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Diesel Emission Reduction Strategies for School Buses and HDDV Trucks

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16. Abstract

The overall purpose of this research was to develop strategies for reducing diesel emissions from mobile sources such as school buses and HDDV trucks. Rowan University took a six prong approach in developing these strategies:

1. Measure HDDV Idle Emissions
2. Measure School Bus Idle Emissions
3. Measure the Effects of Various Alternative Fuels on School Bus Mobile Emissions
4. Measure the Effects of Aftertreatment Devices on School Bus Mobile Emissions
5. Measure Particulate Matter Levels Inside a typical NJ School Bus Cabin
6. Conduct a Life Cycle Analysis of HDDV Idle Reduction Technologies

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EXECUTIVE SUMMARY

This is the final report for the New Jersey Department of Transportation (NJDOT) administered, Federal Highway Administration (FHWA) sponsored research study at Rowan University. The purpose of this research was to develop strategies for reducing diesel emissions from mobile sources such as school buses and HDDV trucks. For HDDV trucks it was found that trucks consume 1.2 gal/hr of fuel and the emissions for one truck idling for 8 hours produces over 1.4 kilograms of NO_X, 95.5 kilograms of CO_2, 0.3 kilograms of HC, and 0.7 kilograms of CO. A comparison of alternatives to idling was done showing reductions in overall emissions using several alternatives. Based on a life cycle and economic analysis of several alternatives to idling, the Truck Stop Electrification showed the most benefits to the truck drivers and the state. Mobile emissions testing was conducted on 3 school buses to characterize several emission reduction strategies. The reduction strategies tested included alternative fuels and aftertreatment devices. It was found that the most significant reductions in emissions is obtained using ultra low sulfur diesel with a diesel particulate filter. In addition to these studies, the particulate concentrations inside school buses were also examined at both idle and mobile conditions.

Since January 2002, 12 undergraduate students and 4 graduate students have contributed to the project. Three master's degrees have been awarded and the project results have been widely disseminated at various SAE, AIChE and Combustion Institute conferences, including 6 SAE papers at the SAE World Congress between 2003 and 2005.

1. HDDV Idle Emissions Measurements

A study was conducted to quantify the idling emissions and fuel consumption rates for

Heavy Duty Diesel Vehicles (HDDVs). Testing was performed in an environmental chamber on five different class 8 trucks with model years ranging from 1990's to 2001. To simulate a wide variety of idling situations, 38 tests were conducted at three different ambient temperatures (0°F, 65°F and 90°F), relative humidity ranging from 22 to 90% and idle speeds from 600 to 1200 RPM. The overall results are shown below in Table 1.

Table 1: Average Results for HDDDV Truck May 2002 Idle Study

	Emissions (g/hr)				
	Nox	CO2	HC	CO	fuel (gal/hr)
600 RPM	101	5158	17	41	0.52
1200 RPM	181	11948	40	92	1.20

These results suggest that just one truck idling for 8 hours produces over 1.4 kilograms of NO_X, 95.5 kilograms of CO_2, 0.3 kilograms of HC, and 0.7 kilograms of CO. The resulting fuel consumption is approximately 10 gallons.

Two Alternative Power Units (APUs) were tested as alternatives to replace an idling truck engine. It was found that Espar Heater consumed 95% less fuel and consequently emitted 99% less NO_X emissions. The results of Pony Pack testing show an 80% fuel reduction than 1200 RPM idling. The NO_X reductions for use of the Pony Pack range from 89% using the air conditioning in warm weather to 94% using the heater in cold weather.

2. School Bus Idle Emissions Measurements

A second study was conducted to examine school bus idling. Testing was done in the environmental chamber within the Aberdeen Test Center where three school buses

Table 2: Engine Data for the School Buses Tested

Chassis	Engine	Rated Power
1998 International	'97 International T-444E	190 at 2300 RPM
1998 International	'97 International DT466	190 at 2300 RPM
1997 Ford	'96 Cummins 5.9L ISB	190 at 2200 RPM

were idled in four temperature conditions (20F, 40F,65F, 85F) and varying humidity (40%-90%). The school bus engines tested are shown in Table 2.

The results from this school bus idling study show an average fuel consumption of 0.5 gal/hr. This result was used by the EPA for their Clean School Bus USA platform. Emissions results show that NO_X emissions ranged from 40-80 g/hr for the International engines and 50-110 g/hr for the Cummins ISB engine.

3. School Bus Mobile Emissions Testing: Alternative Fuels

The primary goal of this school bus study is to identify emission reduction strategies for the existing school buses in NJ. The initial strategy tested was the use of alternative fuels. The same three school buses used in the school bus idle study were also used for the mobile tests. All testing occurred using a standard cycle created by Rowan University. Using actual school bus route data from 5 different school districts the Rowan University Composite School Bus Cycle (RUCSBC) was developed. A graph of the RUCSBC can be shown below in Figure 1.

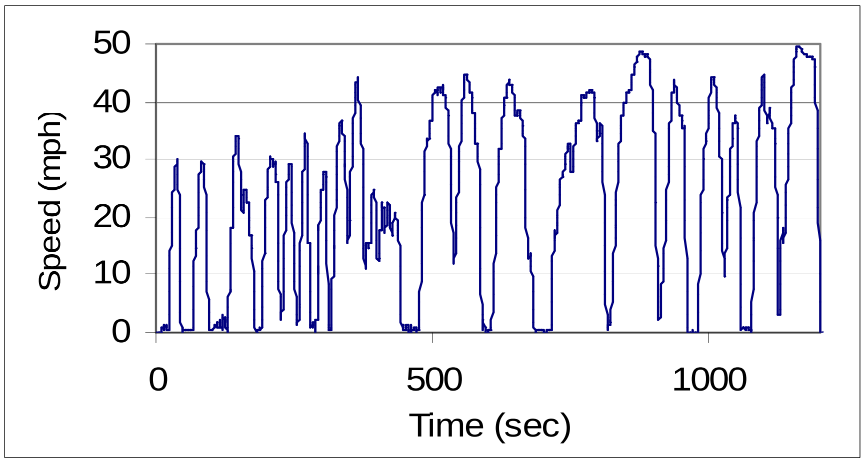

Figure 1: Rowan University Composite School Bus Cycle

One run of the 12 min RUCSBC is defined as a test. Four fuel configurations were tested: #2 diesel (current pump diesel), 20% biodiesel 80% #2 diesel (B20), ultra-low sulfur diesel (ULSD) and 20% biodiesel 80% ULSD. Each fuel makeup was tested three times. The results of the alternative fuels test demonstrate that alternative fuels provide minimal reductions. The fuel that performed the best on each bus was the 20% Biodiesel/ULSD fuel, which provided an average NO_X reduction of 8%. Carbon Monoxide (CO) and unburned gaseous hydrocarbons (HC) reductions reached a maximum of 40% for the same fuel. When comparing these emissions to the 2007 EPA standards, it is evident that the use of alternative fuels alone will not provide enough reduction.

4. School Bus Mobile Emissions Testing: Aftertreatment Devices

The second portion of mobile testing dealt with the use of aftertreatment devices. Diesel particulate filters (DPFs) were purchased from Johnson Matthey and Lubrizol Engine Control Systems. A Diesel Oxidation Catalyst was purchased from Nett Technologies. An Engelhard DPX unit is scheduled to be tested. The three aftertreatments require the use of ULSD fuel which was previously tested during the alternative fuels study. These aftertreatment devices were retrofitted to the school bus, and three tests were performed using the Rowan University Composite School Bus Cycle (RUCSBC).

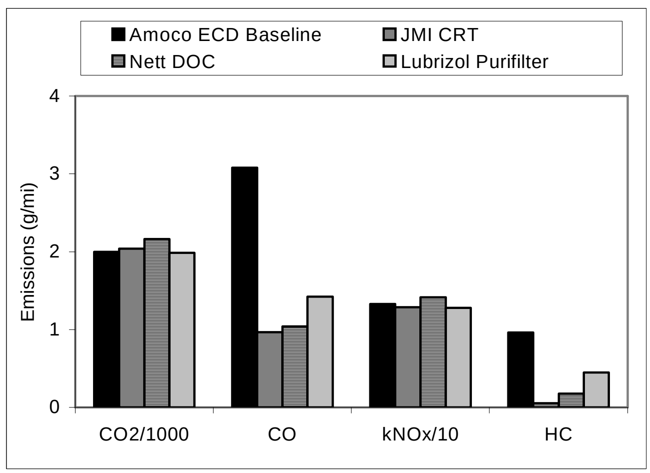

Figure 2: Emissions results for the school bus equipped with the T444E International Engine.

The results shown for the T444E engine above show that the CRT from Johnson Matthey provided the best carbon monoxide (CO) and unburned gaseous hydrocarbon (HC) reductions. Results also show that the use of a DPF will eliminate over 95% of the particulate matter (PM) measured by the particulate analyzer used for these tests. The Lubrizol Purifilter was able to trap slightly more particles than the CRT, but the results from both DPFs were on the same order of magnitude.

When compared to the upcoming 2007 EPA standards, the use of the aftertreatment devices will reduce CO and HC to below the limit. The PM data suggests that the use of DPFs will also conform the PM to the 2007 standard. The use of aftertreatment devices did not reduce NO_X emissions significantly. In order to reduce NO_X emissions, an additional strategy will have to be investigated.

5 Particulate Matter Measurements Inside School Bus Cabin

Previous studies have concluded that particulate matter (PM) concentrations can be found inside the cabin of school buses. Rowan University performed experiments to measure PM within the school bus as a function of bus speed, location in the cab of the bus and the status of the windows (open, closed, or half open). The results of this study showed that the bus speed had the largest impact on the mean particle concentration inside the school bus which ranged from 2.0μg/m^3 at idle to 24.0μg/m^3 at 55 mph greater than the background concentration measured during the tests. The position of the windows is another important parameter giving particle concentrations averaging 16μg/m^3 higher than the background concentration with closed windows compared to 8μg/m^3 higher than the background with the windows either in the half open or full open position. A third conclusion was the relationship between window position and the speed at which the bus was driving. At idle the concentration inside the bus was lower then the background concentration when the windows were closed. At 55 mph the open window positions gave average particle concentrations 4 times lower than the value of 48μg/m^3 observed with closed windows.

6. Life Cycle Analysis of HDDV Idle Reduction Technologies

A life cycle and economic analysis of heavy-duty diesel vehicle idling alternatives was conducted. Since Heavy Duty Diesel Truck (HDDT) drivers are required by law to rest 8 hours for every 10 driving hours, the trucks are idled for long periods of time to heat or cool the cabin, to keep the engine warm, to run electrical appliances, and to refrigerate or heat truck cargo. This idling results in gaseous and particulate emissions and wasted fuel. Various technologies can be used to replace truck idling, including heaters, auxiliary power units, parking space electrification, and heating and air conditioning units in the parking space. This study examined the associated emissions savings and ecological burdens of idling reduction technologies compared to truck idling.

The idle emissions and fuel consumption obtained from the previous study were compared to four technologies used to reduce engine idling. These included an auxiliary power unit, a heater, Truck Stop Electrification (TSE), and Advanced Truck Stop Electrification (ATSE). Of the four evaluated technologies, the Truck Stop Electrification showed the most benefits to the truck drivers and the state. From calculations performed using an average fuel price of $1.50 per gallon, the results show that TSE is most economical for the purposes of this study, with a payback period of 1.53 for the driver and 1.16 for the rest area. ATSE has a payback period of 0.83 years for the driver and a payback period of 3.66 for the rest area, based on a fee of $1.25 per hour for use. The rest area could reduce the payback by charging a higher fee, which would result in a greater payback for the driver. In addition, truck stop electrification showed the most emissions savings and the least ecological burdens. The APU and DFH did show considerable emissions reduction, but were less economical.

