OPERATIONAL EVALUATION OF IN-USE EMISSIONS AND FUEL CONSUMPTION OF B20 VERSUS DIESEL-FUELED HEAVY DUTY VEHICLES

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Abstract

This paper reports on an ongoing project aimed at quantifying the episodic nature of real world emissions of biodiesel and diesel fueled trucks in the NC Department of Transportation fleet. Based upon an analysis of chassis dynamometer data reported in the literature, the substitution of "B20" soy-based biodiesel for petroleum diesel leads to statistically significant reductions in emissions of CO, particulate matter, and hydrocarbons, but a slight increase in NO_x. However, there is a lack of in-use data via which to assess the real world comparison of biodiesel versus diesel and via which to identify opportunities for improved operation and reduced emissions. A pilot data collection effort using a portable emissions monitoring system with an NCDOT truck is reported, toward the goal of evaluating B20 versus diesel emission based upon real-world data.

1.0 Introduction

The purpose of this project is provide real world assessment of the emissions and fuel use of heavy duty diesel vehicles operated by the North Carolina Department of Transportation (NCDOT). There are many needs for this information, each with different implications. For example, an understanding of the episodic nature of emissions and fuel use, which has been demonstrated in recent data collection and modeling efforts, is the foundation for the development of scientifically-sound operational strategies aimed at pollution prevention and energy resource conservation. Moreover, there may be opportunities to reduce emissions and energy use without significant compromise with respect to duty cycles. A second motivation for this work is the impending designation of a significant number of North Carolina counties as non-attainment with respect to both tropospheric ozone and particulate matter of less than 2.5 microns ($PM_{2.5}$) under new National Ambient Air Quality Standards (NAAQS). Because diesel vehicles contribute significantly to both of these air quality problems, and because non-attainment designations have significant impacts for economic development in North Carolina, it is important to be proactive in identifying and implementing opportunities to manage vehicle emissions of both NO_x (a precursor to ozone) and $PM_{2.5}$. A third motivation for this work is to develop a rigorous baseline for estimation of emissions from heavy duty diesel vehicles under conditions typical of North Carolina. A fourth motivation is to establish a baseline for comparison of alternative fuels, lubricating oils, and vehicle technologies, whether included in this project or in future work. For example, by establishing a statistically sound baseline regarding emissions from the current fleet of diesel vehicles, it is later possible to determine whether a new fuel additive or a change in lubricating oil (as examples) leads to significant reductions in emissions and/or fuel use and under what conditions of engine load, ambient temperature, road grade, and so on that such changes are observable.

Biodiesel is a blend of a biofuel feed stock with conventional diesel. The blend stock is typically made from vegetable oils or animal fats. If these fats or oils are chemically reacted with an alcohol (usually methanol), fatty methyl esters and glycerol are produced. Biodiesel has all the essential properties of diesel fuel, but has a higher oxygen content and a narrower range of boiling points (i.e. 327-346°C). Engine efficiency for biodiesel blends is approximately the same as that of diesel fuel. Because of these characteristics, biodiesel can be used directly in diesel engines without major modifications of the engines and vehicles (Sheehan *et al.,* 1998). A typical modification that is required is to replace the existing fuel filter with a larger one to deal with a larger loading of impurities in the biodiesel feedstock compared to petroleum diesel. Particularly for animal fat-derived biofuels, there can be some issues associated with coagulation in cold temperatures.

A pure blend stock for making biodiesel fuel is referred to as “B100.” A typical biodiesel fuel contains 20% blend stock and 80% petroleum diesel, and is referred to as “B20.” The use of B100 and B20, in comparison to pure petroleum diesel, is reported to reduce tailpipe emissions of PM by 68% and 13.6%, respectively. Non-methane hydrocarbon emissions (NMHC) are reduced by 37% when B100 is used and by 7% when B20 is used. CO emissions are reduced by 46% and 9% when B100 and B20 are used, respectively. These results are based upon specific test procedures. Biodiesel fuel effects on CO, NMHC, and PM are likely due to the fact that these fuels contain molecular oxygen, and thus improve overall combustion. However, biodiesel causes an increase in NO_x emissions. For example, B100 has tailpipe emissions that are 9% higher than those of petroleum diesel. At the lower level of biodiesel in B20, this effect is reduced to about 2%. Changes in engine timing can affect a trade-off between PM and NO_x emissions on current engines. Smaller changes in NO_x emissions for B100 and B20 have been observed in recent research (Sheehan *et al.,* 1998). The actual reduction will vary among vehicles and will depend upon operating conditions.

In compliance with the Energy Policy Act of 1992, NCDOT is proceeding with the use of alternative fueled vehicles (AFVs), including B20 biodiesel-fueled medium duty trucks. There is a need to identify opportunities to reduce NO_x emissions associated with the use of B20 fuel. Furthermore, because real world emissions are episodic in nature, it is important to have a thorough understanding of factors that lead to episodes of high emissions, as well as high fuel consumption. Such information will be used to recommend specific operational strategies for reducing emissions and fuel use. Based upon previous work at NCSU and elsewhere using portable on-board emissions and fuel use measurement instruments, a consistent finding is that how a vehicle is driven, and not necessarily how many miles it is driven, plays a critical role with respect to emissions and fuel use. Thus, there are opportunities to reduce emissions and fuel use without reducing miles traveled or without interfering significantly with typical duty cycles.

2.0 Problem Definition and Project Objectives

The key problems to be addressed by this work are the following: (1) what are the baseline real-world in-use emissions and fuel use during actual operation of the vehicle under typical duty cycles?; (2) what factors contribute the most to episodes of high emissions and/or fuel use?; (3) what operational strategies can be demonstrated and verified with respect to reductions in episodes of high emissions and fuel use?; and (4) what is the feasibility of such strategies?

The objectives of this project are to: (1) characterize baseline real-world in-use on-road emissions of selected heavy duty diesel vehicles, including those fueled with B20, during normal duty cycles; (2) characterize the episodic nature of emissions and fuel use; (3) identify factors responsible for variability in emissions and fuel use, with specific focus on factors leading to episodes of high emissions and fuel use; (4) develop recommended strategies for reducing the frequency and duration of high emissions and fuel use episodes, with consideration of operational constraints as well as other possible benefits; and (5) test and verify selected recommendations.

3.0 Biodiesel Fuel Properties and Emissions

In this section, we briefly review the fuel properties of biodiesel versus petroleum diesel and compare emissions based upon the two fuels predicated upon emissions data reported in the literature.

Table 1 summarizes many of the key fuel properties of petroleum diesel, soy-based B20 biodiesel, and soy-based B100 blend stock. Blends of diesel and B100 blend stock to produce a mixture of 80 percent petroleum diesel and 20 percent blend stock have many of the advantages of each constituent component. The heating value of B20 blend is only slightly lower than that of petroleum blend stock. The specific gravity is similar. Unlike petroleum diesel, B20 biodiesel has approximately 2.9 weight percent of oxygen, which is associated with a reduction in emissions of products of incomplete combustion, such as CO, hydrocarbons, and particulate matter. However, B20 has a higher Cetane number than petroleum diesel, which may be related to slightly higher NO_x emissions. B20 has a somewhat higher cloud point and pour point than petroleum diesel, suggesting the potential for handling problems in cold conditions. The aromatic content of B20 is lower than that for petroleum diesel. A reduction in aromatic content is typically associated with a reduction in NO_x emissions compared to similar fuels with higher aromatic content. However, a reduction in aromatic content is also typically associated with a reduction in PM emissions. The effect of aromatic content may be more significant for polyaromatics rather than mono-aromatics. The aromatic content also has some effect on density.

