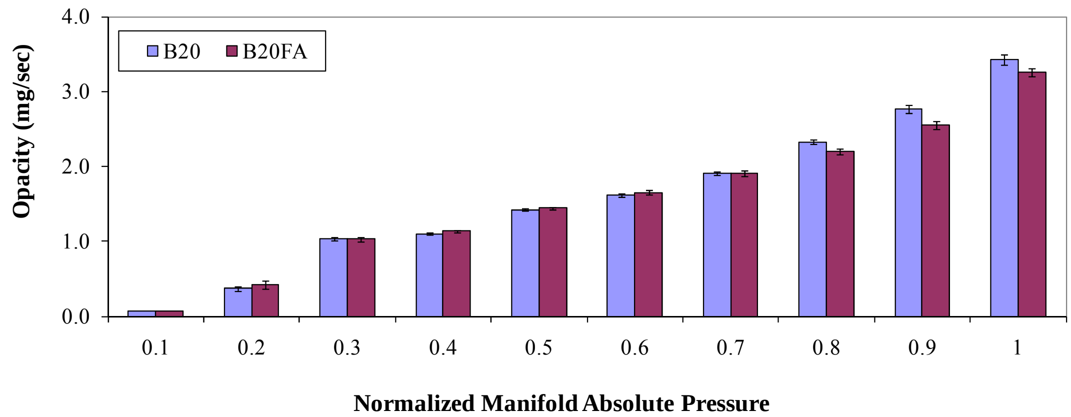


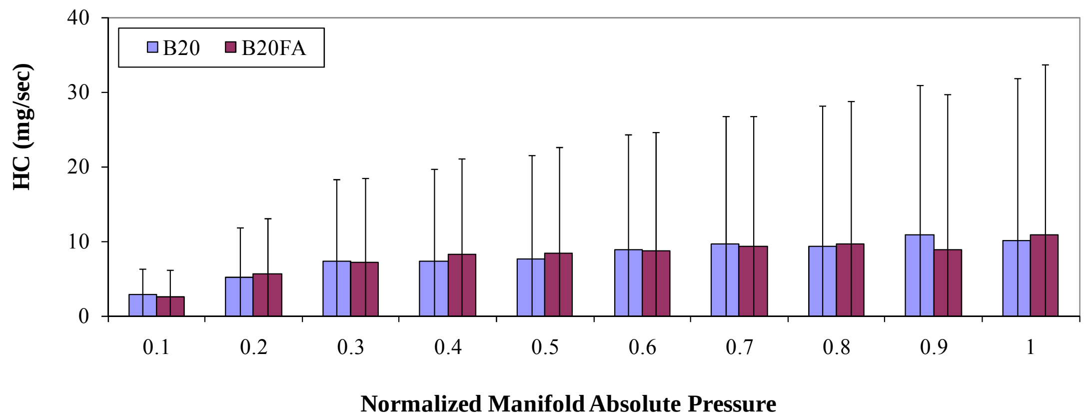



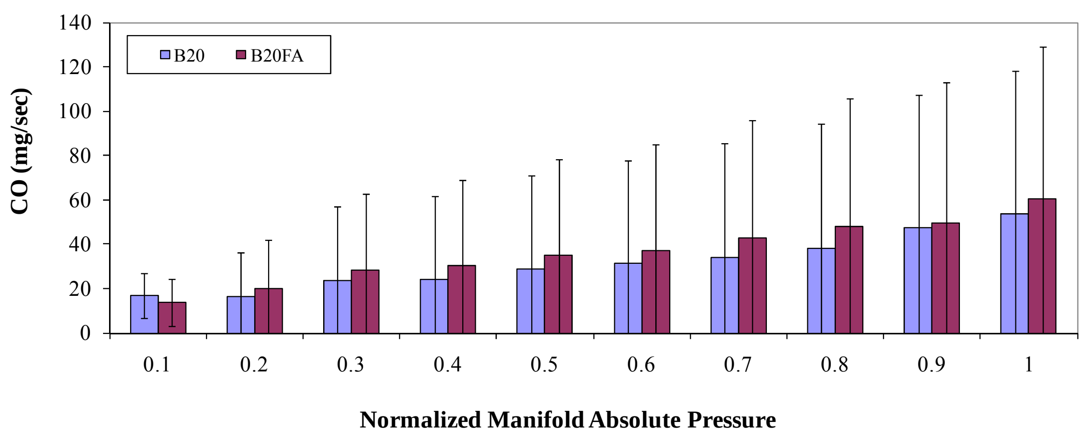



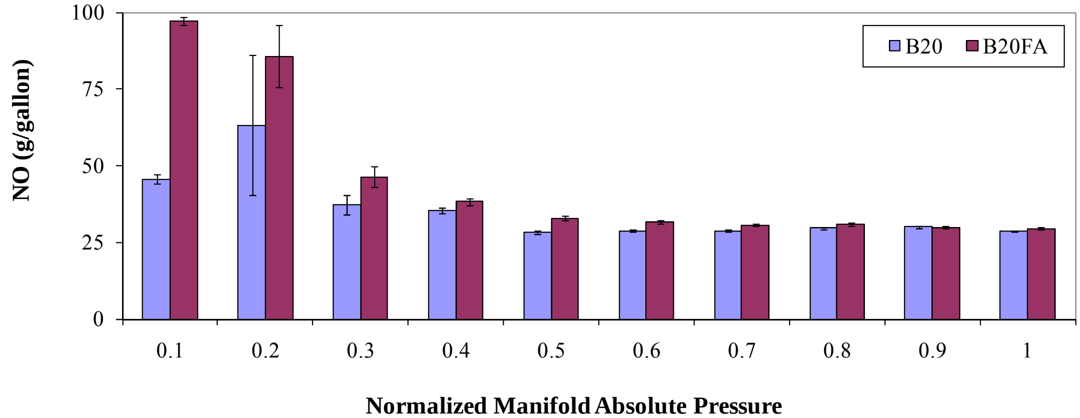

B20 = 20% Biodiesel, 80% Petroleum Diesel. B20FA = B20 with Fuel additive.

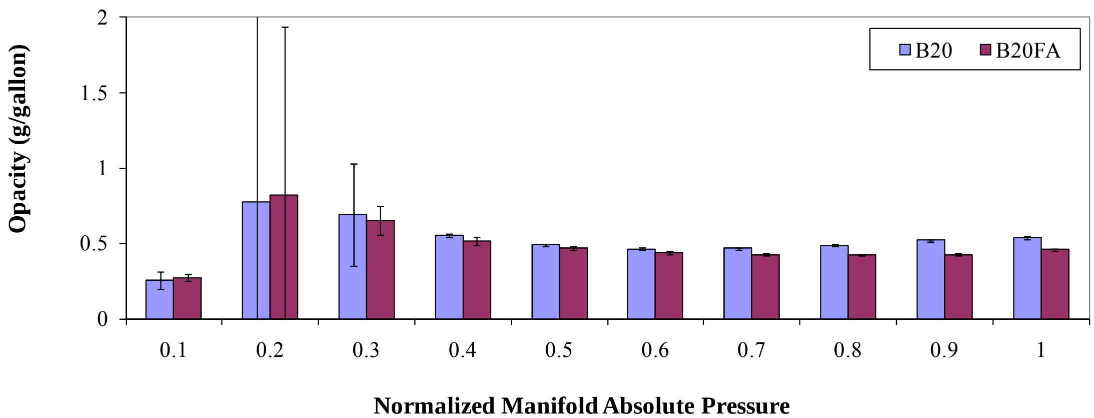
**Figure A-3. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Combination Truck 215-6415**