Table of Contents

Introduction 4
1.1. Background 4
1.2. FHWA Sponsored, NJDOT Managed Project 5
1.3. State Implementation Plan 6
1.4. Project Research Team - Rowan University 7
2. Heavy Duty Diesel Truck Idling 8
2.1. Introduction 8
2.2. Experimental Procedure 10
2.3. Experimental Results 16
2.3.1. Fuel Consumption Results 16
2.3.2. Emissions Results 19
2.3.2.1. NO_X Emissions 20
2.3.2.2. CO_2 Emissions 26
2.3.3. Effect of Humidity on NO_X Emissions 28
2.4. Conclusions 32
3. Life Cycle and Economic Analysis of HDDV Idling Alternatives 34
3.1. Introduction 34
3.2. Idle Emissions Reduction Technologies 37
3.2.1. Auxiliary Power Unit (APU) 37
3.2.2. Truck Stop Electrification (TSE) 38
3.2.3. Advanced Truck Stop Electrification (ATSE) 38
3.2.4. Direct-Fired Heater (DFH) 38
3.3. Methodology 39
3.4. Technologies 42
3.4.1. Idling 42
3.4.2. Auxiliary Power Unit (APU) 43
3.4.3. Truck Stop Electrification and Advanced Truck Stop Electrification 43
3.4.4. Direct Fired Heater (DFH) 44
3.5. Results 45
3.5.1. Environmental Risk Analysis 45
3.5.2. Economic Analysis 49
3.5.2.1. Payback Period 49
3.5.2.2. Net Present Value 52
3.5.2.3. Emissions Savings Per Cost of Technology 53
3.6. Conclusions 54
4. Steady State Particulate Exposure Levels in a 1992 International School Bus 56
4.1. Introduction 56
4.1.1. Particulates 56
4.1.2. Health Effects 57
4.2. Literature Review 57
4.2.1. NRDC Study 58
4.2.2. Connecticut Study 59
4.2.3. Fairfax County Public School Bus Study 60
4.3. Experimental Setup 61

4.3.1. Testing Plan 61
4.3.2. Equipment 65
4.4. Results 67
4.4.1. Bus Speed 68
4.4.2. Windows 72
4.4.3. Load 74
4.4.4. Location 74
4.5. Conclusions 75
5. Tailpipe Emissions from Diesel School Buses 78
5.1. Introduction 78
5.1.1. Literature Search 78
5.1.2. Emissions/ Emission Measurement 81
5.1.2.1. Diesel Emissions 82
5.1.2.2. EPA Diesel Emissions Regulation History 84
5.1.2.3. Units of Measure for Emissions 86
5.1.2.4. Emissions Testing 88
Engine Dynamometer Emissions Testing 88
Chassis Dynamometer Emissions Testing 90
Mobile In-Use Emissions Testing 93
5.1.3. Diesel Emission Reduction Strategies 95
5.1.3.1. Alternative Fuels 96
5.1.3.2. Particulate Traps 99
5.2. Experimental Procedure and Equipment 104
5.2.1. Introduction 104
5.2.2. Rationale for School Bus Selection 104
5.2.2.1. School Bus Types in NJ 104
5.2.2.2. Engine Specifications 107
1997 International T-444E 107
1997 International DT-466E 108
1996 Ford Cummins 5.9 L ISB Series 108
5.2.3. Aberdeen Test Center 113
5.2.3.1. Test Track 113
5.2.3.2. Environmental Testing Chamber 113
5.2.3.3. Chemistry Lab 114
5.2.4. Bus Instrumentation 115
5.2.4.1. Instrumentation Table 116
5.2.4.2. Electronic Control Module (ECM) 118
5.2.4.3. Sensors Inc. Semtech-D 119
5.2.4.4. Sensors Inc. PM-300 128
5.2.4.5. ADOCS ATC Data Acquisition System 130
5.2.4.6. Data Management 131
5.3. Development of a New Mobile Emissions Test Cycle for School Buses 133
5.3.1. Introduction 133
5.3.2. Literature Review 134
5.3.3. Procedure for Generating a New Mobile Cycle 138
5.3.3.1. Types of School Districts /Regions 139

5.3.3.2. GPS Mapping: Experimental Procedure 141
5.3.3.3. Data Reduction/Cycle Development 144
5.4. Rowan On Road Medford Township School Bus Testing 152
5.4.1. Introduction 152
5.4.2. Purpose of Medford Study 152
5.4.3. Medford School District Biodiesel Program 153
5.4.4. Experimental Setup: Test Procedure 155
5.4.5. Test Results 156
5.4.5.1. Medford Fuel Consumption/Total Work 156
5.4.5.2. Medford Emissions 159
5.5. School Bus Mobile Emissions Testing (ATC) 164
5.5.1. Introduction 164
5.5.2. Experimental Procedure: Test Matrix 164
5.5.3. Test Results 165
5.6. Development of a New NO_X Correction Factor 167
5.6.1. Introduction 167
5.6.2. Background 167
5.6.3. Procedure 167
5.6.4. Experimental Results – NO_X emissions 169
5.6.5. Existing Correction Factors 172
5.6.6. Development of Rowan University NO_X Correction Factor 176
5.6.7. Conversion of Measured NO_X Emissions to Reportable Emissions 178
5.6.8. Comparison of correction factors in grams per mile 179
5.7. The Effect of Alternative Fuels on Mobile Emissions 181
5.7.1. Introduction 181
5.7.2. Experimental Procedure 181
5.7.3. Results 182
5.7.3.1. Experimental Results – DT466E 183
5.7.3.2. Experimental Results – T444E 186
5.7.3.3. Experimental Results – Cummins ISB 189
5.7.3.4. Comparison to 2007 EPA Standards 192
5.8. The Effect of Aftertreatment Devices on Mobile Emissions 194
5.8.1. Introduction 194
5.8.2. Experimental Procedure 194
5.8.3. Results 195
5.8.3.1. Experimental Results – DT466E 196
5.8.3.2. Experimental Results – T444E 199
5.8.3.3. Experimental Results – Cummins ISB 202
5.8.3.4. Investigation of NO and NO_2 Emissions 206
5.8.3.5. Comparison to 2007 EPA Standards 208
5.9. Conclusions 210
5.9.1. Alternative Fuels Testing 210
5.9.2. Aftertreatment Testing 211
5.9.3. Rowan University's Partnership for Clean NJ School Buses Website ... 212
6. References 213

Introduction

1.1. Background

It is estimated that heavy-duty diesel vehicle (HDDV) emissions are responsible for 80 % of all particulate matter (PM) emissions and 33 % of all NO_x emissions from mobile sources in the northeast United States.[1] Accordingly, the New Jersey Department of Transportation (NJDOT) Bureau of Freight Services was previously involved in developing emission reduction strategies aimed at reducing harmful emissions from mobile source diesel engines in the state of New Jersey. The NJDOT was focused on three areas of concern with respect to harmful emissions from diesel engines:

- Reduction of emissions from school buses
- Development of low exhaust gas temperature catalytic converter technologies
- Reduction of idling time by interstate carriers (HDDV diesel trucks).

During each school year, about 23.5 million students travel approximately 4.3 billion miles on 450,000 school buses in the United States.[2] Of the 450,000 school buses in the U.S, 390,000 are powered by diesel fuel.[3] Diesel school bus routes produce pollutants in the form of nitrous oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), volatile organic compounds (VOC), and particulate matter (PM), which may be avoidable with the use of alternative fuels and the addition of engine retrofit emission reduction after treatment devices. In addition to the emissions produced by the 4.3 billion school bus miles traveled each year, there are several minutes (possibly hours depending on weather conditions and other factors) of idling time daily that all school buses will incur on a typical route. Reduction of school bus emissions is particularly important because children are the most susceptible to the effects of diesel emissions, which can cause respiratory disease and bring about long-term conditions such as asthma.[3]

The current emissions regulations for school buses are lenient enough that newer school buses are able to operate legally with no after treatment devices or alternative fuels sources. In 2004 and again in 2007, more stringent emission standards are being put in place by the federal government that will mandate the use of some after treatment for new HDDVs in order to meet the new standards. NJ regulations that mandate school buses to be in service for a maximum of twelve years allows for school bus engines manufactured before 2007 to possibly remain in service until 2019 without complying with the 2007 standards. Many state organizations, engine manufactures, universities, and research facilities are conducting research projects to find the most inexpensive and effective way to meet the new standards before they are put into place in the upcoming years.

1.2. FHWA Sponsored, NJDOT Managed Project

NJDOT is committed to the support and implementation of air quality friendly transportation projects and programs and is continually looking for new strategies and initiatives that could provide emission reduction benefits. Through studies conducted by various agencies, FHWA recognizes the potential value of the reduction of mobile and idle emissions from school buses in its efforts to support and implement air quality friendly projects. A grant from FHWA managed by NJDOT, enabled a team of Rowan University faculty and students to conduct this study and evaluate emission reduction strategies.

1.3. State Implementation Plan

In response to the Section 109 of the Clean Air Act, the US Environmental Protection Agency (USEPA) established the National Ambient Air Quality Standards (NAAQS). The NAAQS monitors various pollutants, known as “criteria” pollutants, which adversely affect human health (primary) and welfare (secondary). The primary and secondary transportation-related criteria pollutants include Ozone (O_3) and its precursors, lead, volatile organic compounds (VOC) and oxides of nitrogen (NO_x), particulate matter (PM), sulfur dioxide (SO_2), and carbon monoxide (CO).

Each state is required to submit to the EPA a State Implementation Plan or SIP, which is a collection of strategies/ commitments that explain how the State will achieve the air quality standards, set by the Federal Clean Air Act. In New Jersey, the Department of Environmental Protection (NJDEP) is the agency responsible for assembling and submitting the SIP to the USEPA. The SIP includes strategies and commitments for stationary (factories, etc) and mobile (on and off-road vehicles, auto inspections, etc.) sources. The New Jersey Department of Transportation (NJDOT) provides input to the mobile source portion of the SIP.

New Jersey is regulated under region 2 air quality standards, which also includes New York, Puerto Rico, and the Virgin Islands. Region 2 is one of the most urban regions found in the Unites States. Approximately 30 million residents are concentrated in the Region 2 urban areas, in which 85 percent of the 30 million live in New York and New Jersey, mainly in the New York - New Jersey metropolitan area[4]. When the NJDEP produces a draft of the SIP that contains proposed strategies for improved air quality they first propose the SIP in a public process. The next step is to formally adopt the SIP and submit it the USEPA for approval to the Code of Federal Regulations (Title 40, Part 52)[5]. After approval by the USEPA the state's SIP becomes federally enforceable.

1.4. Project Research Team - Rowan University

The Rowan University research team was responsible for researching emissions reduction literature, obtaining the test vehicles, researching reduction strategies, providing testing instrumentation and the reduction strategies, analyzing the data collected from the U.S. Army Aberdeen Test Center (ATC) personnel testing the buses, and finally recommending the most effective emission reduction strategies to the NJDOT. To date the project has produced three master theses for Rowan Engineering graduate students, six Society of Automotive Engineers (SAE) conference papers, and provided an engineering clinic projects for eleven undergraduate students for three semesters. During this time, students were given the opportunity to travel to a remote testing facility at the U.S. Army Aberdeen Test Center where instrumentation and testing of the school buses occurred.

2. Heavy Duty Diesel Truck Idling

2.1. Introduction

Long-haul HDDVs, which are primarily class 8 trucks, often idle their engines for extended periods of time. Truck operators idle their engines for various reasons including the following:

- To keep the engine and fuel warm in cold weather,
- Provide heat and/or air conditioning to the sleeper compartment,
- Power various appliances, and/or
- Refrigerate/heat cargo.

Idling results in costly fuel consumption and engine wear. Moreover, idling produces pollutants in the form of nitrous oxides (NO_x), carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), volatile organic compounds (VOC), and particulate matter (PM), which may be avoidable with the reduction of unnecessary idling.

The Argonne National Laboratory Center for Transportation Research reported in June of 2000 that there were approximately 458,000 Class 8 trucks (GVW ≥ 26,001 lb) operating at distances greater than 500 miles from their home bases each day in the United States[6]. Considering the long distances traveled by these trucks and the fact that most are equipped with sleeper cabs, it is apparent that a significant fraction of these trucks idle for extended periods. The amount that each truck actually idles each day varies due to several factors including: regional climate, cargo, driver habits, availability of overnight parking, etc. Therefore, estimates on heavy-duty diesel truck idling can vary significantly depending on the source.