Table 2 summarizes a comparison of average changes in emissions for specific types of diesel engines when comparing either soy-based B20 biodiesel or soy-based B100 blend stock versus petroleum diesel (distillate No. 2 oil) with respect to NO_x, PM, CO, and THC. The data reported in Table 2 are based upon a review of data published in references summarized by EPA (2002). The mean and standard deviation (SD) of the percent differences were obtained based upon an analysis of data collected from the literature. For comparison, the mean differences reported by EPA (2002) are also shown for B20. The calculated mean differences and reported

Table 1. Summary of Properties for Typical Petroleum Diesel, Soy-Based B20 Biodiesel, and Soy-Based B100 Blend Stock

Property	Diesel	B20	B100
LHV (BTU/lb)	18,440	17,900	15,940
Specific Gravity	0.84	0.85	0.89
Cetane No.	44	52	55
Carbon, wt-%	85.9	83.5	76.3
Hydrogen, wt-%	13.6	13.2	12.6
Oxygen, wt-%	0.0	2.87	10.87
Sulfur, wt%	0.05	0.01	0
Flash point (°F)	150	180	260
Cloud point (°F)	18	20	40
Pour point (°F)	-4	9	34
IBP(°F)	352	373	573
Distillation Point (°F)	603	640	666
Aromatics, vol%	34		0
Viscosity@40F	2.6	2.36	6.0

mean differences from EPA for B20 agree in sign and magnitude. The average reduction in PM, CO, and THC emissions is substantially larger for B100 than for B20. However, the average reduction in emissions for B20 compared to petroleum diesel are on the order of 10 to 20 percent for these three pollutants. The average increase in NO_x emissions is on the order of two percent for B20 versus petroleum diesel.

The EPA (2002) study does not directly report as to whether the estimated mean differences in emissions between the fuels are statistically significant. Thus, an analysis was undertaken to evaluate the statistical significance of the mean differences. For this purpose, a database was constructed based upon the references cited in the EPA (2002) study. However, it was not possible to construct exactly the same database as that used by EPA because of lack of adequate documentation of the database used by EPA. In order to enable a consistent basis for comparison, the analysis was focused on 4-stroke engines, ranging from 150 to 450 hp, with rated speeds in the range of 1,600 to 3,000 rpm. A total of 35 vehicles were identified that were tested on both petroleum diesel and B20.

Figure 1 summarizes the available data for the selected types of engines operated on petroleum diesel for the example of NO_x emissions. Data were reported inclusive of five test procedures. Three of the procedures, 9Mode, JAP13, and R49, are steady-state modal emissions tests, and two, UDDS and UDDSH, are transient chassis dynamometer tests. For R49, UDDS

Table 2. Summary of the Difference in Emissions Between Soy-Based B20 Biodiesel versus Petroleum Diesel (Distillate No. 2), and Soy-Based B100 Blend Stock versus Petroleum Diesel, Based upon Analysis of Data Reported by EPA (2002) and Others.

Engine type/ Model Year	Fuel Pair	NOx	PM	CO	THC
B20 Emission Effects					
2-stroke<1991	D-2/B-20	3.20%	-1.80%	-13.90%	-20.90%
2-stroke1991+	D-2/B-20	3.90%	-17.80%	-12.00%	-17.50%
4-stroke<1991	D-2/B-20	2.90%	-15.70%	-13.60%	-12.20%
4-stroke 1991-3	D-2/B-20	-0.90%	-15.70%	-12.00%	-2.80%
4-stroke 1994	D-2/B-20	2.80%	-9.80%	-15.20%	-24.00%
Mean		2.38%	-12.16%	-13.34%	-15.48%
SD		1.88%	6.51%	1.36%	8.33%
EPA(2002) Avg.		2.00%	-10.10%	-11.00%	-21.10%
B100 Emission Effects					
2-stroke 1991+	D-2/B-100	19.60%	-33.00%	-42.40%	-72.70%
4-stroke 1991-3	D-2/B-100	13.30%	-68.30%	-41.80%	-38.70%
4-stroke 1994	D-2/B-100	9.90%	-36.60%	-41.50%	-76.30%
Mean		14.27%	-45.97%	-41.90%	-62.57%
SD		4.92%	19.42%	0.46%	20.75%
EPA(2002) Avg.		10.30%	-47.20%	-48.10%	-67.40%

and UDDSH, there is a similar range of NO_x emissions, from approximately 3.9 to 6 g/bhp-hr. The JAP13 cycle has substantially higher NO_x emissions. Thus, there is clearly variability in emissions associated with differences in operating conditions.

Figure 2 summarizes data available for the same types of engines as shown in Figure 1, but in this case the engines were operated on B20 biodiesel fuel. Data for comparison purposes were available only for the UDDS and UDDSH cycles. The inter-vehicle emissions vary from approximately 4.8 to 6 g/bhp-hr.

Figure 3 summarizes a comparison of the mean emissions of the selected vehicles for each of four pollutants, PM, NO_x, CO, and THC, and for three fuels, petroleum diesel, soy-based B20 biodiesel, and soy-based B100 blend stock, when vehicles were operated on the UDDS cycle. Figure 4 provides a similar comparison for the UDDSH cycle. The 95 percent confidence intervals of the mean emissions are shown. For the UDDS cycle, the reductions in PM, CO, and THC emissions when comparing petroleum diesel and B100 blend stock are statistically significant, as is the increase in NO_x emissions. For the UDDSH cycle, the findings are qualitatively similar.

Based upon these and other data reported in the literature, the typical differences in average emissions for vehicles fueled with soy-based B20 biodiesel versus petroleum diesel are as follows: 2 to 4 percent increase in NOx; 11 to 13 percent decrease in PM; 11 to 13 percent decrease in CO; and 18 to 21 percent decrease in hydrocarbons.

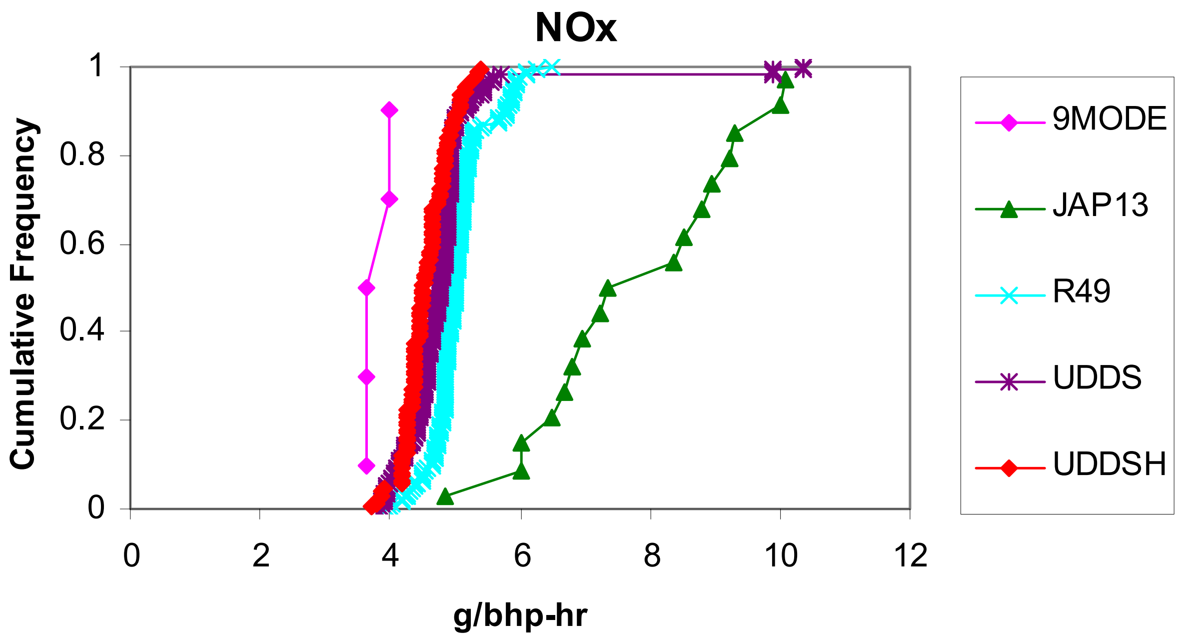


Figure 1. Inter-vehicle Variability in Test Cycle Emissions for Petroleum Diesel-Fueled Vehicles for Three Steady-State Modal Engine Dynamometer Test Cycles (9Mode, JAP13, and R49) and Two Transient Chassis Dynamometer Test Cycles (UDDS, UDDSH).