Opacity (mg/sec)
B20
B20FA
4.0
3.0
2.0
1.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure


HC (mg/sec)
B20
B20FA
40
30
20
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure

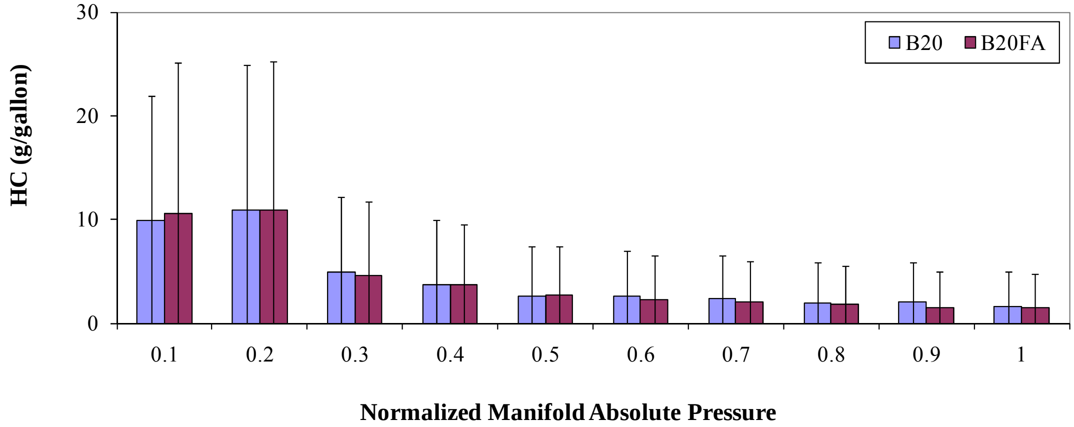

CO (mg/sec)
B20
B20FA
140
120
100
80
60
40
20
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure

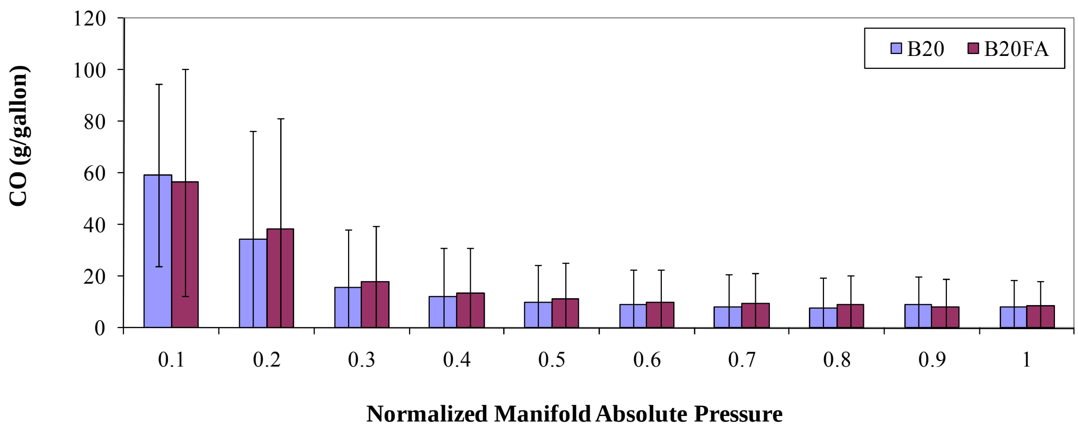


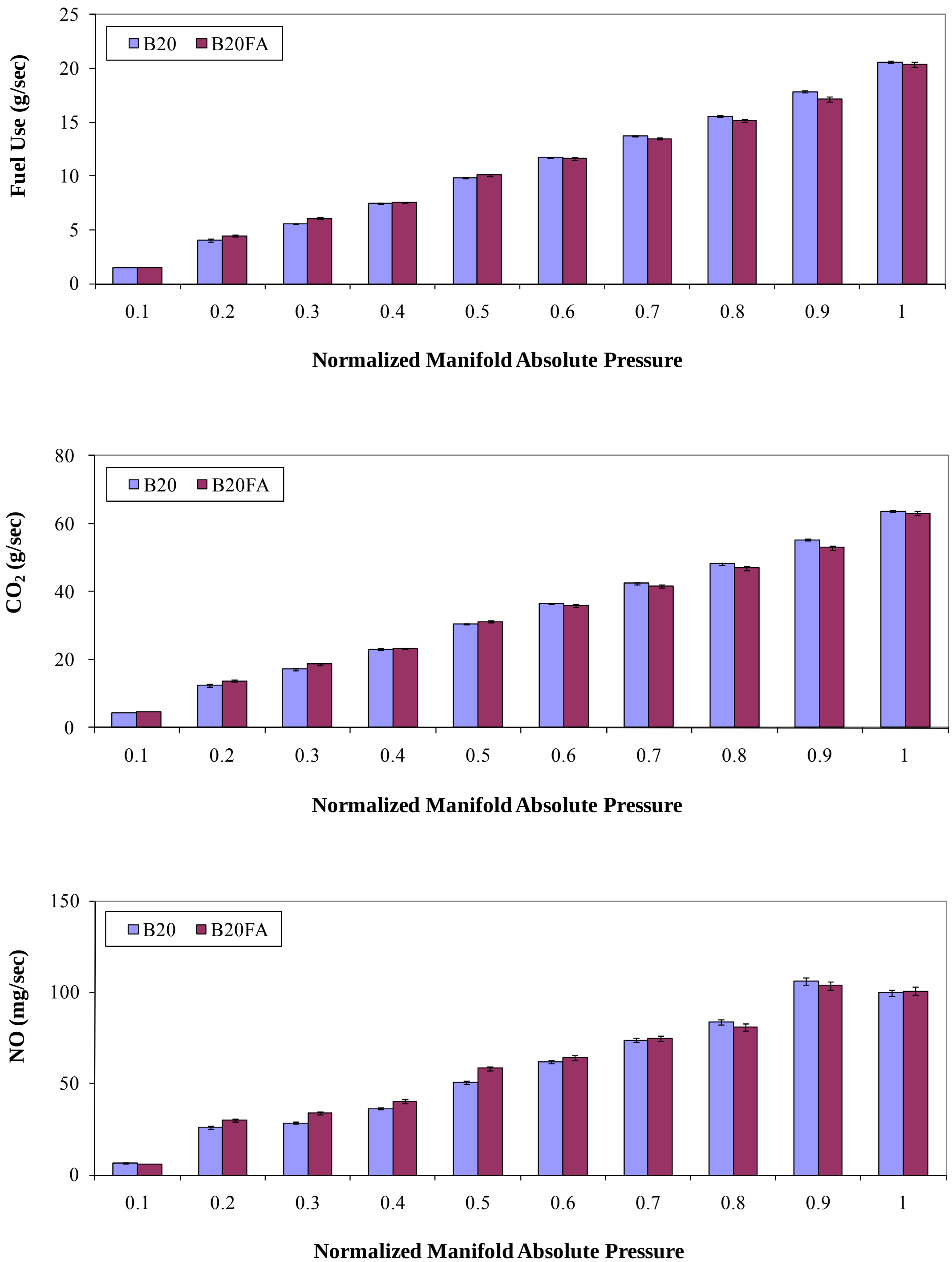




B20 = 20% Biodiesel, 80% Petroleum Diesel. B20FA = B20 with Fuel additive.