The Maintenance Council (TMC) of the American Trucker's Association (ATA) estimates that a truck will average 10 hr/day in the winter to as little as 4.5 hr/day on non-winter days[7]. Argonne used a combination of these averages, 6 hr/day, as a baseline for its report assuming an 85-day winter season. Table 3, reproduced from Argonne's report, shows idling time estimates. The baseline figure, used by Argonne, indicates that a truck will average 1,830 hr/year, and a total of 838 million hr/year for the entire Class 8 population.

Table 3: Estimated idle hours for HDDV trucks[6].

Average Hours per Day	**Hours Per Year**	**Truck-Hours per Year (millions)**
3.3	1,000	458
6 (base case)	1,830	838
9.9	3,000	1,374
16.5	5,000	2,290

Several additional studies suggest that the baseline Argonne estimates for idle hours are conservative. The Edison Electric Institute estimates that each truck idles approximately 2,500 hr/year[8]. IdleAire Technologies Corporation estimates that each truck idles approximately 2,600 hr/year[9]. Until a more detailed study can be done to determine actual idling practices, it will be difficult to quantify fuel consumption, engine wear, and emissions for the entire Class 8 population resulting from idling.

Despite the uncertainty in total idle hours, it is clear that any program aimed at reducing HDDV truck idling represents an opportunity for reducing emissions as required by the Clean Air Act. In the state of New Jersey, for example, a recent survey by the Federal Highway Administration[10] has shown that there are 4,397 parking spaces for HDDV trucks at public rest areas and private truck stops. Thus, even conservative estimates yield approximately 25,000 truck idle hours per day in the state of New Jersey.

Although the state does currently regulate allowable idle times for parked vehicles, long haul HDDVs with sleepers remain exempt to date[11]. NJDOT would like to further explore the potential of idle reduction strategies through a systematic experimental study of emissions and fuel consumption from a variety of HDDV trucks at a variety of idling conditions. Accordingly, the NJDOT, in collaboration with EPA**,** Rowan University and Aberdeen Test Center**,** has initiated an experimental study to quantify the idling emissions and fuel consumption rates for HDDV trucks.

Experiments were conducted at the United States Army Aberdeen Test Center (ATC) in Aberdeen, Maryland. In the experiments described herein as well as in the companion papers[12],[13], five Class 8 vehicles were tested in an environmental chamber in which the ambient temperature and relative humidity of the chamber could be accurately controlled. This paper focuses on the effects of ambient temperature and humidity on exhaust emissions and fuel consumption for these vehicles. Tests were performed at three different ambient temperatures (0°F, 65°F, and 90°F) to simulate actual conditions under which a truck operator might idle their vehicle. As would occur in practice, the cabin heater was operated during the low temperature test, while the air conditioner was operated during the high temperature test. During the 65°F test, neither the air conditioner nor heater was operated. In addition, each test was performed at two different engine speeds (600 and 1200 RPM) to examine the effect of the idling engine speed on emissions and fuel consumption.

2.2. Experimental Procedure

Experiments were conducted in Environmental Chamber No. 4 at the Aberdeen

Test Center in Aberdeen, Md. The environmental chamber is capable of controlling multiple climatic variables, including temperature, humidity, solar radiation, dust, icing, fog, and thermal shock. The test chamber has dimensions of 75 ft x 40 ft x 24 ft and can be divided equally into two smaller independent climatic compartments. Temperature can be varied from –70 to 170 ºF, and relative humidity can be raised to 98 %. Data acquisition and control instrumentation are located in a separate room adjacent to the environmental chamber[14]. To simulate a wide variety of idling situations, 38 tests were conducted at three different ambient temperatures (0°F, 65°F and 90°F), relative humidity ranging from 37 to 90% and idle speeds from 600 to 1200 RPM. Each test was conducted for approximately 3 hours during which HC, NO, CO, CO_2, O_2 and PM emissions were monitored. The Real-time On-board Vehicle Emission Recorder (ROVER) was used during testing at ATC[15]. The ROVER is a portable IBM PC based data acquisition system capable of measuring emission levels along with vehicle and engine parameters. The Rover uses EPA software, a Snap-On MT3505 gas analyzer, and an optional Horiba MEXA-120 zirconia NOx sensor[12]. Figure 3 shows the ROVER system installed inside a vehicle cab during testing. In conjunction with ROVER, the vehicle electronic control module (ECM) supplied several engine parameters including engine RPM, oil temperature, and load percent. The vehicle and engine specifications for each HDDV tested are listed in. Each of the vehicles was tested at three different ambient conditions and two different idle speeds as summarized in Table 5.

Table 4: Vehicle and engine data for HDDV truck investigated.

Vehicle	Engine	Engine Displacement	Rated Power
1999 Volvo	’99 Detroit Diesel Series 60	12.7 L	470 bhp at 2100 RPM
1992 Ford	’92 Caterpillar 3406	14.6 L	425 bhp at 2000 RPM
2001 Freightliner	’00 Detroit Diesel Series 60	12.7 L	500 bhp at 2100 RPM
1998 Freightliner	’97 Cummins N14-370E Plus	14 L	370/435 bhp at 1800 RPM
1997 International	’97 International Eagle (Navistar)	14.6 L	410 bhp at 1800 RPM

For two of the tests performed on the 1998 Freightliner truck, approximately 1-hour of additional testing was added to measure the effect of relative humidity on measured exhaust emissions. For 1200 RPM at 65°F and 90°F, the relative humidity was increased from 37% to 90% and 21 to 67 %, respectively, while emissions and fuel consumption were monitored.

Table 5: Test matrix for each HDDV.

RPM	Chamber Temperature (°F)	Accessories
600	0	Heater On
1200	0	Heater On
600	65	None
1200	65	None
600	90	AC On
1200	90	AC On

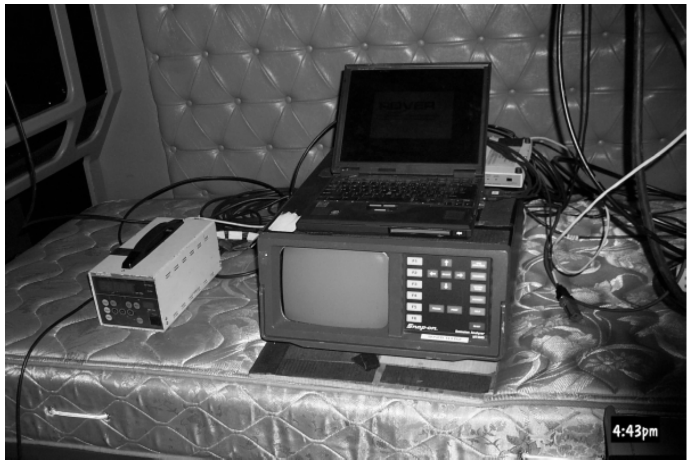

Figure 3: ROVER system used for measuring and recording emissions during HDDV idling conditions.

In addition to the testing of HDDVs, two alternatives were examined for their potential in reducing idling emissions and fuel consumption. The Pony Pack, an alternative power unit (APU), was tested at two ambient temperatures of 0 °F and 90 °F, while operating at 3600 RPM. Also, a direct-fired heater, produced by Espar Heating Systems, was tested at an ambient temperature of 30°F. The NO_x and CO_2 emission levels and fuel consumption were monitored for both systems.

Tests were conducted for approximately three hours allowing for steady state conditions to be reached. The average values for emission levels and fuel consumption over the final hour of testing were determined to be the steady state value for that particular test. Figure 4 is an example of the raw data of NO_x concentration versus time for the 2001 Freightliner vehicle idling at 1200 RPM and at an ambient temperature of 65°F. Figure 4 shows that, at this operating condition, the engine required approximately 2000 seconds to reach thermal equilibrium (as evidenced by the engine oil temperature). For the remaining 8000 seconds of testing, the engine oil temperature cycled between 190 and 200 °F as the engine cooling fan cycled on and off. The figure also shows that, during each 3-hour test, the emissions analyzers were re-calibrated approximately every 1800 seconds. Recalibration is shown in Figure 4 by the periods in which the NO_x concentration intermittently indicates zero ppm.

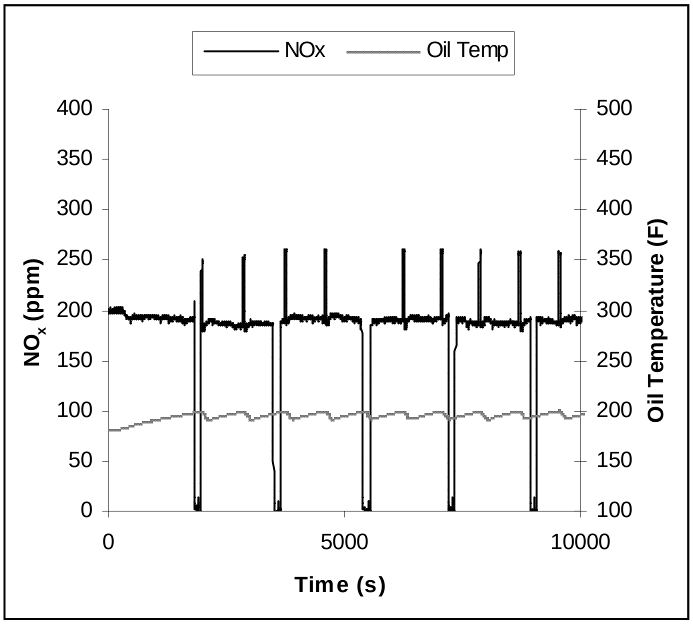

Figure 4: Raw NO_x emission and oil temperature data from typical idle test.

A closer examination of the raw data in Figure 4 shows that the instantaneous fuel consumption and exhaust emissions vary intermittently depending on which vehicle accessories are activated at any given time (see Figure 5).

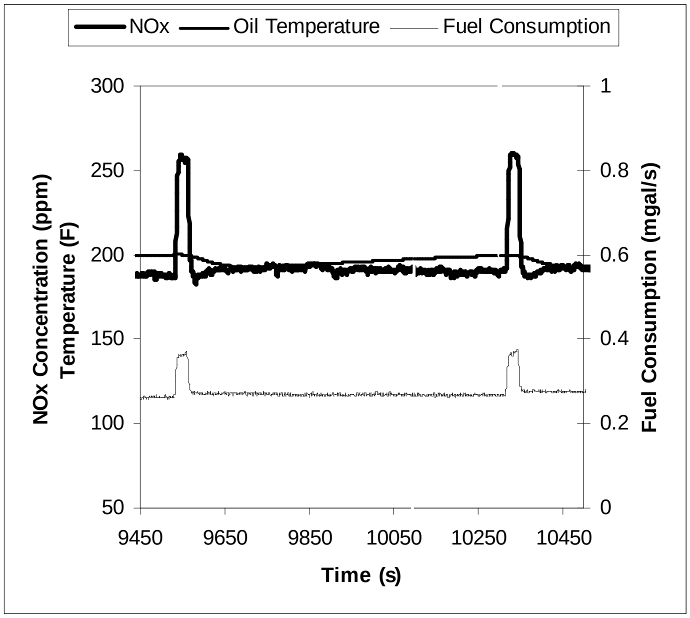

Figure 5: Effect of engine accessories on raw emissions data (over 5-minute period).

As shown in Figure 5, there are two sudden increases in engine load as evidenced by the increased engine fuel consumption. The increased load and fuel consumption results in a corresponding transient increase in NO_x production. This behavior was common in data recorded for several tests, and was attributed to the powering of additional accessories, including the cooling fan, alternator, and the air conditioner compressor. Each of these engine components apply additional loads causing the engine ECU to increase fuel injection to maintain the set engine speed.

For the particular example of Figure 5, the changes in fuel consumption are a result of the engagement of the engine-cooling fan when the engine reaches a preset temperature (approx. 200 °F). Note the decline of the engine's oil temperature following the increase in fuel supplied to the engine. Table 6 and Table 7 list the devices that were powered during each test, along with a generic power draw in horsepower required for each device.

Table 6: Engine accessories engaged at each engine operating condition.

RPM	Chamber Temperature (°F)	Air Conditioner w/Compressor*	Cabin Blower Motors	Engine Cooling Fan (Engaged)
600	0	Off	On	Off
1200	0	Off	On	Off
600	65	Off	Off	Off
1200	65	Off	Off	Periodically
600	90	Periodically	On	On
1200	90	Periodically	On	On

Table 7: Power draw in HP for each HDDV accessory[7].