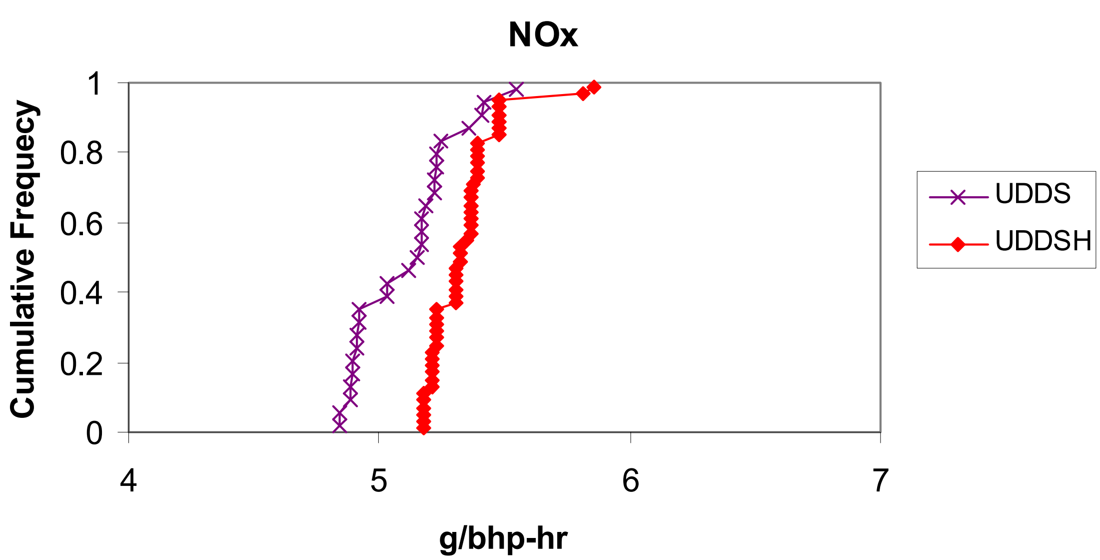
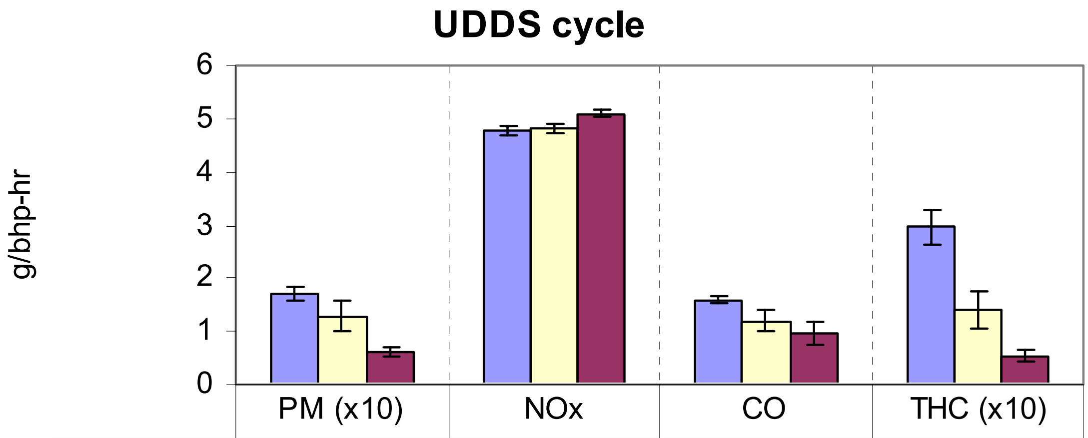
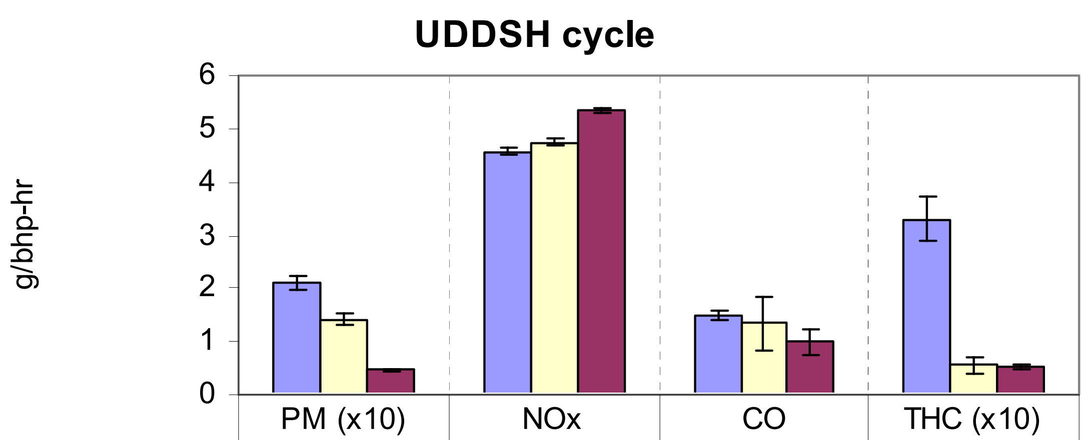


Figure 2. Inter-vehicle Variability in Test Cycle Emissions for B20 Biodiesel-Fueled Vehicles for Two Transient Chassis Dynamometer Test Cycles (UDDS, UDDSH).



	PM (x10)	NOx	CO	THC (x10)
Diesel	1.71	4.79	1.59	2.97
B20(soy)	1.29	4.83	1.20	1.40
B100(soy)	0.61	5.10	0.97	0.54

Figure 3. Comparison of Mean Emissions and 95 Percent Confidence Intervals in Mean Emissions for PM, NO_x, CO, and THC Emissions on Vehicles Fueled with Petroleum Diesel, Soy-based B20 Biodiesel, and Soy-Based B100 Blend Stock and Operated on the UDDS Cycle.



	PM (x10)	NOx	CO	THC (x10)
Diesel	2.12	4.56	1.50	3.30
B20(soy)	1.42	4.75	1.34	0.55
B100(soy)	0.47	5.34	0.99	0.53

Figure 4. Comparison of Mean Emissions and 95 Percent Confidence Intervals in Mean Emissions for PM, NO_x, CO, and THC Emissions on Vehicles Fueled with Petroleum Diesel, Soy-based B20 Biodiesel, and Soy-Based B100 Blend Stock and Operated on the UDDSH Cycle.

The differences in emissions when comparing B20 versus petroleum diesel appear to be consistent. However, the question remains as to whether these differences occur under real-world duty cycles, as opposed to standardized test cycles.

4.0 Measurement and Modeling and Vehicle Emissions

This section provides a brief overview of methods for measuring and modeling vehicle emissions, with a focus on heavy duty diesel vehicles.

Measurement of emissions from heavy duty diesel vehicles have typically been made using the following methods:

- Engine dynamometer tests
  - Steady state, modal tests
  - Transient tests
- Chassis dynamometer tests
- Tunnel studies
- Remote sensing
- Flux measurements
- On-board instrumentation

Engine dynamometer tests produce estimates of emissions on a mass per engine output basis, usually expressed in terms of grams of pollutant emitted per brake horsepower-hour (g/bhp-hr) of engine output. An example of an engine dynamometer test is the 13-mode test. This test is defined in the Code of Federal Regulations (40CFR336), and consists of 13 sequential steady state operating modes with 4.5- 6 minutes sampling time each. The speed for each mode must be held within ± 50 rpm and the load for each mode must be within ±2% of the maximum available torque for each mode. This steady-state test cycle is composed of 3 idle sample points, intermediate speed, and rated speed sample modes. The intermediate speed can be defined as a peak torque speed. The rated speed is defined as a maximum measured, full power speed. The loads correspond to 2%, 25%, 50%, 75%, and 100% of maximum available torque at a given test speed (EPA 2002). However, it is clear that this is an arbitrary set of modes and that these modes do not necessarily correspond to any real world duty cycle. There are several other specific types of modal steady-state tests.