**Figure A-4. Emission Rates of Each Pollutant on a Per Fuel Basis for Engine-Based Modes for 215-6415 Combination Truck**

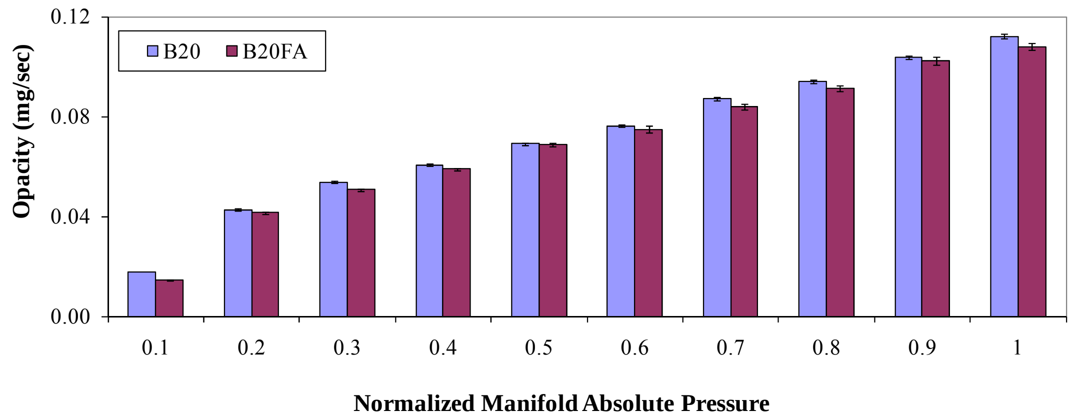

HC (g/gallon)
30
20
10
0
B20
B20FA
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure

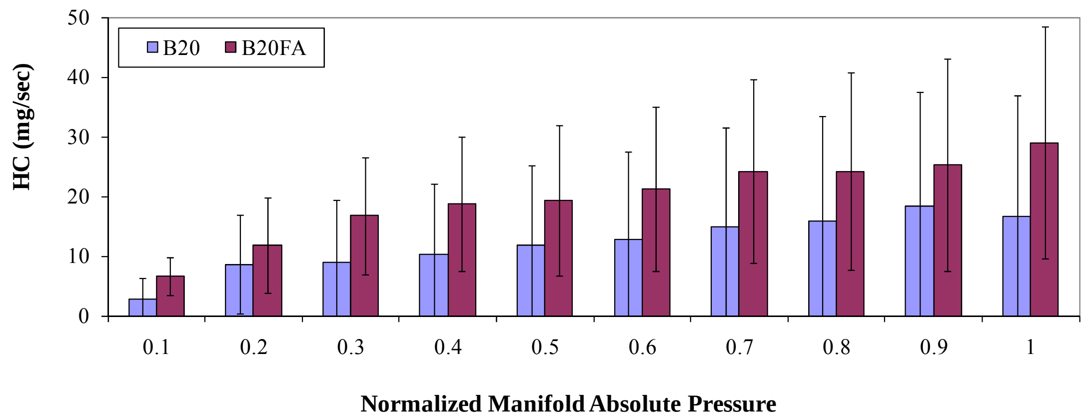

CO (g/gallon)
120
100
80
60
40
20
0
B20
B20FA
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure

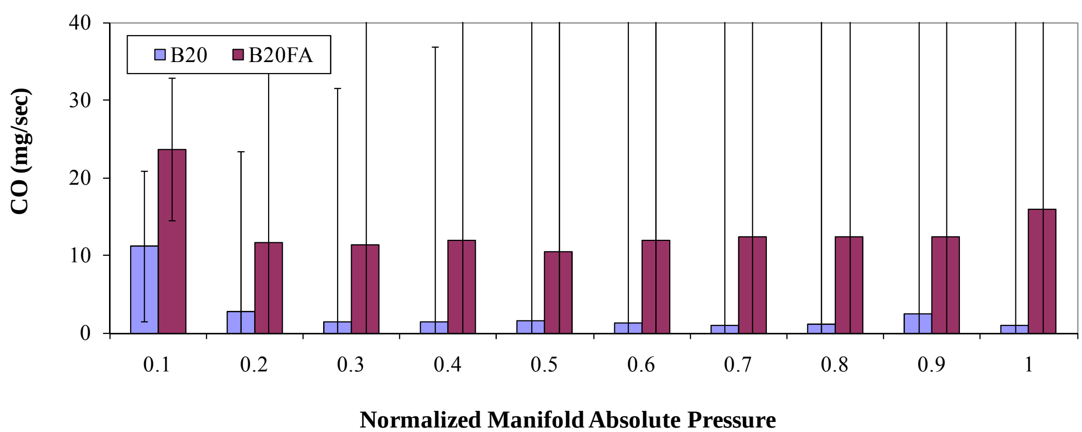


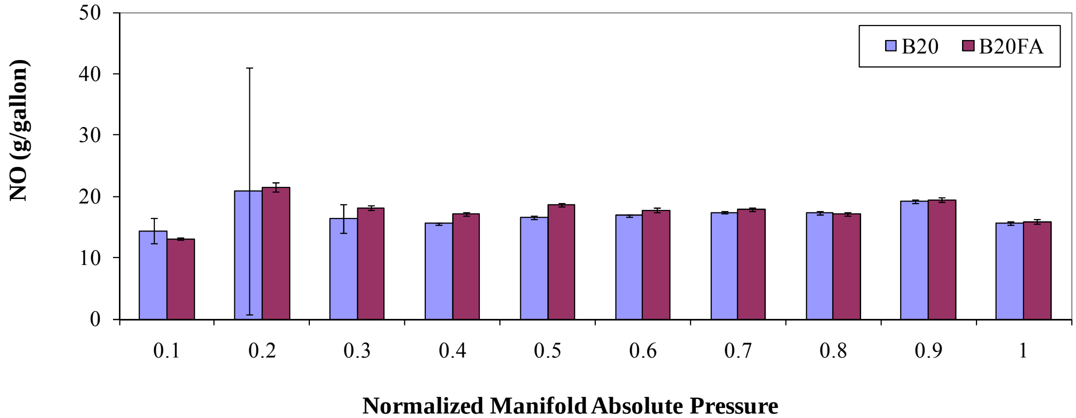

B20 = 20% Biodiesel, 80% Petroleum Diesel. B20FA = B20 with Fuel additive.