Accessory	HP at 600 RPM (HP)	HP at 1200 RPM
Air Conditioner		
90° Day/Drawn Down (hot cab)	7.5	7.5
90° Day/Maintain (cool cab)	3.5	3.5
Blower Motors	0.4	0.4
Cooling Fan		
On/Off (Engaged)	1.5	5.0
On/Off (Disengaged)	0.0	0.0

2.3. Experimental Results

2.3.1. Fuel Consumption Results

Previous studies by the Argonne National Laboratory and The Maintenance Council of The American Trucker's Association suggest that, on average, a truck will consume approximately 1 gallon of fuel per hour of idling time[16]. Using Argonne's baseline figures, this amounts to 838 million gallons of fuel used inefficiently each year in the United States. Assuming a price for diesel fuel of $1.50/gallon, HDDV idling therefore results in a cost of approximately $1.3 billion/yr to the U.S. economy. On a per truck basis, the Argonne study suggests that idling fuel costs are approximately $2,745 per year per truck. These figures do not include additional maintenance and depreciation costs incurred as a result of engine idling.

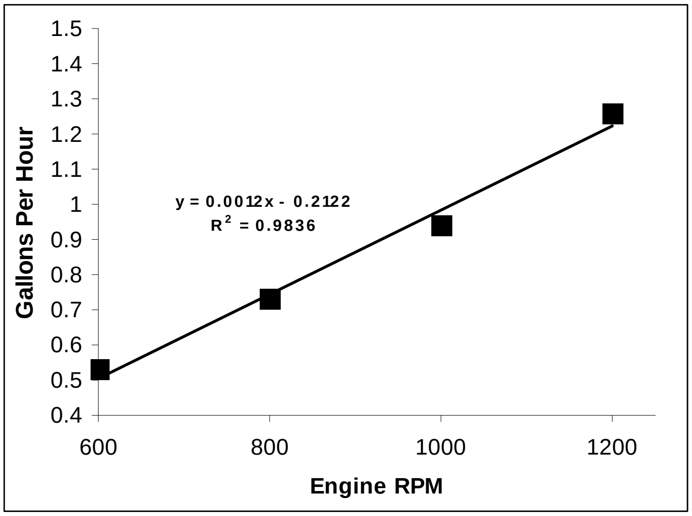

Figure 6: Fuel consumption for various idling engine speeds, 1998 Freightliner truck, 65°F ambient condition.

The values quoted in the Argonne study represent a simplified analysis for idling fuel costs. It is known that fuel consumption can depend on several factors including engine speed. Figure 6 shows the fuel consumption of the 1998 Freightliner Truck as a function of engine idling speed. Fuel consumption rate was estimated for engine idling speeds varying from 600 to 1200 RPM. For the test results shown in Figure 6 no climate control accessories were powered. As the graph illustrates, the fuel consumption rate varied almost linearly from 0.53 g/hr to 1.26 g/hr as a function engine RPM. The effect of the temperature and relative humidity of the inlet air on fuel consumption were also examined during testing.

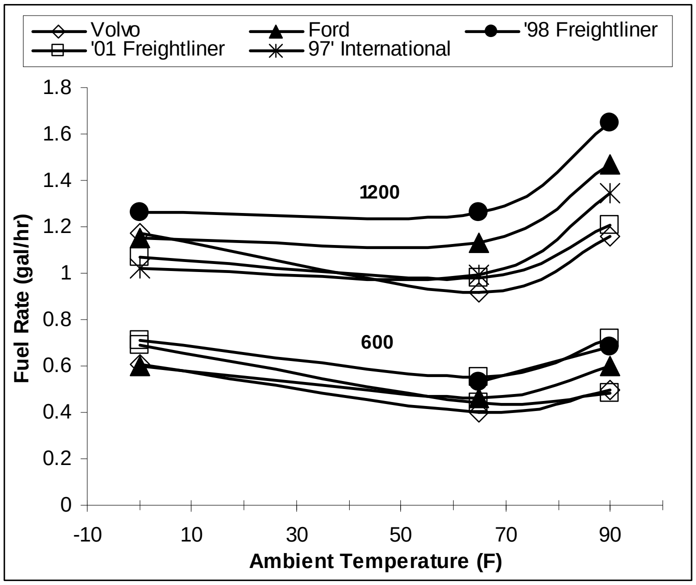

Figure 7: Fuel Consumption at Various Ambient Temperatures.

Figure 7 is a plot of fuel consumption as a function of ambient temperature for five different trucks idling at two different speeds. As the figure illustrates, fuel consumption is larger when the additional accessories are powered. Generally speaking, for each of the trucks tested, operation of the air conditioning system results in a higher rate of fuel consumption than operation of the heating system for both the low and high engine speeds. This result agrees with the power requirements for each auxiliary device as listed in Table 7. It should be noted as well that, although neither the cab heater nor air conditioner were operated during the 65°F cases, the engine cooling fan engaged periodically. This result explains why only a modest decrease in fuel consumption is exhibited in the 65°F cases. Table 8 shows the average fuel consumption rates for all five vehicles at both engine speeds. For all trucks tested at all temperatures, the average fuel consumption rate was 0.52 g/hr and 1.20 g/hr at 600 and 1200 RPM respectively.

Table 8: Average fuel consumption rates for all five HDDVs tested (gal/hr).

	0°F	**65°F**	**90°F**
600 RPM	0.53	0.46	0.57
1200 RPM	1.16	1.07	1.37

2.3.2. Emissions Results

In addition to the high costs associated with idling, a variety of chemical species present in the exhaust gases from diesel engines have adverse effects on the environment and human health. Volatile organic compounds and particulate matter (soot), which are abundant in diesel exhaust, are known to contain carcinogens[17,18], while NO_x, CO, and CO_2 can lead to respiratory problems and the formation of smog, ozone, acid rain, and also contribute heavily to the greenhouse effect[19]. Argonne National Laboratory has reported previously the average emissions for a single truck as shown in Table 9 below. The estimates in Table 9 are consistent with the EPA estimates of emission rates, determined using its MOBILE5b and PART5 models for winter conditions as reported in January of 1998 and summarized in Table 10. The EPA did not provide estimates for CO_2.

Table 9: HDDV idling emission estimates from Argonne National Laboratory[6]

Emissions (g/hr)				
VOC OR THC	CO	NO_x	PM*	CO_2
12.6	94.6	56.7	2.57	10,397

* Particulate matter with Sauter mean diameter of 10 μm and less.

Table 10: EPA emission estimates for HDDV trucks from MOBILE5b and PART5 models*

Pollutant	Units	Winter Conditions (30 °F)	**Summer Conditions (75 °F)**
VOC	g/hr	12.6	12.5
CO	g/hr	94.6	94.0
NO_x	g/hr	56.7	55.0
PM**	g/hr	2.59	2.59

*The values from the EPA represent the national averages of the entire in-use fleet as of January 1, 1998 (winter) or July 1, 1998 (summer).

**EPA claims particulate emissions are relatively insensitive to temperature (winter ≈ summer)

As Table 10 indicates, ambient temperature operating conditions only slightly affect HDDV idling emissions as predicted by the EPA MOBLE 5b model. As will be described in detail below, the results of the present study show that, in fact, measured VOC, CO, NOx and PM emissions from HDDV vary widely with ambient temperatures.

In the present study, idling emissions were measured for five different trucks at three different ambient temperatures (0, 65 and 90 °F) and two engine speeds (600 and 1200 RPM).

In the companion papers[12,13] it is shown that measured emissions under actual idling conditions vary widely depending on the vehicle/engine type, ambient temperature and idling speed. Moreover, a comparison with the average predicted values of MOBILE5b suggests that prior EPA estimates are generally quite conservative.

2.3.2.1. NO_X Emissions

Figure 8 and Figure 9 show steady state values of NO_x in ppm for each test performed using the test procedure described in Section 2.2 Experimental Procedure.

As shown in Figure 8 and Figure 9, NO_x emission levels vary widely depending on the vehicle type, ambient temperature and idle speed. Depending on the idling speed and the vehicle type, NO_x emission can increase monotonically with increasing ambient temperature (see for example, 1999 Volvo at 600 RPM) or, in many cases, NO_x emission can exhibit a minima at 65 °F (see for example the 2001 Freightliner at 1200 RPM). These seemingly inconsistent results are attributed to the composite effects of ambient air temperature, engine load and the engine thermal management system. Increased engine inlet temperature results in increased combustion temperature, which results in increased NO_x production as explained by the Zeldovich mechanism of NO_x production[19,20].

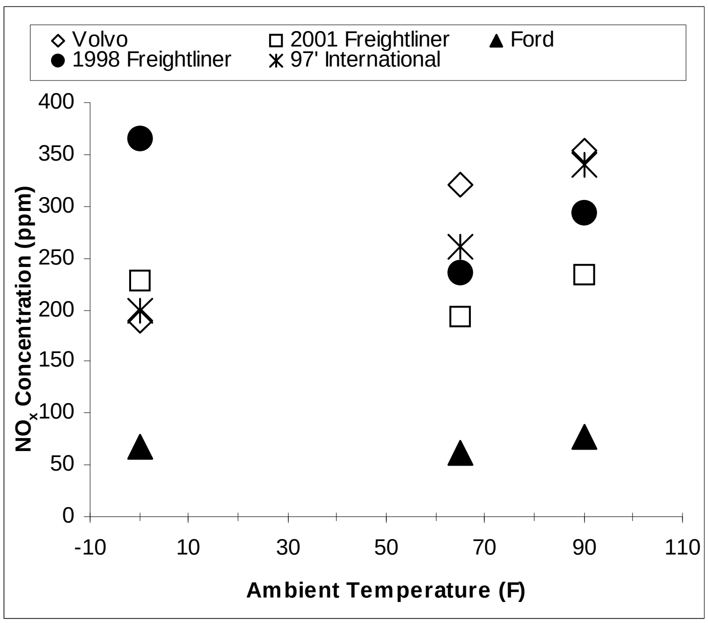

Figure 8: NO_x concentration at 600 RPM (ppm).

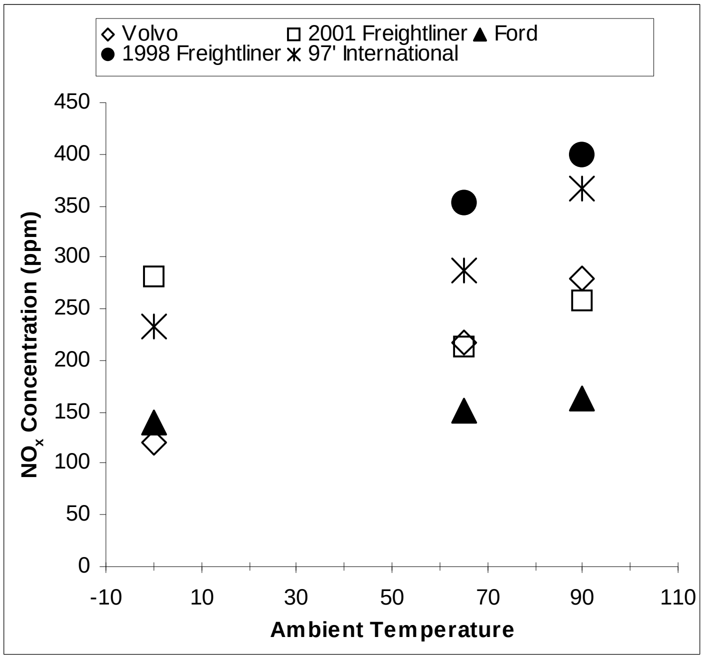

Figure 9: NO_x concentration at 1200 RPM (ppm).