A transient test procedure would continuously vary engine load based upon an observed real-world engine duty cycle. Such procedures may be more realistic but could be limited in that they represent only one particular duty cycle.

Chassis dynamometer tests involve testing of an entire vehicle placed upon a dynamometer. The heavy-duty, on-highway Federal Test Procedure consists of 4 phases and a variety of different speeds and loads that are sequenced to simulate the urban operation running of the vehicle that corresponds to the engine being tested. The average load factor of the heavy-duty FTP cycle is roughly 20~25 % of the maximum engine horsepower available at a given speed. The Urban Dynamometer Driving Schedule (UDDS) follows the EPA transient test. The EPA transient cycle run with a hot start only is referred to as UDDSH (EPA, 2002). The advantage of chassis dynamometer tests over engine dynamometer tests is the ability to measure emissions in terms of grams per vehicle mile of travel, taking into account fuel economy, and to simulate real-world driving on a flat road. However, the extent to which the test represents real world operation depends upon the choice of the driving cycle.

Tunnel studies typically involve measuring the total flux of pollutants from vehicles passing through the tunnel and correlating the pollutant flux to traffic flow. Using statistical analysis, it may be possible to apportion the emissions among major categories of vehicles (e.g., gasoline versus diesel, or light duty versus heavy duty). An advantage of a tunnel study is that it can capture a cross-section of the on-road vehicle fleet and represents real world operation at the location of the tunnel. A disadvantage is that it is difficult to apportion emissions to specific vehicle classes (i.e. subcategories within diesel fueled-vehicles) and the traffic conditions of the tunnel may not be representative of conditions elsewhere. Emissions can be estimated on a fuel consumed basis if a carbon balance can be assumed, or on an average per mile basis. Flux measurements are similar conceptually to tunnel studies, but involve measurement of flux of pollution surrounding a roadway.

Remote sensing involves measuring emissions at a specific location, typically using non-dispersive infrared (NDIR) and non-dispersive ultraviolet (NDUV) techniques. A large sample of vehicles can be captured at a single remote sensing site. However, the measurements typically are captured during a time period of less than one second and therefore represent a “snapshot” of emissions. The emissions can be reported as mass of emissions per gallon of fuel consumed, assuming a carbon balance. A disadvantage of remote sensing is that it is a snapshot and may not be representative of traffic conditions elsewhere. Additional assumptions are required to convert fuel-based emissions to distance- or time-based estimates. For purposes of area-wide emissions estimation, a fuel-based approach may be adequate, but for meso-scale or micro-scale emissions inventories, it is not clear that a fuel-based approach is appropriate.

On-board measurements involve instrumenting a vehicle and collecting activity and emissions data during real world operation. A disadvantage of this approach is that it can be time and resource consuming to collect data for a large number of vehicles, in comparison to tunnel studies or remote sensing. However, advantages are that data are obtained for actual, real-world operating patterns, at any location traveled by the vehicle, under any weather condition, under any traffic condition, and for any roadway facility type and traffic control systems encountered by the vehicle.

On-board instrumentation can be elaborate and expensive, or can be relatively simple and inexpensive. Although there can be some trade-off in terms of precision and accuracy, the use of repair grade five gas analyzers as a basis for measuring CO, CO_2, and NO emissions has been shown to be reasonably precise and accurate when compared to laboratory dynamometer measurements. Repair grade analyzers use NDIR to measure hydrocarbons. Thus, like NDIR-based remote sensing, there is a known bias in the HC measurements because NDIR is mostly sensitive to straight chain alkanes. However, the mix of hydrocarbons in vehicle exhaust can include other types of compounds for which NDIR provides only a partial response. Recently, methods for measuring particulate matter in portable emissions measurement systems (PEMS) have been introduced.

In order to estimate effects associated with driving dynamics, the modal operation of a vehicle and related emissions need to be analyzed. Modal emissions-based models relate emissions directly to the operating mode of vehicles. The operating modes include cruise, acceleration, deceleration, and idle (NRC, 2000; Barth and Norbeck, 1997; Frey *et al.*, 2002a,b&c; Tong *et al.*, 2000). Several research studies have been performed using dynamometers and instrumented vehicles producing second-by-second emissions data to investigate vehicle emissions associated with modal events (e.g., Cicero-Fernandez and Long, 1994). By testing a small set of newer technology vehicles, these studies found that CO and HC emissions are greatly affected by various acceleration modes. However, much of this work has focused on light duty gasoline vehicles.

Several researchers have developed modal-emissions models. One way of developing a modal-emissions model is to set up a speed-acceleration matrix in order to characterize vehicle operating modes of idle, cruise, and different levels of acceleration/deceleration and to determine corresponding emissions (West and McGill, 1997). According to Barth *et al.* (1996), the problem with such an approach is that it does not properly handle other variables that can affect emissions, such as road grade or use of accessories. Another disadvantage is that the vehicle history is not properly considered, as the vehicle emissions in a given second might be a function of the previous second's speed and acceleration (NRC, 2000). In statistical terminology, this refers to autocorrelation in the time series of second-by-second emissions measurements.

Another type of modal-emissions model is based on engine mapping. The conceptual approach is to translate real-time speed and route information into instantaneous vehicle rpm and load parameters, use an engine map to look-up the instantaneous emission rates for the specific rpm and load conditions, and continuously integrate the instantaneous emission rates to estimate the total emissions from a given set of vehicle activities. A potential weakness is that emissions occurring under transient conditions may not be adequately represented by the emissions map that is derived under steady-state conditions. Mapping models have been developed by LeBlanc *et al*., (1994); Shih and Sawyer, (1996); and Shih *et al*., (1997).

The aggregate modal modeling approach used by the Georgia Institute of Technology for the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE) model is similar to emission mapping, but it is based upon emissions 'bag' data to derive modal activities (Washington, 1997). The model estimation data consisted of more than 13,000 laboratory tests conducted by the EPA and CARB using standardized test cycle conditions and alternative cycles (Bachman, 1999). Hierarchical tree-based regression analysis was applied to the database using several vehicle technologies and operating characteristics as variables to explain variability in emissions. Vehicle activity variables include average speeds, acceleration rates, deceleration rates, idle time, and surrogates for power demand.

The Center for Environmental Research and Technology at University of California Riverside (UCR-CERT) has developed a modal emissions model that reflects Light-Duty Vehicle (LDV) emissions produced as a function of the vehicle's operating mode. The model predicts second-by-second tailpipe (and engine-out) emissions and fuel consumption for different vehicle categories in different states of condition (e.g., properly functioning, deteriorated, and malfunctioning) (Barth *et al.*, 1997). In developing the model 315 vehicles from 24 different vehicle/technology groups were tested on the FTP (Federal Test Procedure) test, EPA's high-speed driving cycle (US06), and a newly developed modal driving cycle (Barth *et al.*, 1997).

In the UCR-CERT model second-by-second tailpipe emissions were modeled as the product of three components: fuel rate (FR), engine-out emission indices ($g_{emission}/g_{fuel}$), and time-dependent catalyst pass fraction (CPF). The model is composed of six modules: (1) engine power demand; (2) engine speed; (3) fuel/air ratio; (4) fuel-rate; (5) engine-out emissions; and (6) catalyst pass fraction. Power demand was estimated using environmental parameters (wind resistance, road grade, air density, and temperature), and vehicle parameters (velocity, acceleration, vehicle mass, cross-sectional area, aerodynamics, vehicle accessory load, transmission efficiency, and drive-train efficiency). Power demand was combined with other engine parameters (gear selection, air/fuel ratio, and emission control equipment) to develop dynamic vehicle or technology group emission rates (Barth *et al.*, 1996). The model uses a total of 47 parameters to estimate vehicle tailpipe emissions.