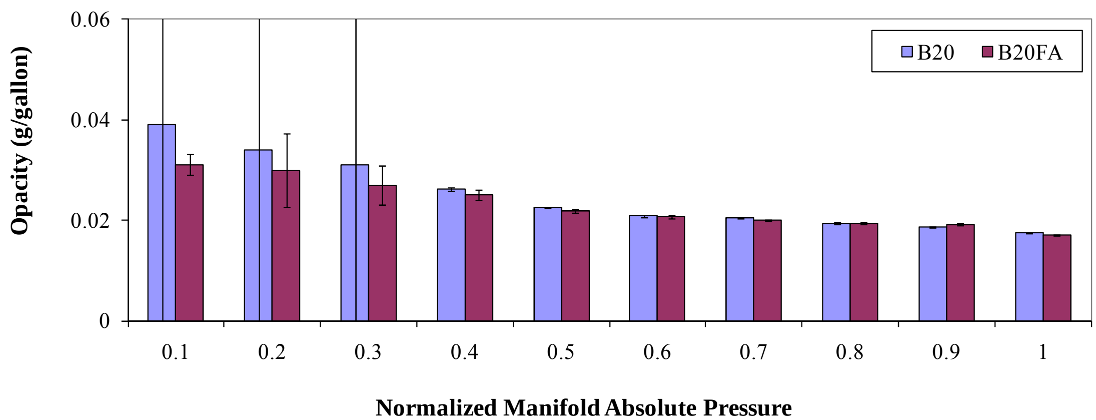
**Figure A-5. Average Fuel Use and Emission Rates of Each Pollutant on a Per Time Basis for Engine-Based Modes for Combination Truck 215-6667**


Opacity (mg/sec)
0.00
0.04
0.08
0.12
B20
B20FA
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure


HC (mg/sec)
0
10
20
30
40
50
B20
B20FA
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure

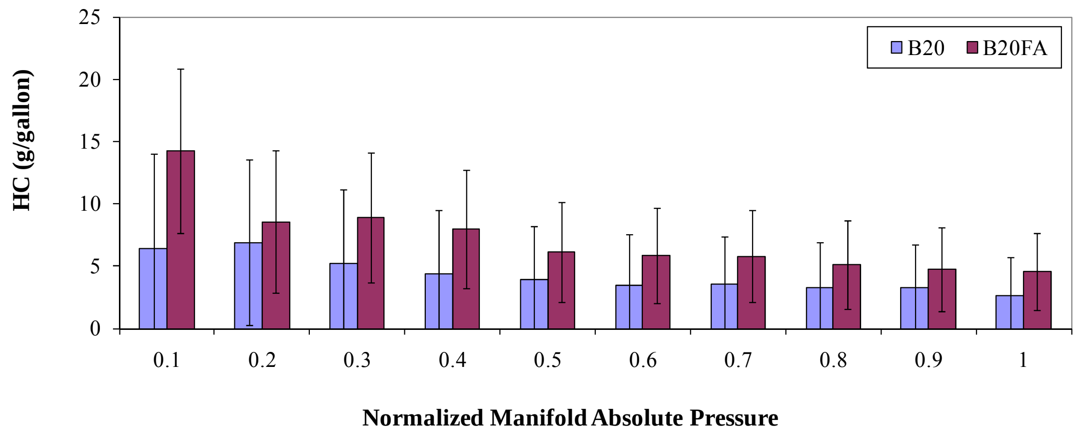

CO (mg/sec)
0
10
20
30
40
B20
B20FA
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure

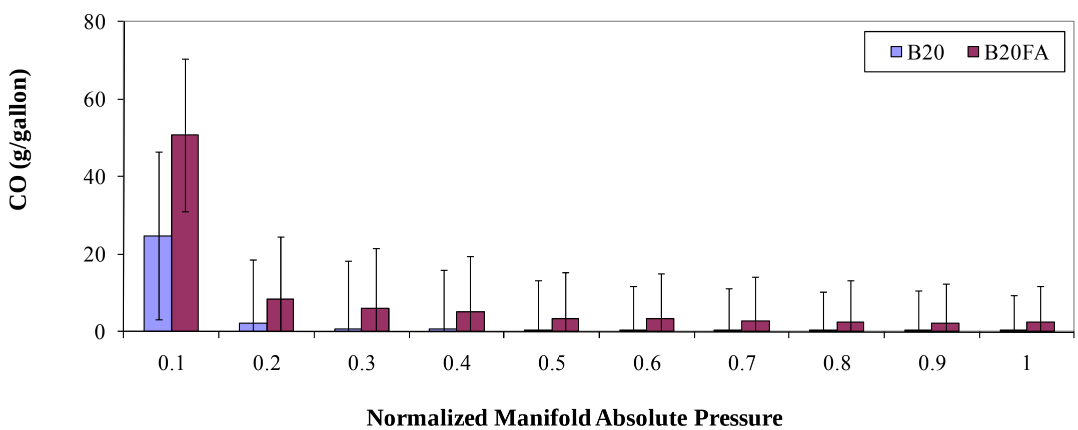



B20 = 20% Biodiesel, 80% Petroleum Diesel. B20FA = B20 with Fuel additive.

**Figure A-6. Emission Rates of Each Pollutant on a Per Fuel Basis for Engine-Based Modes for Combination Truck 215-6667**


HC (g/gallon)
B20
B20FA
25
20
15
10
5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure


CO (g/gallon)
B20
B20FA
80
60
40
20
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Normalized Manifold Absolute Pressure

**Evaluation of Non-Detected Measurements of Modal Average Gas Concentrations**

**Table A-1. Average Concentrations for Each Pollutant Based on 215-5715 Combination Truck Fueled for B20**

| MAP Range | N MAP | NO (ppm) | HC (ppm) | CO (%) | $CO_2$ (%) | $O_2$ (%) |
|---|---|---|---|---|---|---|
| 91-107 | 0.1 | 157 | 13 | 0.010 | 1.45 | 18.8 |
| 108-123 | 0.2 | 232 | 14 | 0.010 | 2.70 | 16.9 |
| 124-139 | 0.3 | 363 | 15 | 0.008 | 3.97 | 15.1 |
| 140-155 | 0.4 | 492 | 15 | 0.006 | 4.84 | 14.2 |
| 156-171 | 0.5 | 547 | 16 | 0.005 | 5.20 | 13.6 |
| 172-187 | 0.6 | 600 | 18 | 0.005 | 5.35 | 13.5 |
| 188-203 | 0.7 | 660 | 22 | 0.005 | 5.47 | 13.2 |
| 204-219 | 0.8 | 669 | 21 | 0.005 | 5.87 | 12.7 |
| 220-235 | 0.9 | 644 | 17 | 0.006 | 6.42 | 11.9 |
| 236-262 | 1 | 605 | 18 | 0.007 | 6.88 | 11.3 |