Because each engine has its own unique thermal characteristics, the ambient air temperature also has an indirect effect on NO_x production. Depending on the thermal management characteristics of the engine, the steady state engine block temperature (as indicated by the measured oil temperature, for example) varies as a function of the ambient air temperatures. Since the steady state engine block temperature affects combustion temperature, the thermal management system will affect the NO_x production. In terms of engine load, any increase in engine load (for example, due to auxiliary devices) also results in increased NO_x production because of increased fuel consumption rate. This is likely also a consequence of increased combustion temperatures resulting in an increase in thermal NO_x. It is quite evident that the amount of fuel supplied to the vehicle's engine greatly influences the emission of NO_x, as seen in the transient response of Figure 5. The results shown in Figure 7, show that for all trucks tested, the steady state fuel consumption rate is higher at 0°F and 90°F than at 65°F. Therefore, at 0°F, the effects of engine inlet temperature and increased engine load are competing effects. Specifically, the lower inlet temperature favors lower Zeldovich NO_x production but the increased engine load associated with the cabin fan yields increased NO_x production. Therefore, depending on the engine type and the idling speed, NO_x production can either increase or decrease for 0°F idling conditions.

Figure 10 and Figure 11 are plots of measured NO_x concentration as a function of fuel flow rate for the 2001 Freightliner and the 1999 Volvo respectively. Figure 10 suggests that, in the case of the 2001 Freightliner, the increased fuel flow rate caused by the increased engine load is the determining factor for NO_x emission, since the figure shows a monotonic increase in the NO_x concentration with increasing fuel consumption rate for both the low and high engine speeds. Conversely, Figure 11 suggests that, in the case of the 1999 Volvo truck, the ambient air temperature is the governing parameter since the measured NO_X concentration does not correlate well with fuel consumption rate.

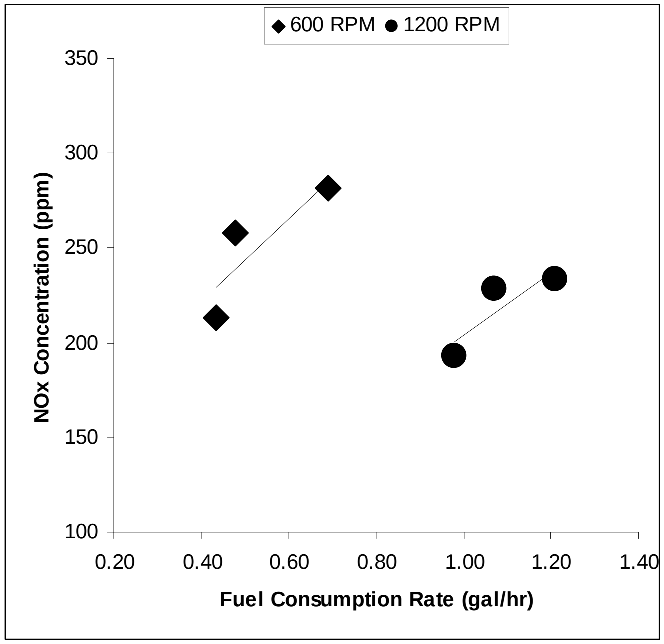

Figure 10: NO_x emission as a function of fuel consumption for 2001 Freightliner.

As mentioned previously, the ambient air temperature has both a direct effect on the average combustion temperature, as well as an indirect effect through the thermal characteristics of the engine block as maintained by the thermal management system of the engine. The engine oil temperature is an indication of the temperature at which combustion is occurring inside the cylinders. Figure 12 is a plot of oil temperature for the 1999 Volvo, 1998 Freightliner, 1997 International, and 2001 Freightliner as a function of ambient temperature for the 600 RPM tests. Tests performed at 1200 RPM produced similar data amongst the vehicles. The 1992 Ford truck was not equipped with an ECM, and the oil temperatures were not obtained for this vehicle. As Figure 12 shows, the oil temperature was lowest at an ambient temperature of 0°F for all vehicles tested. However, the figure also shows that the oil temperature was lowest for the 1999 Volvo, which had the lowest NO_x emission at 0°F. Figure 12 also shows the perhaps unexpected result that the engine oil temperatures were not, in fact, highest at 90°F ambient temperature. Rather, due to the behavior of the thermal management system, the highest temperatures actually occur at 65°F ambient temperature for all trucks tested. It should also be noted that the measured engine exhaust temperature was found to correlate very closely the engine oil temperature. This confirms that the oil temperature is a good indicator of the effective combustion temperature.

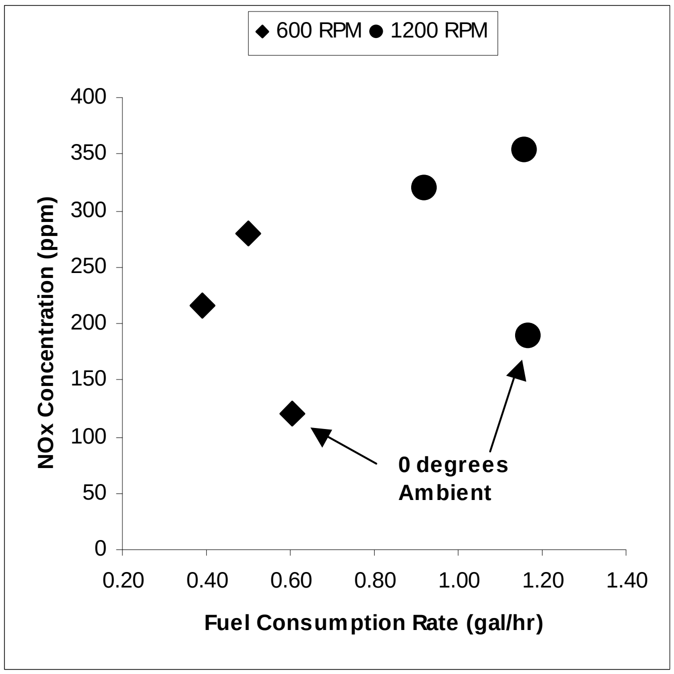

Figure 11: NO_x emission as a function of fuel consumption rate for Volvo truck.

As noted above, the engine thermal management system is a key controlling parameter in the NOx production. The operation of the engine cooling system is controlled by the system's coolant temperature, which determines the opening/closing of the thermostat and the powering of the engine's cooling fan. These factors alter the operating temperature of the engine and, consequently, affect the combustion temperature inside the cylinders. The engine manufacturer presets the prescribed coolant temperature. These inconsistencies result in the wide variety of NO_x emission throughout the test matrix as shown in Figure 8 and Figure 9.

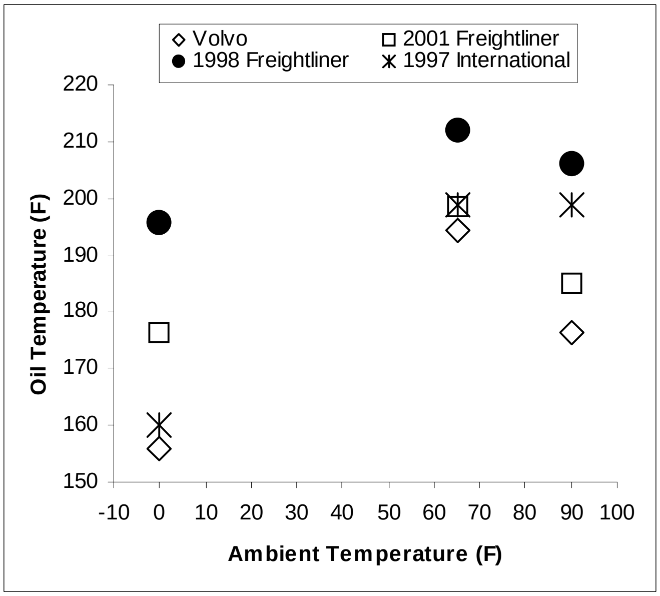

Figure 12: Engine oil temperature at various ambient temperatures.

2.3.2.2. CO_2 Emissions

Figure 13 and Figure 14 are plots of measured CO_2 emission as a function of ambient temperature at 600 and 1200 RPM for all trucks tested. As shown in the figures, the measured CO_2 emission exhibited similar trends for both the low and high idling speeds. For 600 RPM, the lowest levels of CO_2 emission occurred at 65°F, when no accessories were operated. Indeed, since the ROVER system relies on measured CO_2 emission to calculate fuel consumption rate, the same explanation that was made in describing Figure 6 can be applied to Figure 13 and Figure 14. Specifically, the production of CO_2 is directly related to engine load, which is directly related to the power requirements of the vehicle accessories.

In summary, Table 11 is a comparison of the measured emission results reported here and those previously estimated by Argonne National Laboratory[6] and EPA[121]. The table lists the average measured NO_x and CO_2 emissions for all five trucks at all ambient temperatures and both engine speeds. In general, the results show that the emissions estimates reported in the Argonne study are generally quite conservative. For example, the measured NO_x emission levels were higher than Argonne estimates by a factor two to three. Moreover, the results also clearly show that the effect of idle speed should be considered when estimating total emissions in g/hr.

Table 11: Average emission levels for the five trucks tested in this study compared to the estimates of Refs. 6 and 121.

	NO_x		**CO_2 (g/hr)**	
	This Study	**Ref. [121]**	**This Study**	**Ref. [6]**
Low Engine Speed	97.0	55.8	5,170	10,379
High Engine Speed	181.4	55.8	11,948	10,379

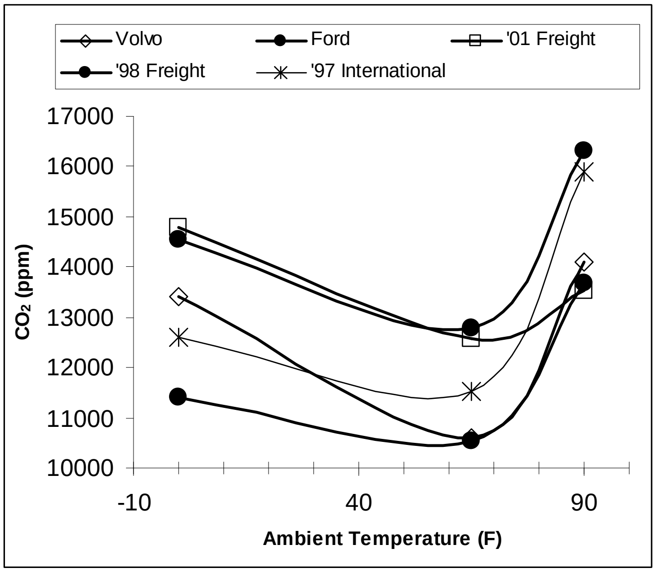

Figure 13: CO_2 emission vs. ambient temperature at 600 RPM for all five trucks tested.

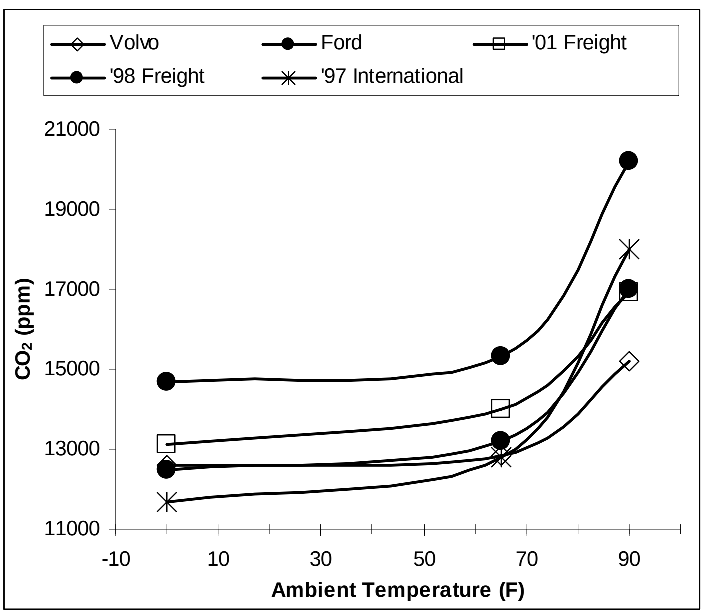

Figure 14: CO_2 emission vs. ambient temperature at 1200 RPM for all five trucks tested.

2.3.3. Effect of Humidity on NO_X Emissions

The effect of relative humidity on emissions was examined using the 1998 Freightliner vehicle idling at 1200 RPM in an environmental chamber. The chamber controlled the ambient temperature and humidity. Two runs were conducted at 65°F and 90°F with the relative humidity increased at a rate of 0.89 %RH/min and 0.63 %RH/min, respectively.