In the fuel-based method, emission factors are normalized to fuel consumption and expressed as grams of pollutant emitted per gallon of gasoline burned instead of grams of pollutant per mile. In order to obtain an overall fleet-average emission factor, average emission factors for subgroups of vehicles are weighted by the fraction of total fuel used by each vehicle subgroup. The fleet-average emission factor is multiplied by regional fuel sales to compute pollutant emissions (Singer and Harley, 1996). The fuel based approach is amenable to the use of emissions data collected for on-road vehicles using either remote sensing or tunnel studies, as opposed to relying on laboratory tests in the driving cycle approach. Therefore, this approach may yield a key benefit of being more representative of on-road emissions than dynamometer-based approaches. Emissions can be calculated by vehicle class by applying the multiplication separately for each class. The accuracy of a fuel-based model depends on how well the vehicles and driving modes from which emission factors were measured represent the entire area under study. The accuracy of the age distribution used to weight emissions data from each vehicle model year is another important consideration. NCSU has conducted two on-road studies using remote sensing. One resulted in fuel-based emission factors for CO and HC for school and transit buses (Frey and Eichenberger, 1997), and the other resulted in fuel-based emission factors for a variety of light duty vehicles (Rouphail *et al.*, 2000).

Remote sensing devices uses infrared (IR) and, in some cases, ultraviolet (UV) spectroscopy to measure the concentrations of pollutants in exhaust emissions as the vehicle passes a sensor on the roadway. Some applications of RSD include: monitoring of emissions to evaluate the overall effectiveness of inspection and maintenance programs; identification of high emitting vehicles for inspection or enforcement purposes; and development of emission factors. The major advantage of remote sensing is that it is possible to measure a large number of on-road vehicles (e.g., thousands per day). The major disadvantages of remote sensing are that it only gives an instantaneous estimate of emissions at a specific location, and cannot be used across multiple lanes of heavy traffic. Furthermore, remote sensing is more or less a fair weather technology (Frey and Eichenberger, 1997; Rouphail *et al.*, 2000). Thus, remote sensing produces only an instantaneous snapshot of vehicle emissions under limited conditions, and does not provide insight regarding how emissions vary at different points of a trip by any one vehicle.

The National Research Council (2000) reviewed the structure and performance of the Mobile model, investigated ways to improve the model, and made recommendations to EPA regarding development of a new model. One of the recommendations of the NRC study is to develop the capability to estimate emissions at different scales such as microscale, mesoscale, and macroscale. To be able to develop this kind of model, new measurement techniques are needed.

On-board emissions measurement is widely recognized as a desirable approach for quantifying emissions from vehicles, since data are collected under real-world conditions at any location traveled by the vehicle. Until recently, on-board emissions measurement has not been widely used because it has been prohibitively expensive. Therefore, instrumented vehicle emissions studies have typically focused on a very small number of vehicles (Kelly and Groblicki, 1993; Cicero-Fernandez and Long, 1997; Gierczak *et al.*, 1994; Tong *et al.*, 2000, as well as the work of Richard Shores, Bruce Harris, and others at EPA). In other studies, researchers have measured engine parameters only (Denis *et al.*, 1994; LeBlanc *et al.*, 1994; Guensler *et al.*, 1998; West *et al.*, 1997). However, in the last few years, efforts have been underway to develop lower-cost instruments capable of measuring both vehicle activity and emissions (Scarbro, 2000; Vojtisek-Lom and Cobb, 1997). More recently, the concepts employed by Vojtisek-Lom and Cobb have been commercialized by Clean Air Technologies International, Inc., which markets the OEM-2100™ portable emissions measurement system. Other companies are also entering the on-board emissions measurement market with instruments of their own (e.g., Sensors, Inc., Horiba, and others). These instruments are capable of measuring in-use emissions during real-world on-road operation under any ambient conditions, traffic conditions, and operational/duty cycles.

With respect to heavy duty diesel vehicles, equivalence ratio (a non-dimensional indicator of the fuel-to-air ratio) is one of the parameters that affects emissions the most. The brake mean effective pressure increases with equivalence ratio, so higher equivalence ratio corresponds to higher engine power output (Flagan and Seinfeld, 1988). CO and PM emissions drop sharply with increasing equivalence ratio, whereas HC and NO_x emissions drop sharply as equivalence ratio is increased above about 0.2, reaching relatively low levels at an equivalence ratio of about 0.4 (Degobert ,1995). Driver behavior and vehicle speed are two parameters that have significant effect on vehicle emissions since they have an effect on the power required from the engine (Clark *et al.*, 2002).

5.0 Instrumentation Used in This Study

The instrument used in this study is the Clean Air Technologies International, Inc (CATI) “Montana” system. The Montana system is a refinement of the OEM-2100 system used by NCSU in previous work (Frey et al, 2002a). CATI monitoring systems have been commercially available for over five years, with the first system delivered to NCSU in July 1999. The first Montana System was delivered to a customer in October 2001, and the system has received many different ‘field specific’ challenges. The Montana model can be configured in four fashions. CATI provides a Universal System, for light and heavy duty vehicles with or without electronic controls, a Heavy-Duty System for electronically controlled heavy duty vehicles, a

Light Duty System for passenger cars and light trucks, 1996 and newer, and a Non-Road System for non-electronically controlled vehicles, including forklifts and construction vehicles. The specific system used in this work is the universal system for electronically controlled vehicles.

The gases and pollutants measured include O_2, HC, CO, CO_2, NO_X, 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_x measured as NO using electrochemical cell. On most vehicles, NO_x can be inferred from NO. On diesel engines with CRT traps, NO, NO_2, and NO_x can be inferred by simultaneous measurement of NO before and after the trap
- PM is measured using light scattering, with measurement range from ambient levels to low double digits opacity

All pollutants are measured continuously, on a second-by-second basis. Where an analyzer modules requires periodic zero and/or span calibration, two modules are used in parallel.

Exhaust flow is calculated from engine operating data, known engine and fuel properties, and exhaust gas concentrations. The engine operating data is acquired from electronically controlled vehicles through the Engine Control Unit Diagnostic port.

The Montana System is designed to measure emissions during the actual use of the vehicle or equipment in its regular daily operation. The system is inherently safe and has been used on shuttle, school and transit buses during their regular operation, with passengers on board.

The Montana System can be used with virtually any internal combustion engine, with virtually any fuel. Cars, light trucks, vans, shuttle, school transit and coach buses, box trucks, over-the-road tractor-trailers powered by gasoline, CNG, diesel fuel and biodiesel are tested on a routine basis. Non-road equipment including, Cat loaders, Penske generators, excavators, drillers and compressors are examples of construction equipment that before and after tests were successfully conducted on using DPF and DOC. Off-road equipment that the system has been successfully been used on includes yard tractors, ATVs, recreational boats, small aircraft (ground use only), locomotives, passenger ferryboats and electric generators.

Typical swap times, measured as a complete removal of the system from one vehicle and a subsequent complete installation of the system on another vehicle, range from 30 to 60 minutes. The monitoring system weighs approximately 35 lbs., and is routinely transported as a carry-on luggage on commercial flights. 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. 24V DC and 110V/60Hz AC adapters are available. The complete system comes in two weatherproof plastic cases, one of which contains the monitoring system itself, and the other containing sample inlet and exhaust lines, tie-down straps, AC adapter, power and data cables, various ECU diagnostic link connectors, sensor array, calibration gas pressure regulator and other parts.

The following parameters are typically available on a second-by-second basis: Road speed, engine rpm, turbocharger boost pressure, concentrations of the measured pollutants, exhaust flow, air fuel ratio, fuel consumption, mass flow rates of the measured pollutants. The user can define the beginning and end of different test segments, as well as enter user-defined flags (i.e., encountering a certain traffic condition). Total time, distance, fuel consumption and emissions are calculated for each defined test segment.

The Montana System gas analyzer utilizes a two-point calibration system. 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.