Detection Limits for HC and CO are approximately 13 ppm and 0.012 *vol*-%

**Table A-2. Average Concentrations for Each Pollutant Based on 215-5715 Combination Truck Fueled for B20 with Fuel additive**

| MAP Range | N MAP | NO (ppm) | HC (ppm) | CO (%) | $CO_2$ (%) | $O_2$ (%) |
|---|---|---|---|---|---|---|
| 91-107 | 0.1 | 165 | 17 | 0.014 | 1.50 | 18.8 |
| 108-123 | 0.2 | 281 | 20 | 0.016 | 2.61 | 16.4 |
| 124-139 | 0.3 | 424 | 19 | 0.014 | 4.47 | 14.5 |
| 140-155 | 0.4 | 538 | 18 | 0.012 | 5.46 | 13.4 |
| 156-171 | 0.5 | 604 | 18 | 0.013 | 5.94 | 12.9 |
| 172-187 | 0.6 | 643 | 18 | 0.012 | 5.95 | 12.8 |
| 188-203 | 0.7 | 676 | 18 | 0.013 | 5.97 | 12.7 |
| 204-219 | 0.8 | 693 | 20 | 0.014 | 6.48 | 12.1 |
| 220-235 | 0.9 | 738 | 21 | 0.014 | 7.22 | 11.1 |
| 236-262 | 1 | 631 | 21 | 0.015 | 7.60 | 10.5 |

Detection Limits for HC and CO are approximately 13 ppm and 0.012 *vol*-%

**Table A-3. Average Concentrations for Each Pollutant Based on 215-6415 Combination Truck Fueled for B20**

| MAP Range | N MAP | NO (ppm) | HC (ppm) | CO (%) | $CO_2$ (%) | $O_2$ (%) |
|---|---|---|---|---|---|---|
| 91-112 | 0.1 | 90 | 11 | 0.020 | 2.09 | 18.1 |
| 113-133 | 0.2 | 112 | 10 | 0.010 | 1.99 | 18.2 |
| 134-155 | 0.3 | 122 | 9 | 0.009 | 3.44 | 15.9 |
| 156-176 | 0.4 | 137 | 8 | 0.008 | 4.05 | 15.4 |
| 177-198 | 0.5 | 142 | 7 | 0.008 | 5.25 | 13.9 |
| 199-219 | 0.6 | 156 | 7 | 0.008 | 5.64 | 13.4 |
| 220-241 | 0.7 | 166 | 7 | 0.008 | 5.99 | 13 |
| 242-262 | 0.8 | 183 | 6 | 0.008 | 6.42 | 12.4 |
| 263-284 | 0.9 | 193 | 7 | 0.010 | 6.67 | 12.2 |
| 285-306 | 1 | 202 | 6 | 0.010 | 7.34 | 11.4 |

Detection Limits for HC and CO are approximately 13 ppm and 0.012 *vol*-%

**Table A-4. Average Concentrations for Each Pollutant Based on 215-6415 Combination Truck Fueled for B20 with Fuel additive**

| MAP Range | N MAP | NO (ppm) | HC (ppm) | CO (%) | $CO_2$ (%) | $O_2$ (%) |
|---|---|---|---|---|---|---|
| 91-112 | 0.1 | 159 | 9 | 0.015 | 1.71 | 18.5 |
| 113-133 | 0.2 | 147 | 10 | 0.011 | 1.94 | 17.8 |
| 134-155 | 0.3 | 158 | 8 | 0.010 | 3.52 | 15.2 |
| 156-176 | 0.4 | 160 | 8 | 0.009 | 4.35 | 14.6 |
| 177-198 | 0.5 | 171 | 8 | 0.010 | 5.37 | 13.4 |
| 199-219 | 0.6 | 181 | 7 | 0.009 | 5.94 | 12.7 |
| 220-241 | 0.7 | 189 | 7 | 0.010 | 6.38 | 12.1 |
| 242-262 | 0.8 | 201 | 7 | 0.010 | 6.75 | 11.7 |
| 263-284 | 0.9 | 203 | 6 | 0.009 | 7.06 | 11.3 |
| 285-306 | 1 | 220 | 6 | 0.010 | 7.71 | 10.5 |

Detection Limits for HC and CO are approximately 13 ppm and 0.012 *vol*-%

**Table A-5. Average Concentrations for Each Pollutant Based on 215-6667 Combination Truck Fueled for B20**

| MAP Range | N MAP | NO (ppm) | HC (ppm) | CO (%) | $CO_2$ (%) | $O_2$ (%) |
|---|---|---|---|---|---|---|
| 91-112 | 0.1 | 43 | 11 | 0.014 | 3.41 | 16.7 |
| 113-133 | 0.2 | 78 | 13 | 0.002 | 3.96 | 16 |
| 134-155 | 0.3 | 67 | 11 | 0.001 | 4.29 | 15.7 |
| 156-176 | 0.4 | 75 | 11 | 0.000 | 5.05 | 14.9 |
| 177-198 | 0.5 | 94 | 12 | 0.000 | 5.93 | 14 |
| 199-219 | 0.6 | 103 | 11 | 0.000 | 6.38 | 13.4 |
| 220-241 | 0.7 | 110 | 12 | 0.000 | 6.63 | 13.1 |
| 242-262 | 0.8 | 117 | 12 | 0.000 | 7.02 | 12.7 |
| 263-284 | 0.9 | 135 | 12 | 0.001 | 7.37 | 12.3 |
| 285-306 | 1 | 120 | 11 | 0.000 | 8.02 | 11.6 |

Detection Limits for HC and CO are approximately 13 ppm and 0.012 *vol*-%

**Table A-6. Average Concentrations for Each Pollutant Based on 215-6667 Combination Truck Fueled for B20 with Fuel additive**

| MAP Range | N MAP | NO (ppm) | HC (ppm) | CO (%) | $CO_2$ (%) | $O_2$ (%) |
|---|---|---|---|---|---|---|
| 91-112 | 0.1 | 45 | 28 | 0.031 | 3.76 | 16.6 |
| 113-133 | 0.2 | 90 | 19 | 0.006 | 4.44 | 15.1 |
| 134-155 | 0.3 | 85 | 22 | 0.005 | 4.90 | 14.6 |
| 156-176 | 0.4 | 87 | 22 | 0.004 | 5.33 | 14.2 |
| 177-198 | 0.5 | 111 | 20 | 0.003 | 6.27 | 13.1 |
| 199-219 | 0.6 | 112 | 20 | 0.003 | 6.56 | 12.7 |
| 220-241 | 0.7 | 117 | 20 | 0.003 | 6.85 | 12.4 |
| 242-262 | 0.8 | 117 | 19 | 0.003 | 7.14 | 12.1 |
| 263-284 | 0.9 | 139 | 18 | 0.003 | 7.48 | 11.6 |
| 285-306 | 1 | 127 | 19 | 0.003 | 8.29 | 10.7 |

Detection Limits for HC and CO are approximately 13 ppm and 0.012 *vol*-%

**Table A-7. Summary of Fuel Use**

| Run | Actu | Measur | % | Actual | Estimate | Actu | Measur | Durati |
|---|---|---|---|---|---|---|---|---|
| **5715_B20[1]** | 50.0 | 39.9 | 20.2 | 269 | 265 | 5.4 | 6.6 | 22875 |
| **5715_B20F** | 48.3 | 42.9 | 11.2 | 270 | 268 | 5.6 | 6.3 | 24581 |
| **6415_B20** | 61.5 | 64.2 | -4.3 | 323 | 323 | 5.3 | 5.0 | 25833 |
| **6415_B20F** | 110 | 72.4 | 34.3 | 320 | 322 | 2.9 | 4.5 | 26936 |
| **6667_B20** | 67.1 | 68.3 | -1.8 | 328 | 327 | 4.9 | 4.8 | 26557 |
| **6667_B20F** | 71.5 | 69.5 | 2.8 | 316 | 316 | 4.4 | 4.6 | 29254 |