The SAE standard J1243 section 16.5 gives a correction factor for the effect of inlet air temperature and humidity on *wet* NOx values given below:

$$NO_{x\,corr} = NO_{x\,measured} / K$$
$$K = 1.0 + A*(H - 75) + B*(T - 85)$$
$$A = 0.044*F/A - 0.0038$$
$$B = -0.116*F/A + 0.0053$$

where H is the absolute humidity in grains water/lb dry air; T inlet air temperature in °F and F/A the mass fuel to air ratio. This correction factor is designed to correct wet NOx values to what would be expected at inlet air conditions of 85 ºF and 75 grains H_2O / lb dry air (39%RH).

Additionally the CFR40 86.1342-90 also contains a correction for humidity for engine tests of heavy duty diesel engines.

$$NO_{x\,corr} = NO_{x\,measured} * K'$$
$$K' = \frac{1}{(1 - 0.0026*(H - 75))}$$

where H is the absolute humidity in grains water/pound of dry air.

This correction factor is similar to the SAE J1243 correction equations, but neglects the effect of the fuel to air ratio and inlet air temperature on NO_x emissions. The CFR40 correction factor has been used by equipment manufacturers for emissions testing, but it must be applied under the appropriate conditions of temperature and humidity. This CFR40 engine testing code requires the inlet air temperature to be in the range of 68ºF to 85ºF.

The NO_x values from these tests are shown in Figure 15 and Figure 16 and as expected NO_x values decrease with increasing humidity of the inlet air. In Figure 15 the inlet air temperature was 65ºF and the absolute humidity increased from 35 to 86 grains H_2O/lb Dry Air (37-90%RH). In Figure 16, the inlet air temperature was 90°F and the absolute humidity was increased from 47 to 153 grains H_2O / lb Dry Air (21-67% RH).

A constant value of NO_x (horizontal line) should result in Figure 15 and Figure 16 when the correction factor is applied to the measured NO_x values. In Figure 15 the SAE correction factor for NO_x is nearly horizontal with a mean of 52.3 g/hr and a standard deviation of ±2.29 (± 4.4%). Using the CFR correction factor resulted in a mean of 47.8 g/hr.

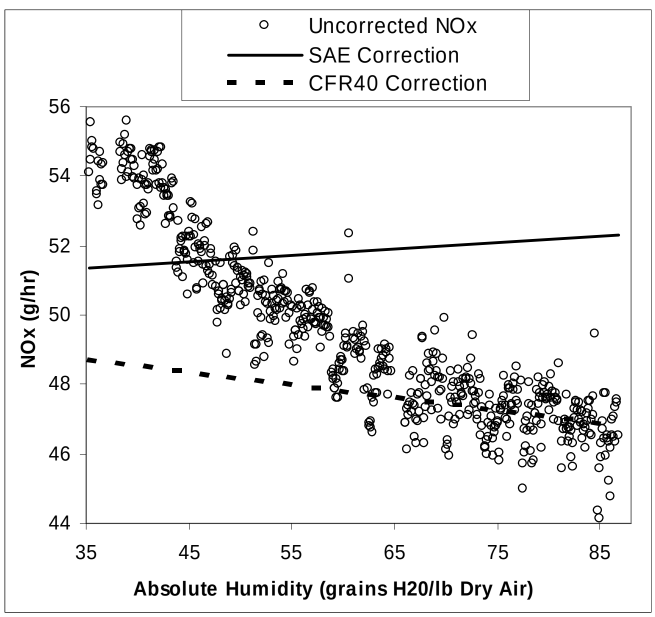

Figure 15: Corrected and uncorrected NOx as a function of absolute humidity for 1998 Freightliner at 65ºF.

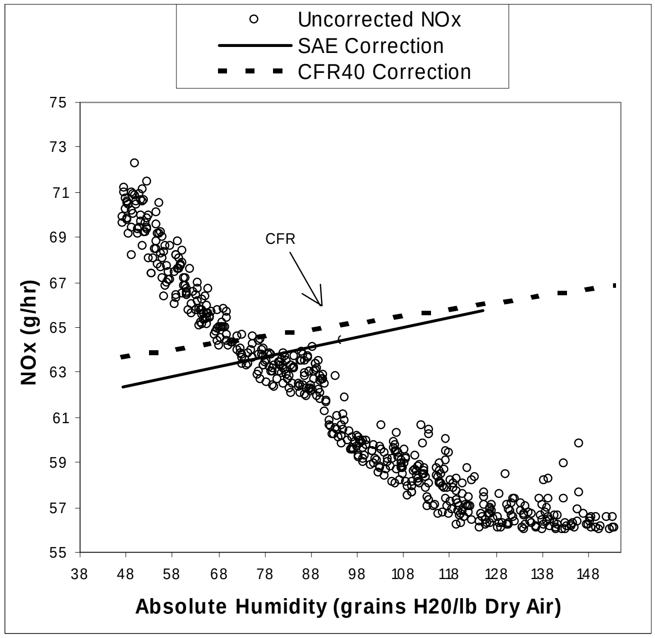

Figure 16: Corrected and uncorrected NOx as a function of absolute humidity for 1998 Freightliner at 90ºF.

The SAE correction for humidity was not correlated for values of absolute humidity greater than 125 grains H_2O/lb dry Air. The range for this correlation, is from absolute humidity of 35 to 125 grains H_2O/lb dry air[21]. In Figure 16 the SAE correlation is plotted only to the value of 125 gr/lb DA. The mean value within the range of the SAE correction factor was 64.4 g/ hr of NOx with a standard deviation of 4.00 (±6.0%). Since both correction factors produce similar results, it is presumed that the CFR40 correction factor is using a basis temperature of approximately 85°F.

The differences between the CFR40 and SAE correction factors shown in Figure 15 are attributed to the inlet air temperature and fuel to air ratio. Since, the CFR humidity correction factor does not include a temperature correction or fuel to air ratio correction, then it gives a poor result under these conditions. The absence of a fuel to air correction is significant under idle conditions, since the idling F/A ratio was approximately 0.008. Assuming that the temperature was 85°F, the back-calculated air to fuel ratio is approximately 0.03. The SAE correlation is based on tests of F/A ranging from approximately 0.0025 to 0.06 and a percent engine load from idle to 100%. It appears that the value of 0.03 corresponds to a loaded condition indicating that the CFR correction should not be used for idling. Based on these observations, the SAE correction factor is most likely a better correction factor for NO_x under idling conditions.

The results of this section show that the SAE standard NO_x correction for humidity appears to be applicable for the humidity range (35 – 125 grains H_2O / lb Dry Air) under which the correlation was originally developed. It should be noted that only the temperature range is reported in the current SAE standard.

2.4. Conclusions

With increasing pressure to meet the National Ambient Air Quality Standards (NAAQS) set by USEPA, New Jersey continues to actively research and develop strategies to help meet the standards, which may include future technological or other idle reduction strategies. However, prior to the present study, very little data was available to quantify emission levels for HDDV trucks under realistic idle conditions. Moreover, prior to the present study, very little data was available to quantify fuel consumption rates during HDDV idling to determine the potential economic benefits for truck fleet owners to incorporate idle reduction technologies. This study now provides quantitative data on NO_x and CO_2 emissions, as well as fuel consumption rates for a variety of HDDV trucks at various seasonal conditions and idling speeds. The results show that previous HDDV idling emissions and fuel consumption estimates are, generally, conservative, particularly in the case of NO_x emissions.

To simulate a wide variety of idling situations, 38 tests were conducted at three different ambient temperatures (0°F, 65°F and 90°F), relative humidity ranging from 22 to 90% and idle speeds from 600 to 1200 RPM. The following major conclusions were found:

- Fuel consumption (gal/hr) and overall average mass emissions (g/hr) increase with increased idling speed. Previous estimates of fuel consumption and emissions did not consider idling speed.
- For all trucks tested at all temperatures, the average fuel consumption rate was 0.52 g/hr and 1.20 g/hr at 600 and 1200 RPM respectively.
- Fuel consumption and CO_2 production was a maximum at 90°F ambient conditions because of increased parasitic load of air conditioning system.
- The SAE standard NO_x correction for humidity was effective for the humidity range under which the correlation was originally developed, although this range is not reported in the current SAE standard. The CFR40 NO_x correction factor should not be used for idling emissions corrections.
- Depending on the idling speed and the vehicle type, NO_x emission increased monotonically with increasing ambient temperature or, in many cases, NO_x exhibited a minimum at 65°F. These results were most likely attributed to the composite effects of ambient air temperature, engine load and the engine thermal management system.

3. Life Cycle and Economic Analysis of HDDV Idling Alternatives

3.1. Introduction

The 1990 Clean Air Act sets ambient emission standards that help to regulate the emissions of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxides (NO_x), particulate matter (PM) and volatile organic compounds (VOC) in the United States atmosphere. Because of this act, each state is required to implement emissions reduction strategies, called State Implementation Plans (SIPs). To develop the New Jersey SIP, Rowan University, the Environmental Protection Agency (EPA), and the New Jersey Department of Transportation (NJDOT) have collaborated to develop a plan to reduce Heavy Duty Diesel Vehicle (HDDV) emissions. It is estimated that heavy-duty diesel emissions are responsible for 80% of all PM emissions and 33% of all NO_x emissions from mobile sources in the northeast United States. CO, CO_2, HC, and VOC emissions are also a result of HDDV idling. Accordingly, the New Jersey Department of Transportation Bureau of Freight Services was developing strategies aimed at reducing harmful emissions from diesel engines in the state of New Jersey. This report attempts to quantify the effects of idling HDD trucks and the implementation of idling alternatives using a life cycle assessment (LCA).

Many different approaches to LCA have been found in the literature. However, few studies have attempted to assess the effects of HDDV idling and alternative options through an LCA. This report is the first known attempt to quantify the life cycle of HDD Truck idling and idling reduction technologies. Ari Rabl and Edgar Furuholt present LCAs of gasoline, diesel, and natural gas[22,23]. These studies analyze life cycle emissions and environmental impacts of fuel technologies and HDD vehicles. Rabl used a LCA to quantify the positive effects of natural gas for buses compared to diesel buses, and quantify ecological and health impacts through a damage cost method. The damage cost method relates the emissions to the impacts on human health and the environment in terms of crop damage, wage and productivity losses, years of life lost, etc. The natural gas bus had lower emissions compared to the same bus with diesel fuel. Two technologies also evaluated were a diesel engine with a particulate filter and a natural gas multi-point injection (MPI) engine. Their results show that the damage costs associated with a MPI engine were 3 - 5 times lower than the damage costs associated with a diesel bus with the particulate filter.

Furuholt[23] assessed the life cycle of various fuel products, including gasoline, gasoline with MTBE, and diesel. The life cycle analysis included an impact assessment of global warming potential, photo-oxidant formation, eutrophication, acidification, consumption of fossil energy, and waste generation. For the production portion of the fuel life cycle, Furuholt used experimental data from the partitioning of the Statoil refinery. Two methods were used to assess ecological burdens in this study. The first method was used to assess the impacts as a relative scaling of the world total contribution of each impact category. The second method evaluates the impacts as a function of ecological scarcity, which gives different weights to the emissions from each geographical location, based on their distance to set targets. Based on Furuholt's results, it is evident that the relative ecological impacts for the three types of fuel are independent of the method of impact analysis. The conclusions showed that gasoline with MTBE has the greatest environmental impacts, which is caused by increased refining processes, and diesel has the least impacts, which is the result of decreased refining. The total environmental impact from gasoline and diesel were 80% and 45% of that of gasoline with MTBE, respectively

As a consequence of the requirement that Heavy Duty Diesel Truck (HDDT) drivers must rest 8 hours for every 10 driving hours, the driver usually idles the engine to supply power to maintain a comfortable temperature in the cab, to keep the engine warm, and to run electrical accessories. This engine idling results in excessive fuel consumption, increased engine wear, and the emission of toxins into the atmosphere.

In order to reduce HDDV idling, various technologies have been developed to supply power to the truck more efficiently with reduced emissions. In order to quantify the benefits of such technologies, data was collected and assumptions were made to assess the life cycle of each option.