Span calibration is recommended approximately once a month, and is performed using a BAR-90 low concentration calibration gas mixture. This interval is given primarily by the aging of the electrochemical NO and O_2 sensors. The NDIR system was observed to hold its calibration for at least one year. NCSU experience with the precursor OEM-2100 system is that the instrument will hold a calibration for three months or more for all gases (Frey et al, 2002a).

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. Data from the EPA laboratory in Ann Arbor, MI, also shows that the difference between the portable system and two laboratory systems (modal and bag sampling) was comparable to the differences between the two laboratory systems.

The PM system utilizes light scattering as a detection method for PM measurement. An undiluted sample of exhaust is passed through a sample chamber. A laser beam is passed across the chamber, perpendicular to the flow of the sample. As particles contained in the sample pass through the laser beam, a portion of the beam is scattered by the particles. A detector placed at an angle from the laser beam measures the intensity of the scattered light. The signal is virtually zero when no particles are present, and increases proportionally to the concentration of the particles. The response is also dependent on the size and composition of the particles.

The instrument provides a reading in milligrams of PM per cubic meter (mg/m3). This reading is multiplied by the exhaust flow to obtain grams per second PM mass emissions.

Figure 5 illustrates the use of a portable on-board emissions measurement system in a diesel transit bus. The figure illustrates the placement of the instrument inside the vehicle, the exhaust gas sampling probe, and an example of the display on the instrument computer regarding real time emissions and engine data.

Figure 5. Example of a portable on-board emissions and fuel use measurement system installed in a heavy duty diesel transit bus: (a) the portable unit on a passenger seat; (b) the exhaust gas sampling probe; (c) the instrument display panel showing traces of emissions versus time.

6.0 Pilot Data Collection

A key step in the evolution of the current project is to conduct a pilot study for the purpose of establishing the protocols for working with the instrumentation, screening the data, and analyzing the data. Once the protocols are established, future work will focus on wider scale testing of a larger number of vehicles under a variety of operation conditions. Thus, this section focuses on presenting the procedures and results of a pilot data collection effort, featuring the application of the Montana system to an NCDOT diesel truck. The pilot study also illustrates the four major project tasks, which include: (1) design of the field data collection study; (2) field data collection; (3) data reduction and analysis; and (4) development of strategic recommendations. Thus, the description of the pilot study is organized along these four themes.

6.1 Design of Field Data Collection Pilot Study.

The design of an on-road data collection effort involves selection of vehicles, drivers, routes, scheduling, and number of replications. The intent is for NCSU to instrument existing NCDOT vehicles and to collect data during normal duty cycles. Thus, the drivers for the vehicles will be the same NCDOT personnel who currently operate these vehicles. The routes will be based upon the service requirements of the vehicle. With the GPS system that is part of the portable on-board instrumentation, the actual route traveled by the vehicle will be stored in terms of second-by-second x, y, and z coordinates.

Because there is variability in traffic conditions and environmental factors, it is prudent to repeat the measurements for a given vehicle/driver combination in order to obtain a statistically stable estimate of the mean emission rates for each pollutant and for specific driving modes. Thus, where possible, data should be collected over the course of at least a day, and preferably more than one day, for a specific vehicle/driver combination. The intent is to represent approximately 5 to 20 multiple "trips" with each vehicle. This type of experiment is an observational, rather than a purely controlled, study. However, with the portable on-board instrument, we will obtain data regarding vehicle activity (e.g., second-by-second speed, road grade, engine data) that will be used to help explain the variability in the measured emission rates, and to develop benchmarks for comparison of emissions between vehicles. Although the need for replications of measurements might be considered a drawback of this approach, it should be kept in mind that even dynamometer-based measurements in the laboratory are subject to considerable inter-test variability. Thus, the need for replications with on-board data is qualitatively no different than the need for replications with laboratory data. The key difference is that the cost of data collection per test is much lower with portable on-board instrumentation than in the laboratory, and testing can be done during normal vehicle duty cycles in the local area. There is no need to take the vehicle to a lab.

The selection of a truck and driver was coordinated with NCDOT via the NCDOT Research and Development Unit, the Equipment and Maintenance Unit, and the Wake County maintenance yard.

6.2 Pilot Field Data Collection

The key elements of field data collection include the vehicle, driver, route, and scheduling. In addition to these, the actual field data collection must include consideration of instrument calibration, instrument verification, and instrument deployment logistics.

For the pilot study, measurements were made on March 10, 2004 on a 2002 International truck, with a gross weight of 17,180 pounds (as measured on a weigh scale the same day). The engine is rated at 195 horsepower at 2,300 rpm and the vehicle has an automatic transmission. The vehicle was driven by an NCDOT driver. The vehicle is an "infrared" truck, and is equipped with a large heating element that is placed over pavement for use in paving operations. However, for purposes of the pilot study, on-road data were collected for highway operation only. The vehicle was driving primarily on interstate highways (I-40 and I-540) and primary arterials (e.g., NC 55 and others). The vehicle was fueled with conventional diesel fuel. Operating speeds varied from zero (idle) to approximately 60 mph. Pilot data were collected continuously over a period of approximately 135 minutes.

Figure 6 illustrates several aspects of the installation of the PEMS. The portable instrument is shown, including its placement inside the vehicle and the data connection to the engine diagnostic link located under the dashboard near the driver's door. Figure 7 illustrates some of the connections made external to the passenger cabin, including connection to the vehicle battery (located beneath the driver's door) using alligator clips, routing of hoses and cables using ties to secure these to the chassis, and the location of the exhaust pipe and gas sampling probes. Figure 8 displays the routing of sampling hoses to the instrument via the passenger window, the hose used to collect outside air for reference purposes, and an external side view of the vehicle in motion after PEMS installation. The side view includes notation of the relative locations of the on-board diagnostic link (inside the vehicle), the battery, the exhaust pipe, and the routing of hoses and cables. Figure 9 is a photograph of the instrumented vehicle as it was leaving the maintenance yard.

The vehicle was driven in the Research Triangle Park, NC region on interstate highways and primary arterials during normal daytime shift hours. The trip included a stop at a weigh station and had a large proportion of operation at highway speeds.

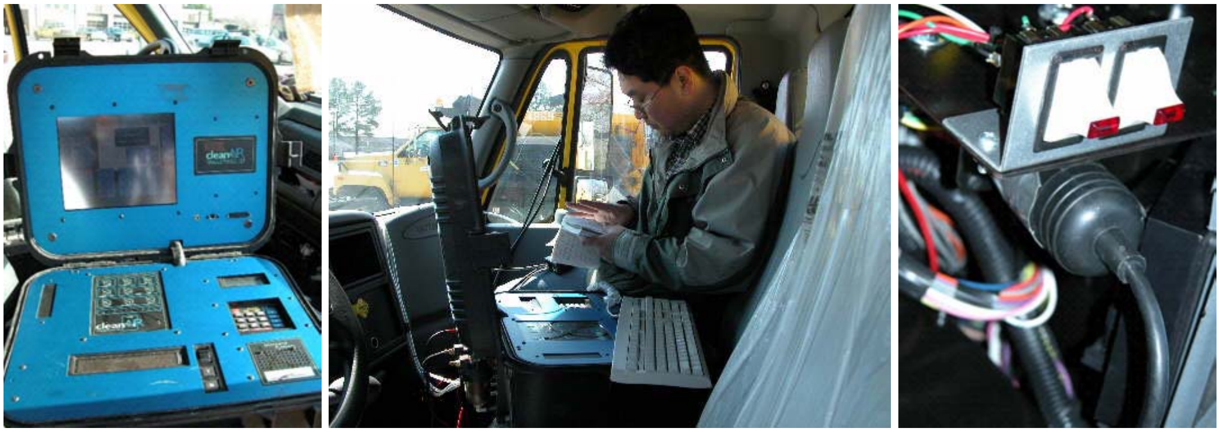


Figure 6. Installation of the portable emissions measurement system (PEMS) in a NCDOT heavy duty diesel vehicle: (a) the portable unit on a passenger seat; (b) entering vehicle data into the PEMS; (c) engine diagnostic link using a 9-pin Deutsch connector.