[1] Estimated fuel use is biased low because of exhaust pipe rupture. Displayed in Figure A-7, but excluded from the regression analysis trendline
[2] NCDOT did tank up at start of test, so actual fuel use is biased high. Not displayed in Figure A-7
[3] Based on fuel station refilling after test. The truck is tanked up before the test and then refueled to same level after the test
[4] Calculated from Modal Model fuel g/sec and total seconds for each mode
[5] (Actual-Measured)/Actual *100
[6] Difference of Odometer reading at start and end of test
[7] Calculated from sec by sec speed data from GPS

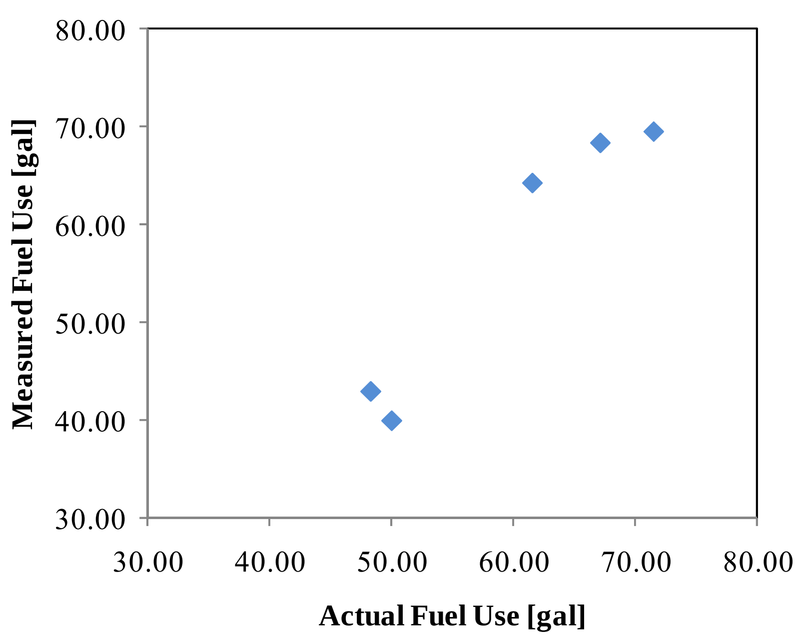
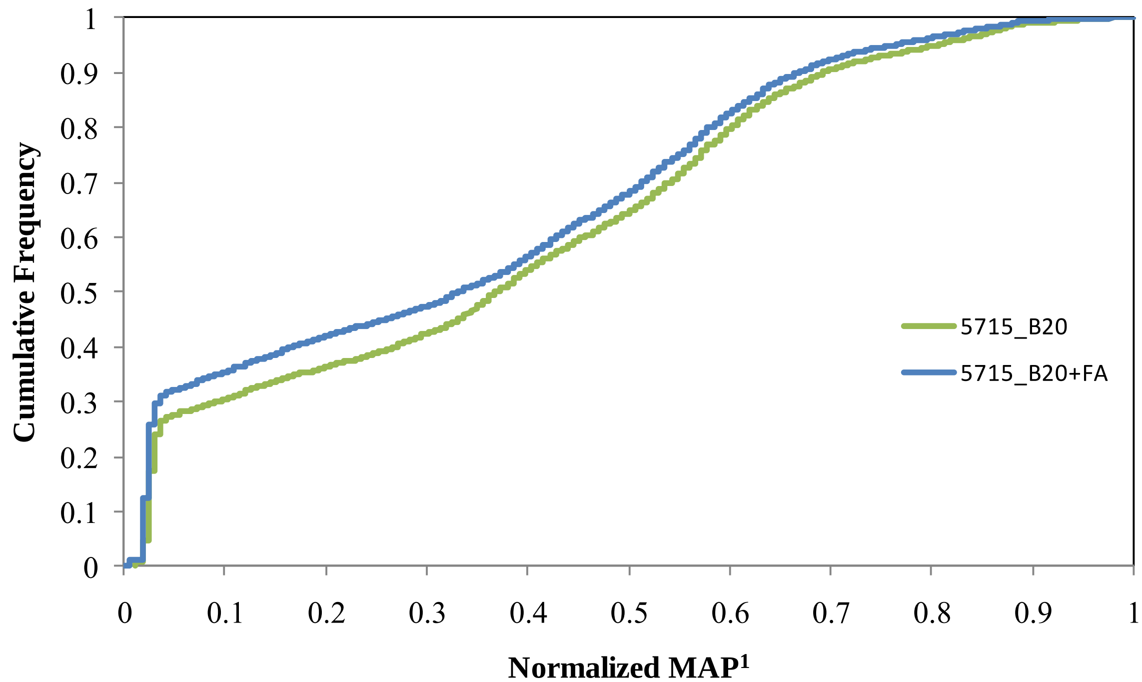



**Figure A-7. Scatter plot of Actual Fuel Use vs. Measured Fuel Use**

## Table A-8. Rate of Loss of Data Because of Data Quality Errors

| ID | Fuel [a] | Raw [b] (sec) | Amount of Data Lost for Specific Type of Error | | | | | | | | Error [d] | QA Data [e] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | | |
| 215-5715 | B20 | 22,875 | 0 | 0 | 0 | 0 | 5,065 | 0 | 0 | 8 | 22.2 | 17,802 |
| | B20FA | 24,581 | 0 | 0 | 0 | 0 | 942 | 0 | 70 | 0 | 4.1 | 23,569 |
| 215-6415 | B20 | 25,833 | 0 | 0 | 0 | 0 | 3,804 | 0 | 0 | 1 | 14.7 | 22,028 |
| | B20FA | 26,936 | 0 | 0 | 0 | 0 | 4,077 | 0 | 0 | 2 | 15.1 | 22,857 |
| 215-6667 | B20 | 26,512 | 0 | 0 | 0 | 0 | 937 | 0 | 0 | 29 | 3.6 | 25,546 |
| | B20FA | 29,254 | 0 | 179 | 0 | 0 | 865 | 1031 | 0 | 31 | 7.2 | 27,148 |
| **Overall** | | | | | | | | | | | | |
| **Total Seconds** | | **155,991** | 0 | 179 | 0 | 0 | 15,690 | 1,031 | 70 | 71 | - | **138,950** |
| Percentage of raw data (%) | | | 0 | 0.11 | 0 | 0 | 10.06 | 0.66 | 0.04 | 0.05 | 10.92 | 89.08 |