The fuel consumed and emissions produced by an idling truck were measured in experiments conducted at Aberdeen Test Center (ATC), in Aberdeen, Maryland. Five trucks were tested and each was idled under different conditions in a climate-controlled environmental chamber[24]. To simulate the conditions of air conditioning in the summer and heating in the winter, the air conditioning was turned on while the ambient temperature was set to 90°F and the heat was turned on in a 0°F environment. The amount of fuel used and emissions produced by the trucks during these runs were recorded for 600 and 1200 RPM. For the purposes of this report, an average temperature and RPM value was used to arrive at an average fuel consumption of 0.86 gal/hr. The HDDT fuel consumption data is located in Table 12.

Table 12: Average Fuel Consumption of the Five Trucks Tested in gal/hr

Fuel Consumption (gal/hr)			
Idle Speed / Ambient Temperature	**0°F**	**65°F**	**90°F**
600 RPM	0.53	0.46	0.57
1200 RPM	1.16	1.07	1.37

As shown in Table 12, fuel consumption of the five trucks increased with increasing idle speed as expected. Trucks equipped with two technologies were also tested at ATC. The technologies are described in detail below.

3.2. Idle Emissions Reduction Technologies

The technologies evaluated in this report to reduce engine idling are as follows:

- Pony Pack auxiliary power unit (APU)
- Truck Stop Electrification (TSE)
- IdleAire Advanced Truck Stop Electrification (ATSE)
- Espar Direct-fired heater, model D1LC (DFH)

3.2.1. Auxiliary Power Unit (APU)

The Pony Pack is a 2-cylinder Kubota™ diesel engine that is attached to the truck and used to run an air conditioning compressor or heater, and an alternator. The APU was tested for fuel consumption and emissions. Prices of the APU have been estimated to be between $6,000 and $7,000. The fuel consumption data for the APU test follows in Table 13.

Table 13: Average Fuel Consumption of the APU Equipped Truck in gal/hr

Fuel Consumption (gal/hr)			
Idle Speed / Ambient Temperature	**0°F**	**90°F**	**average**
3600 RPM	0.20	0.23	0.215

Comparing the fuel consumption shown in Table 12 to that shown in Table 13, the APU consumes from 50 to 85% less fuel than engine idling.

3.2.2. Truck Stop Electrification (TSE)

TSE supplies electricity to run the trucks heating and air conditioning systems and power. This option requires an electrical hookup to be installed at truck stops, and each truck must be equipped with an AC/DC power inverter. The EPA estimates that the inverter costs $2,500.

3.2.3. Advanced Truck Stop Electrification (ATSE)

The second type of truck stop electrification is ATSE, which uses an external heating, ventilation, and air conditioning (HVAC) unit installed at each truck parking space. Hot or cold air is sent through a vent from the external HVAC device and controlled using a console. Advanced options of ATSE include temperature controls, internet service, phone service, and television. An additional 110 VAC outlet can be mounted on the rear of the console to provide an external power hookup for an engine block heater. TSE costs approximately $2,500 per space, for a 30-space structure, while ATSE costs $300,000 for 30 spaces due to HVAC installation. The EPA assumed the electricity costs to be $1.25 to $1.50 per kWh for the truck drivers for both TSE and ATSE.

3.2.4. Direct-Fired Heater (DFH)

The Espar DFH is able to cycle through four heat levels to maintain the desired cabin temperature by the operator. The heater typically runs for 21-23 hours on a gallon of diesel fuel. Experimental data was used for the actual fuel consumption of the heater and its emissions. The heater cost is approximately $2,000 and the average experimental fuel consumption of the DFH is 0.04 gal/hr.

3.3. Methodology

Life cycle assessment (LCA) is a "cradle-to-grave" approach for assessing the major industrial activities in the production, use, and final disposal of each technology. The methodology of conducting this LCA included assessing all inputs and outputs of implementing each technology through a life cycle inventory and assessing associated emissions and ecological burdens through a tier 3 analysis[25]. Since gathering the data for an LCA can be problematic and the availability of data can greatly affect the accuracy of the final results, many sources were used in making assumptions and defining system boundaries.

This LCA methodology consists of defining the functional unit, quantifying production emissions through the Carnegie-Mellon developed Economic Input-Output Life Cycle Analysis (EIOLCA) web software[26][27], calculating use emissions through experimental data and Argonne National Labs Greenhouse Gases, Regulated Emissions & Energy use in Transportation Model (GREET model), and estimating the end of life impact. With this method, four idle reduction strategies were assessed and compared to idling. Quantifying the overall ecological burdens from the manufacture and use of each technology, along with ecological impacts and an economic analysis, determined which strategies should be implemented to reduce HDDV idling.

The first step in a life cycle analysis is to define the functional unit. The functional unit is what allows the life cycle of idling technologies to be compared. For this study, the idled hours per year and the number of trucks for the study were defined. Since there is no precise number of long-duration truck idling hours, several sources were used for this estimation. Argonne National Laboratory estimates that the average long haul semi tractor idles for 1,830 hours per year[28]. Other sources, such as the EPA, estimate that trucks idle over 2,400 hours each year.

In New Jersey, the Federal Highway Administration has shown that there are 4,397 parking spaces available for trucks in rest areas and private truck stops[29]. It is evident that truck idling also occurs on ramps and along the highway. From a national survey published in 1996[30] it is estimated that there was a truck-parking shortfall of approximately 28,400 parking spaces at public rest areas, According to a NJDOT Technical Memorandum[31], as many as 200 trucks park illegally on NJ Interstate shoulders and ramps on the average weekday night. This additional idling, outside of designated rest stop areas, has been taken into consideration for emissions calculations, and led to the assumption that parking spaces were continuously occupied throughout the day. Thus, this report assumes that one truck idles eight hours per day, 300 days per year.

To adequately compare the technologies, the functional unit was defined as 30 trucks, idling 2,400 hours per year, for three years. The total idling hours for the functional unit is 216,000 hours. Over the functional unit period, half of the hours were assumed to run heat, and the remaining hours were assumed to run the air conditioning.

The production portion of a life cycle assessment includes the manufacturing of a product, and all the activities related to it. To quantify production emissions, sources in literature use various methods. Furuholt conducted an LCA comparing gasoline and diesel fuel.[23] The report used production emissions monitored by the refinery and partitioned the refining process into several process units for the study. Rabl conducted an LCA to compare natural gas and diesel fueled buses.[22] To quantify production emissions, Rabl uses an External Costs of Energy Conversion Method from ExternE and the MEET Methodology of Calculating Transport Emissions and Energy Consumption. For this study, data for the production section of the life of each technology was obtained from an economic input-output life cycle assessment (EIOCLA) program developed by the Green Design Initiative at Carnegie Mellon University. [26]

The EIOLCA software was used to find the impact of increased production in a certain sector of the economy. The production cost of each technology was entered into the program and the associated emissions were reported. For the purposes of this study, the production costs were estimated to be the same as the reported market price of each unit. Emissions from fuel production are included in the production portion of this LCA. The EIOLCA software then reported conventional pollutants released during the production of the APU, DFH, TSE, and ATSE.

The EIOLCA software was created using the 1992 US Department of Commerce's 485x485 commodity input-output model of the US economy, which requires that 2002 costs must be converted to 1992 values. This conversion was performed using the Consumer Price Index (CPI). The CPI is a measure of the value of the US dollar. To obtain a factor for converting 2002 values to 1992 values, the CPI for 1992 (140.3) was divided by the CPI for 2002 (179.5). The conversion factor is 0.78. Therefore, before the unit costs were entered into the software, they were multiplied by 0.78.

The use portion of the life cycle includes all emissions released throughout the functional unit, based on the GREET model from Argonne National Laboratory (for TSE and

ATSE) and ATC testing (for idling and other technologies)[32]. Similar methods have been used to compare types of technologies where experimental data was not available. Rabl used a series of curve fits for diesel emissions from the MEET project, coupled with bus emissions data for the gas bus in his study.

The end of life portion of the LCA was assumed negligible. The end of life of a truck would not be affected by increased wear of an engine due to idling. Therefore, there would be no significant end of life calculations for engine idling. For the APU, DFH, and TSE, the units would most likely end up in a landfill. Therefore, the idling alternatives would have little impact on the environment compared to the end of life of a HDDV. Therefore, this section of the life cycle was assumed negligible for all technologies.

3.4. Technologies

3.4.1. Idling

The production phase of engine idling is based on the amount of diesel fuel required for the functional unit. This was determined by calculating the amount of fuel consumed over the functional unit, at $1.50 per gallon[33]. The sector of the economy used to calculate emissions from producing diesel fuel was petroleum refining.

The idling data for the use portion of the life cycle of a truck came from ATC test data. From the results, the emission mass flow rates were multiplied by the functional unit. The values were manipulated to show the emissions from an average fuel consumption rate from the tests. The SO_2 values were calculated by assuming that all #2 diesel fuel sulfur was converted into SO2, where sulfur content was assumed to be 368ppm[34].

3.4.2. Auxiliary Power Unit (APU)

The first alternative to idling to be assessed was the auxiliary power unit. The cost of this unit used for this report is approximately $7,000. After converting to 1992 values, this cost was $5,640. This 2-cylinder diesel engine was classified in the EIOLCA economic sector of internal combustion engines not elsewhere classified. Also included in the production portion of the APU was the associated fuel consumption over the functional unit of idled hours, which was classified in the petroleum refining sector. The average RPM fuel consumption rate was found from ATC data and the total APU costs for this analysis was $69,660 and $54,334 in 1992 values. The use data for the APU was obtained by the ATC data.

3.4.3. Truck Stop Electrification and Advanced Truck Stop Electrification

Truck stop electrification was the second technology that could reduce wasted emissions and energy of idling trucks. In order to take advantage of TSE power, the truck must have an electrical heating and air conditioning system and power inverter. The price of this inverter was estimated to be $2,500 per unit in 2002 dollars and $1,950 in 1992 dollars. Another technology assessed was IdleAire's ATSE. The production sections of both TSE and ATS were also estimated using the EIOLCA program. The estimated cost of the infrastructure for TSE is $2,500 per parking spot. This is equivalent to $1,953 in 2002 values. The infrastructure was assumed to be produced in economic sectors for Power, Distribution, and Specialty Transformers, and Iron and Steel Forgings. The production emissions of the infrastructure were calculated over the functional unit.

Because there were no emissions from the TSE device, the factor that was evaluated for TSE use portion was the amount of electricity produced. Energy use data were located in an Argonne National Laboratory report. The data for carbon monoxide and NO_x emissions were calculated using factors found in Argonne's GREET model. The model showed that for each kWh of electricity produced, there would be a release of 1.37g NO_x, 0.1g CO, 0.01g VOC, 0.08g PM10, 0.003 g CH_4, and 665g of CO_2.

It was assumed that a truck would need 2.58kW of power to run the accessories regularly powered by idling an engine during an 8-hour resting period. This 2.58kW would be enough to run a block heater, sleeper lights, marker lights, and either the heat or the air conditioning[35]. When this was multiplied by the functional unit, it was determined that a truck would need 185,760kWh of electricity during its lifetime.

For this report, TSE and ATSE were assumed to use the same amount of electricity although ATSE had more electrical options. This assumption was made because the EPA estimated the same fee per hour for both TSE and ATSE.

3.4.4. Direct Fired Heater (DFH)

A 1990's D1LC model direct-fired heater provides cabin heating only, and would be used for half of the total required idling time over the functional unit. The remaining idled hours of the functional unit were calculated as idling the engine. The production portion of the heater life cycle was calculated using the Electric Housewares and Fans, and Petroleum Refining sectors of the economy.

The use portion of the DFH life cycle was calculated based on an experimental fuel consumption rate of 0.04 gallons per hour. It was assumed that the heater would be used for half of the functional unit (during winter months), while the engine was idled for the other half (during summer months), because of a lack of separate air conditioning units. However, such technologies are in progress.

3.5. Results

Figure 17 shows the results of the emissions of each technology during production and use portions of the lifecycle, compared to truck idling. For each type of pollutant, truck idling results in the most emissions.