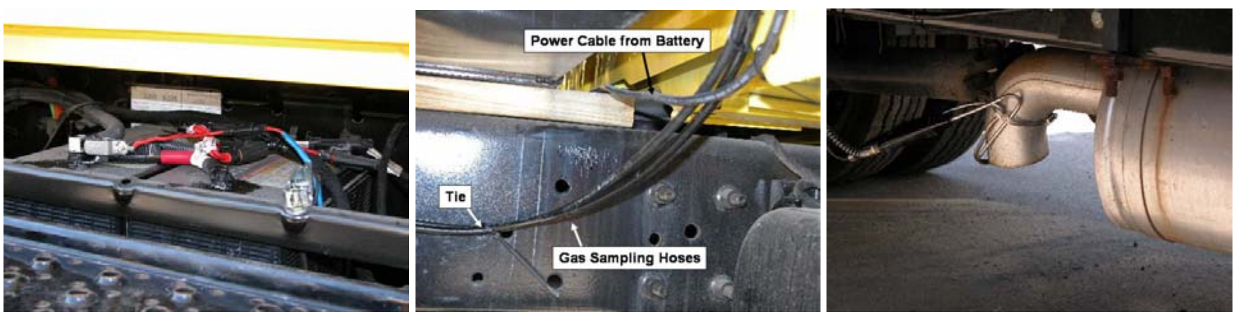


Figure 7. Installation of the portable emissions measurement system (PEMS) in a NCDOT heavy duty diesel vehicle: (a) accessing power from the vehicle battery; (b) roauting hoses and cables along the chassis using ties; (c) samping exhaust gases using a probe secured with a hose clamp.

Figure 8. Installation of the portable emissions measurement system (PEMS) in a NCDOT heavy duty diesel vehicle: (a) routing sampling hoses through the window, secured with ties; (b) obtaining outdoor air for "zeroing"; (c) side-view of truck in motion, illustrating relative locations of the on-board diagnostic link (inside the vehicle), battery, exhaust, and cables/hoses.

Figure 9. Instrumented NCDOT vehicle in motion as it leaves the maintenance yard after installation of the portable emissions measurement system..

6.3 Pilot Data Reduction and Analysis.

The objective of data reduction and analysis of the data is to enable: (1) benchmarking emissions, energy use, and vehicle performance; (2) development of emission factors and fuel economy estimates; and (3) identification of opportunities to reduce emissions, reduce fuel use, and improve vehicle operation. Frey *et al*. (2001, 2002a, 2002b) have developed analysis methods for the use of on-board measurements for NCDOT and for the U.S. Environmental Protection Agency's Office of Transportation and Air Quality. Data reduction includes multiple quality assurance checks for data errors, including loss of signal of one or more instruments, improper synchronization of data streams, and improper zeroing of the gas analyzer.

Vehicle activity, emissions, and fuel are evaluated initially based upon time traces. In general, the time traces indicate that there is a significant contribution to total emissions from short-term events that occur within the trip. Examples of time traces are shown in Figures 10, 11, and 12 for vehicle speed, engine RPM, and NO emissions, respectively, based upon on-road data collected for an NCDOT truck. NCSU has developed modal emissions analysis methods in which trips are divided into driving modes (e.g., acceleration, cruise, deceleration, idle) and in which emissions and fuel use are estimated separately for each mode. The calculation of modal emissions rates provides a consistent basis for comparison of different trips. The criteria for each mode are listed below:

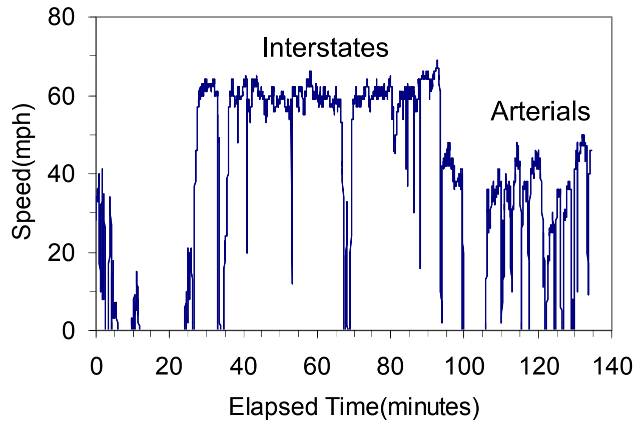


Figure 10. Example Speed Trace Obtained from On-Road Operation of an NCDOT Heavy Duty Diesel Vehicle. Data Collected on March 10, 2004.

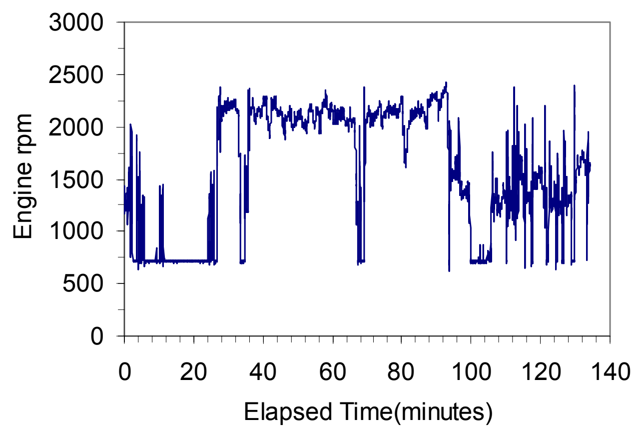


Figure 11. Example Engine RPM Obtained from On-Road Operation of an NCDOT Heavy Duty Diesel Vehicle. Data Collected on March 10, 2004.

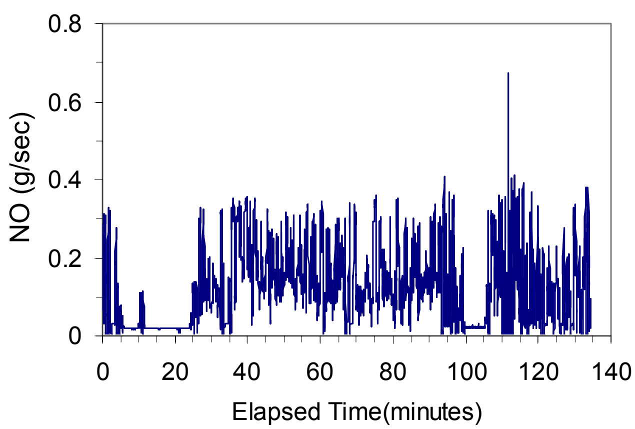


Figure 12. Example Emissions Data Obtained from On-Road Operation of an NCDOT Heavy Duty Diesel Vehicle. Data Collected on March 10, 2004.

- Idle (speed = 0)
- Acceleration
  - Speed increases by
    - » 1 mph in 1 sec
    - » 2.9 mph in 3 sec
    - » 4 mph in 5 sec
- Cruise
  - "Low Cruise" (speed < 30 mph)
  - "Medium Cruise" (30 mph < speed < 45 mph)
  - "High Cruise" (speed > 45 mph)
- Deceleration (negative of acceleration)

The results of the modal analysis are shown in Figure 13. In most cases, the highest average emission rates are associated with acceleration and high speed cruising. The lowest emission rates are typically associated with idling and deceleration. For NO, CO_2, and PM, the difference between the highest and lowest mean modal emission rates is approximately an order-of-magnitude or more, whereas for HC and CO the difference is approximately one-half order-of-magnitude. Thus, there is substantial variability in emissions among the modes for a given pollutant. There are substantial differences in cruising mode emissions as a function of cruising speed.