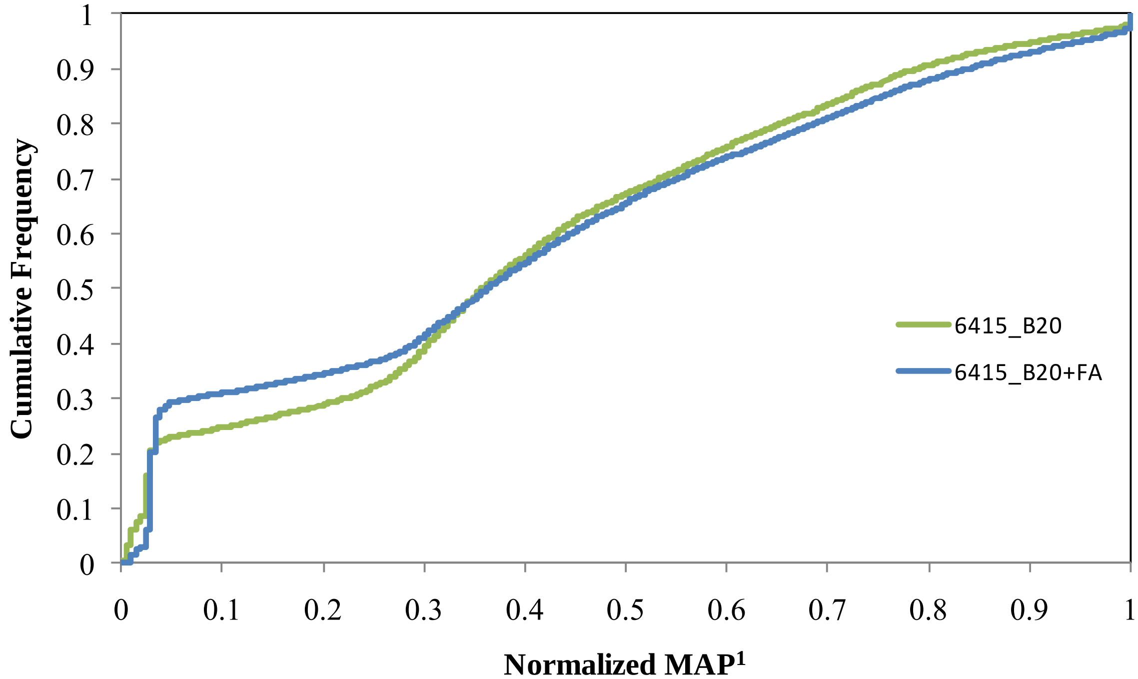
[a] B20: 20% Biodiesel, 80% Petroleum Diesel; B20FA: B20 with Fuel additive
[b] Total Raw Data
[c] Definition of Errors
1: Missing Manifold Absolute Pressure (MAP)
2: Unusual Engine Speed (engine RPM)
3: Analyzer Freezing
4: Inter-analyzer Discrepancy (IAD)
5: Air Leakage
6: Unusual Intake Air Temperature (IAT)
7: Negative Emission Value
8: Invalid Data as Flagged by the PEMS software
[d] Average Error Rate
[e] Quality Assured Data




[1] The normalization of MAP is between 96 and 262 kPa

| | Sample Size | Min. MAP | Max. MAP | Avg. MAP | SD of MAP |
|---|---|---|---|---|---|
| **B20** | 22875 | 98 | 262 | 154 | 45 |
| **B20FA** | 24581 | 96 | 262 | 149 | 44 |

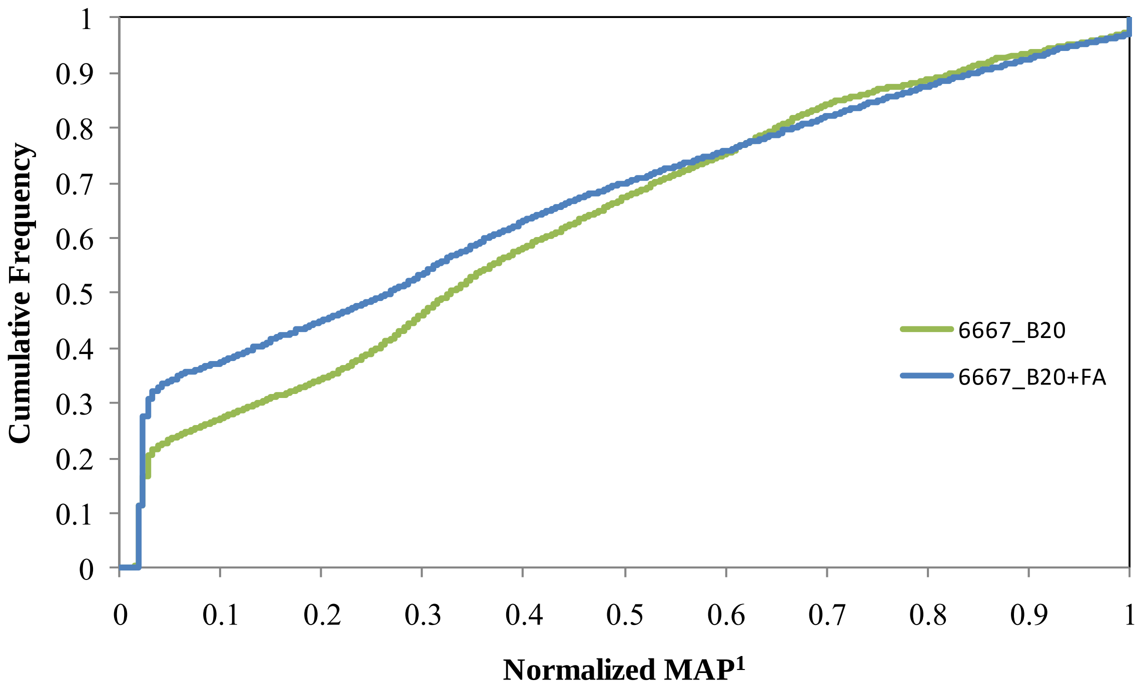
**Figure A-8. Cumulative Frequency of Normalized Manifold Absolute Pressure for Truck 215-5715**




[1] The normalization of MAP is between 96 and 306 kPa

| | Sample Size | Min. MAP | Max. MAP | Avg. MAP | SD of MAP |
|---|---|---|---|---|---|
| **B20** | 25833 | 96 | 306 | 177 | 60 |
| **B20FA** | 26936 | 96 | 306 | 176 | 65 |

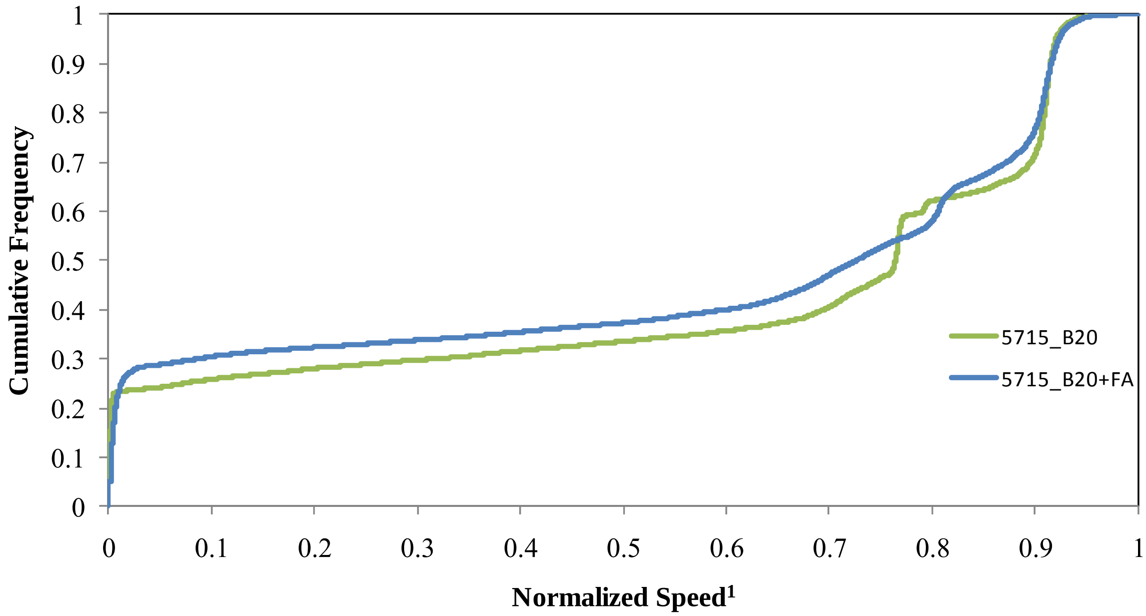
**Figure A-9. Cumulative Frequency of Normalized Manifold Absolute Pressure for Truck 215-6415**