As shown in Figure 14, for the pilot data, the high speed cruising mode comprised approximately 50 percent of the trip time, almost 80 percent of the trip distance, and approximately 65 to 85 percent of the total emissions of each pollutant. This result is in large part because of the specific duty cycle of the pilot data collection, and may not be generalizable to other duty cycles with the same vehicle. Thus, an objective of future data collection would be to establish if there are other operating conditions for this vehicle that might lead to different proportional contributions from each of the modes.

Although idle comprised approximately 20 percent of the time of the pilot study, this mode contributed approximately one to ten percent of the total emissions of a given pollutant. Similarly, the deceleration mode contributed a smaller proportion of emissions compared to its proportion of time or distance. Conversely, although the acceleration mode comprised approximately five percent of the time and distance of the trip, it was responsible for slightly more than five percent to as much as ten percent of the total emissions. Thus, the contribution of the acceleration mode to total emissions is in larger proportion than its share of time or distance traveled. The modal emission results shown here are illustrative of a methodology for analyzing the on-road data. However, since these results are based upon only one data collection effort with one vehicle, they are not considered to be definitive.

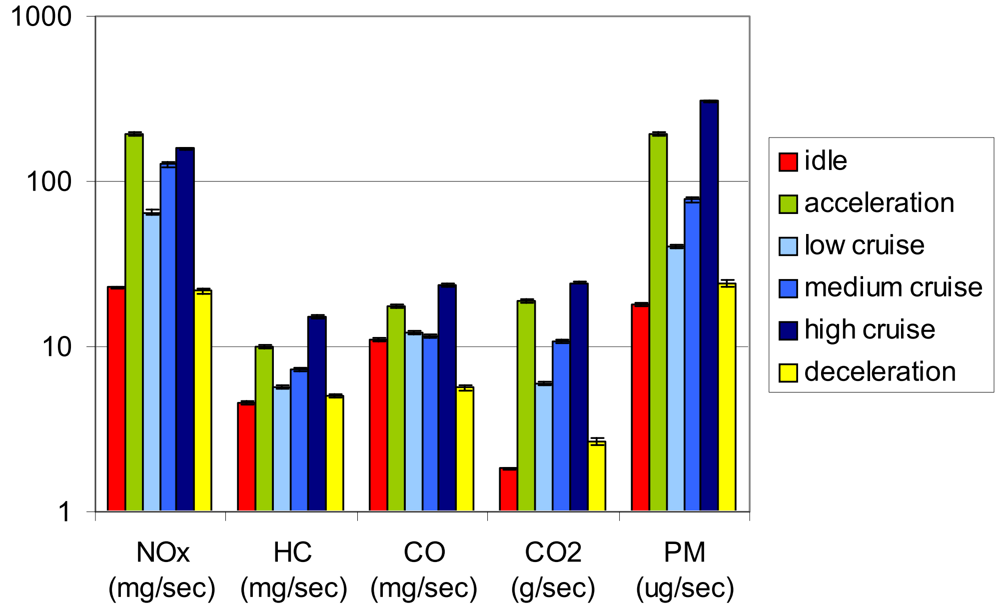


Figure 13. Average Emission Rates for Selected Driving Modes for NO_x, HC, CO, CO_2, and PM Obtained from On-Road Operation of an NCDOT Heavy Duty Diesel Vehicle. Data Collected on March 10, 2004

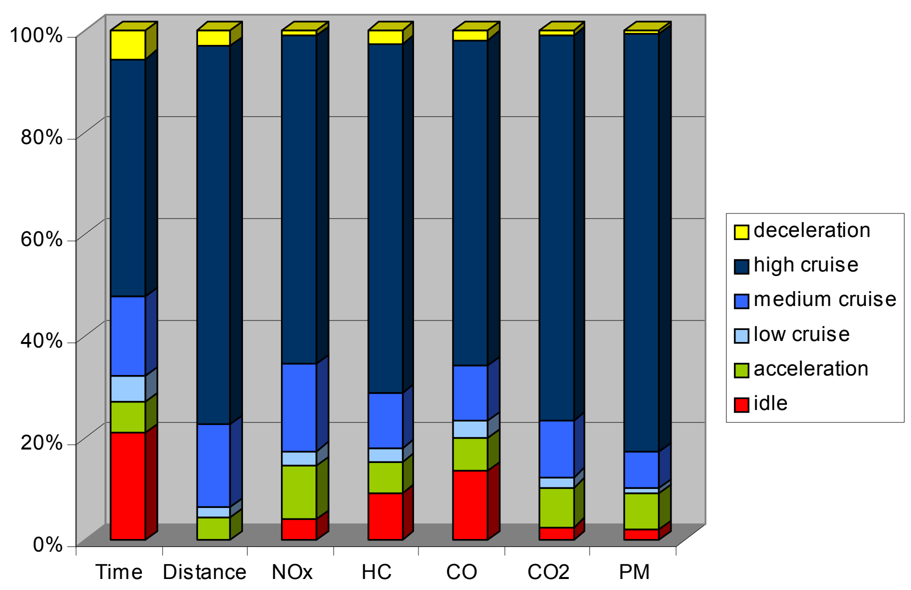


Figure 13. Distribution by Driving Modes of Time, Distance, and Emissions (NO_x, HC, CO, CO_2, and PM) Based Upon On-Road Operation of an NCDOT Heavy Duty Diesel Vehicle. Data Collected on March 10, 2004

6.4 Development of Strategic Recommendations in Future Work

A goal of this project is to use results from PEMS data as a basis for developing long-term strategic recommendations including the following issues: (1) benchmark comparison of biodiesel and conventional diesel vehicles to assess the emissions, energy use, and operational benefits of biodiesel fuel; (2) development of empirical emission factors representative of real-world operation in North Carolina from which to develop more accurate local and statewide emission inventories for evaluating compliance and air quality management with respect to the new ozone and PM standards; (3) improvements in operating practices to reduce emissions and fuel use, such as clarification on the role of idling with respect to emissions vis-à-vis acceleration, the influence of different acceleration rates on emissions, and the important role of driver behavior with regard to energy use and emissions, among others. For each of these issues, specific recommendations will be made based upon evidence obtained from the field data collection and data analysis.

7.0 Discussion and Conclusions

This project will be useful to NCDOT as a guide for continued implementation of AFV programs. The results of this work will enable NCDOT to quantify changes in real world in-use emissions associated with use of biodiesel instead of conventional diesel fuel. The results of this work will enable detailed insight into factors influencing both emissions and fuel consumption on a second-by-second basis and development of recommendations for improved operation to reduce emissions and/or fuel consumption. These benefits accrue in both short and long term.

The key conclusions to date are that data reported in the literature indicate a substantial reduction in emissions of some pollutants (e.g., CO, HC, and PM) when switching from petroleum diesel to soy-based B20 biodiesel, and a slight increase in NO_x emissions. The available emissions data for biodiesel vehicles is based upon engine and chassis dynamometer data. Thus, there is a need for comparison of biodiesel and diesel fuels based upon real world in-use data. Therefore, this project is addressing a data gap.

A pilot study with one NCDOT truck has demonstrated the feasibility of deploying a PEMS for on-road data collection. A preliminary analysis of the pilot data provides insight into factors that contribute to variability in emissions during vehicle operating, including differences in emissions at different cruising speeds, as well as comparisons of emissions between idle, acceleration, cruise, and deceleration modes. The modal analysis suggests that it is possible to stratify the data in order to enable comparisons, such as between vehicles.

Future work will include measurements of a larger number of vehicles and refinement of the data analysis procedures to provide insights in response to the project objectives. The primary product of this work will be a database, analysis, and recommendation pertaining to operational practices and their implications for fuel use and emissions. The analysis will address key questions such as what factors contribute to episodes of high emissions and high fuel use, and how do emissions differ for different operating modes, fuels, vehicles, and other explanatory variables.

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Disclaimer

The contents of this paper reflect the views of the authors and not necessarily the views of the University. The authors are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the North Carolina Department of Transportation, the Federal Highway Administration, or the Center for Transportation and the Environment at the time of publication. This report does not constitute a standard, specification, or regulation.

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