[1] The normalization of MAP is between 93 and 306 kPa

| | Sample Size | Min. MAP | Max. MAP | Avg. MAP | SD of MAP |
|---|---|---|---|---|---|
| **B20** | 26556 | 93 | 306 | 172 | 63 |
| **B20FA** | 29254 | 93 | 306 | 165 | 68 |

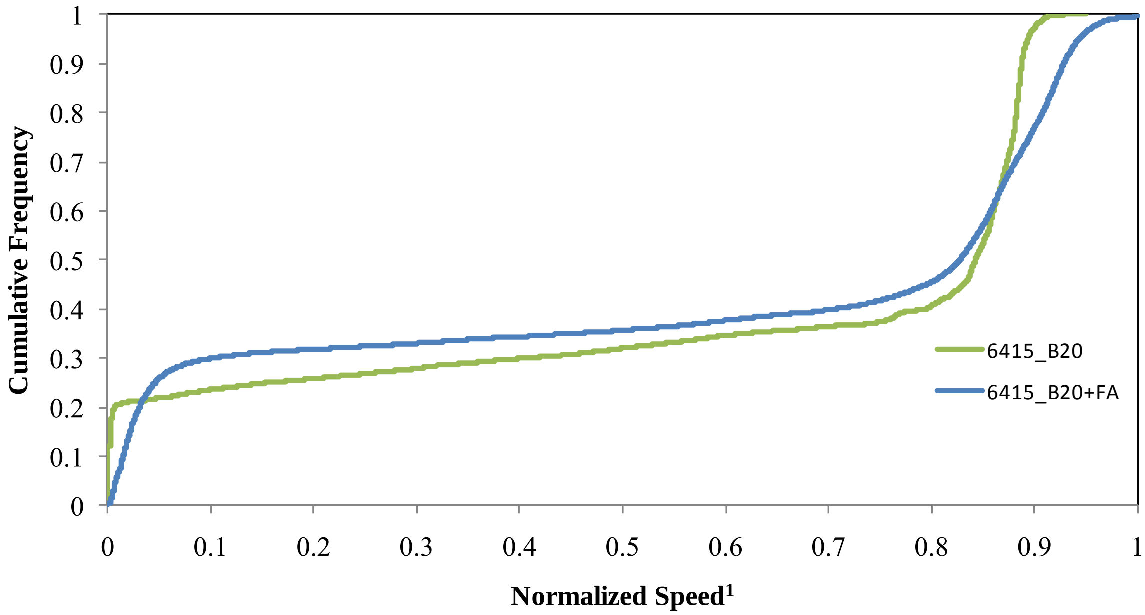
**Figure A-10. Cumulative Frequency of Normalized Manifold Absolute Pressure for Truck 215-6667**




[1] The normalization of speed is between 0 and 72.72 mph

| | Sample Size | Min. Speed | Max. Speed | Avg. Speed | SD of Speed |
|---|---|---|---|---|---|
| **B20** | 22875 | 0 | 70.87 | 41.75 | 27.16 |
| **B20FA** | 24581 | 0 | 72.72 | 39.25 | 27.95 |

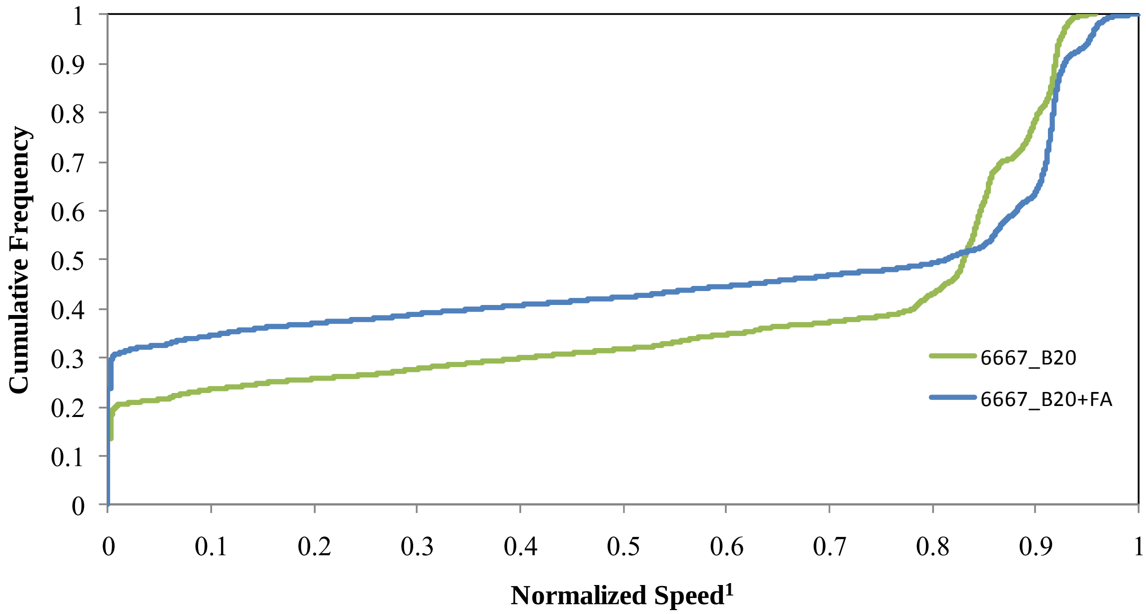
**Figure A-11. Cumulative Frequency of Normalized Vehicle Speed for Truck 215-5715**




[1] The normalization of speed is between 0 and 75 mph

| | Sample Size | Min. Speed | Max. Speed | Avg. Speed | SD of Speed |
|---|---|---|---|---|---|
| **B20** | 25833 | 0 | 71.25 | 45.04 | 27.66 |
| **B20FA** | 26841 | 0 | 75 | 43.13 | 29.27 |

**Figure A-12. Cumulative Frequency of Normalized Vehicle Speed for Truck 215-6415**




[1] The normalization of speed is between 0 and 73.52 mph

| | Sample Size | Min. Speed | Max. Speed | Avg. Speed | SD of Speed |
|---|---|---|---|---|---|
| **B20** | 26556 | 0 | 70.43 | 44.34 | 27.28 |
| **B20FA** | 29254 | 0 | 73.52 | 38.93 | 30.78 |

**Figure A-13. Cumulative Frequency of Normalized Vehicle Speed for Truck 215-6667**