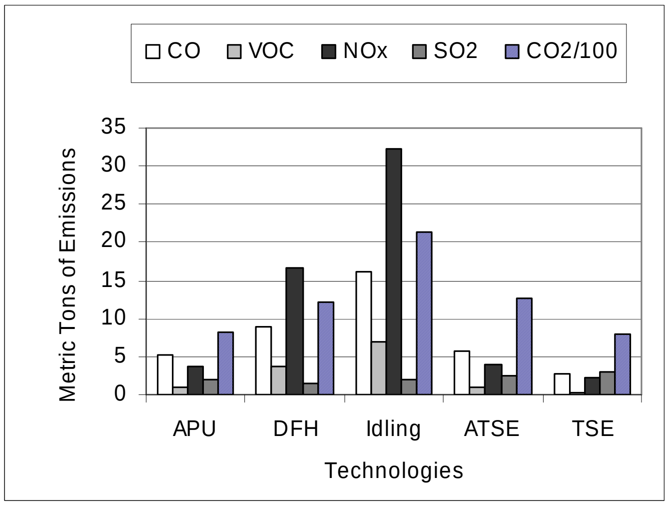

Figure 17: Total Criteria Pollutant Emissions from the Production and Use Portions of the LCA

As shown in Figure 17, the DFH results in the most emissions of the four alternatives to idling. This is due to the assumption that the DFH would be in use for half of the functional unit hours, while the remaining hours would be spent idling. The majority of the SO_2 emissions are a result of the production process of each technology and the required amount of petroleum refining.

3.5.1. Environmental Risk Analysis

There is no single methodology that has been universally accepted to estimate environmental risks. Therefore, many ecological impact methods have been found in literature. Furuholt presented two methods in his study.[23] One impact method was a relative scaling of the world total contribution of each impact category. Another impact method proposed by Furuholt was based on ecological scarcity, which gives different weights to the emissions from each country depending on their distance to set targets. Based on his results, it is evident that the relative ranking of each type of fuel is the same. Therefore, this report should be able to assess which technologies are best suited for use as an idling alternative.

A Tier 3 metrics or indexes, defined by Allen and Shonnard, was chosen to rank impacts for this LCA. This metric uses indexes for abiotic impacts, including smog formation, acid rain, ozone depletion, and global warming[36].

The general form of the environmental impact equation is the sum of the environmental risk index multiplied by the toxin emissions rate. The equation is as follows:

$$I = \sum_i (DimensionlessRiskIndex)_i \times m_i$$

where I is the impact and m_i the emissions rate in kg/hr.

The Ozone Depletion Potential (ODP) is the change of $[O_3]$ in stratospheric ozone caused by certain chemical releases, relative to the benchmark compound, trichlorofluoromethane (CFC-11). The chemicals found in diesel emissions that pertain to ODP are chlorofluorocarbons (CFCs). The average value for the ODP of CFCs is 1.0. To calculate the I_{OD} of each technology, the emissions rates were multiplied by the average ODP (1.0). The ozone depletion impact equation is as follows:

$$I_{OD} = \sum_i (ODP_i \times m_i)$$

Acid Rain Potential (ARP) is related to the number of moles of H^+ created by the release of a chemical, relative to the benchmark compound (SO_2). The diesel emissions that pertain to acid rain potential are SO_2 and NO_2. The ARP for each chemical was multiplied by the emissions rate of each chemical for each technology. The acid rain impact equation is as follows:

$$I_{AR} = \sum_i (ARP_i \times m)_i$$

Smog formation is the direct result of an increase in tropospheric ozone, which results from hydrocarbon and NO_x emissions. Photodissociation of NO_2 causes the O_3 concentration in the atmosphere (tropospheric ozone) to increase. The main component in smog formation is the ratio of reactive organic gases to NO_x. When NO_x concentration is high, tropospheric ozone most readily forms.

The maximum incremental reactivity scale of Carter was used to find the SFP for each pollutant and is given as follows[37]:

$$SFP_i = MIR_i \div MIR_{ROG}$$

where MIR_{ROG} is the average value for reactive organic gases. The MIRs for various hydrocarbons was reported, but diesel emissions contain mostly aromatic hydrocarbons[38]. To estimate the I_{SF} for each technology, an average aromatic hydrocarbon MIR was used (4.34) relative to the base reactive organic gas mixture (3.10). The I_{SF} was then multiplied by the hydrocarbon (HC) emissions rates.

$$I_{SF} = \sum (SFP_i \times m_i)$$

Global Warming Potential (GWP) is a commonly used index for global warming. The same procedure for the other impacts is used.

$$I_{GW} = \sum (GWP_i \times m_i)$$

Rabl used damage cost estimates to compare the emissions and impacts for the LCA of gas and diesel fueled buses. For impact assessment, Rabl used trajectory model software, EcoSense. The impacts were quantified using exposure-response functions, relating the emissions to human and ecological receptors, such as asthma, bronchitis, premature deaths, and crop damage. The sum of the impacts was compared as damage costs per kg pollutants. Dose-response function follows:

$$Y = f_{impact}(X)$$

where X is the quantity of the pollutant and Y is the physical impact on receptor.

Human and crop effects are not provided in this report because of the uncertainty of assumptions required for conducting an LCA. Human and other ecological impacts were provided in the source used to calculated the indexes, but different chemical isomers have different toxicities and the emissions data used for this report was not tested in such detail. Therefore, human and crop impacts would contain greater uncertainty, and it seems that ecological impacts used in this LCA are sufficient to compare the capabilities of the idling alternatives.

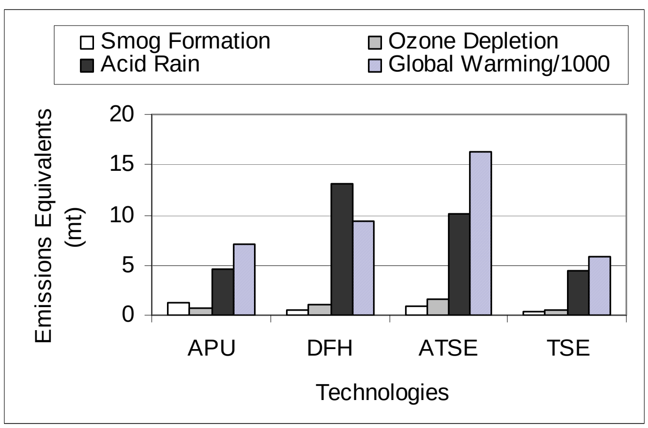

Figure 18: Ecological Impacts of Each Option

Figure 18 shows that the heater (DFU) results in the most overall ecological impact because of its use only during the winter months. However, the production emissions from the ATSE structure caused the ATSE units to have the second highest negative ecological impacts.

3.5.2. Economic Analysis

While the environmental impacts of idling need to be reduced, the economics of the situation must also be considered. If the technologies are exceedingly expensive, the drivers and trucking companies will be unlikely to use them. Therefore, two types of economic analysis have been conducted.

3.5.2.1. Payback Period

The payback period of a product is the amount of time it would take the purchaser to make back the amount of money spent on the product. In order for the option to be economical for the truck owners, the payback period must be less than three years. This value was assumed since most fleets replace trucks after approximately three to four years. In order to assess savings associated with each option, the amount of money a driver is saving on fuel and maintenance was calculated. The amount of money saved on fuel was calculated from the gallons of fuel saved each year, and the current average price of diesel fuel, at $1.50 per gallon. The EPA estimates that engine idling accounts for $0.72 per day of maintenance and $4.41 per day in oil and filter changes[39]. The overall maintenance and wear savings were then calculated for the functional unit. The payback period is the ratio of the amount of money spent on the unit to the amount of money saved.

The EPA reported the cost of the Espar DFH and installation to be $2,000 per unit. The associated maintenance and wear savings for using the Espar heater for three years are relatively low because the heater would be used as an alternative to half of the idling (150 hours per year). The remaining hours would be spent idling the engine. The payback period for the heater is shown in Table 14.

The cost of a Pony Pack APU is $7,000, so the payback period for this option is the amount of time it will take the driver to save $7,000 on fuel and maintenance. According to the EPA's research of available technologies, the Pony Pack requires maintenance every 150 in-use hours, which results in $1,339 per year per truck. The payback period for the Pony Pack is shown in Table 14.

There are two payback periods for ATSE. One is for the truck driver, whose costs include a window adapter and the cost of technology use, per hour. The other payback period is for the truck-stop, which installs the HVAC units and pays for the required electricity. The truck charges will include a $10 adapter to be added to the window of the truck and will include a payment to the truck-stop per hour for the electricity. For this analysis the assumed price will be $1.25 per hour (for fleets with contracts), provided by IdleAire[40].

The payback period for the owner of the truck stop is also important when looking at this type of system. The owner of the truck stop will pay approximately $10,000 per spot plus the cost of electricity. This average price of electricity for highway electricity for 2002 was approximately $0.16 per kWh[41]. It is assumed in this paper that a truck would need 2.58 kW of power to run the accessories that are normally powered by an idling engine. Since the ATSE unit is capable of supplying Internet and telephone access, the kWh requirements will fluctuate depending on the accessories used by the driver, which was not accounted for in this analysis. The corresponding payback periods are shown in Table 14.

For the truck driver, TSE is more costly than ATSE technology. However, TSE is less expensive than ATSE for the truck stop owner. This is because the driver is required to purchase the power inverter for the truck for TSE technology. The price of having a power inverter in truck is $2500. The additional engine load effects as a result of added weight were not taken into consideration, and more research must be done to quantify the effects for all technologies. The corresponding payback periods are shown in Table 14.

Table 14: Costs and Savings (over a Three Year Period) for Each Technology.

	Initial Costs	Savings / Profit	Payback (years)
DFH	$60,000	$59,670	3.02
APU	$210,000	$295,590	2.13
ATSE- Truck	$90,300	$324,810	0.83
ATSE- Rest Area	$329,722	$90,000 Profit	3.66
TSE- Truck	$165,000	$324,810	1.53
TSE- Rest Area	$104,722	$90,000 Profit	1.16

Table 14 shows the initial costs, including installation, and the maintenance and wear savings associated with using each option. Overall, each option has a low payback period and all options will payback the driver in approximately one year. The payback periods are low due to the significant amount of wasted fuel and increased engine wear and maintenance associated with truck idling. For both types of electrification, the driver would be charged an hourly fee for the use of the technology, assumed to be equal for both types of electrification, regardless of the amount of kWh required for additional accessories. Also shown in Table 14, ATSE charges for the stop owner results in the longest payback period. This is due to the high cost of 30 ATSE units. In the previous emissions analysis, although ATSE would be an extremely costly option, ATSE showed dramatic decreases in overall emissions. Therefore, the emissions savings associated with each option must be compared to the overall costs and savings.

3.5.2.2. Net Present Value

A more accurate method of economic analysis is to perform a net present value (NPV) cost calculation. This approach takes into account the time value of money. The value of each dollar spent in the future is less than the value of a dollar spent today. This type of assessment favors spending money over time and in the future, rather than up front. With this type of calculation, the best economic option is that which reduces the net present value cost at the end of the time period being examined. The interest rate for this calculation was assumed to be 5% annually. Obviously, the results of each of these analyses are highly dependent on the current price of diesel fuel. The graph below shows the net present value of the cost of each option vs. the cost of diesel fuel. The graph shows how the net present costs will compare as the price of diesel fuel changes. The equation used for NPV is as follows:

$$NPV = TC \div (1.05^3)$$

where 1.05 represents 5% interest, TC the total cost, and 3 a period of 3 years.

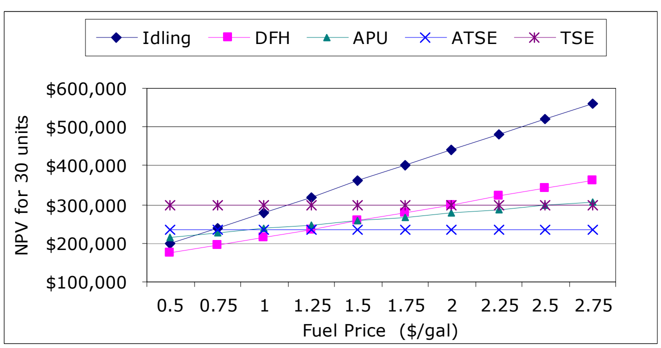

Figure 19: NPV of Each Option

Figure 19 shows that ATSE is the most economical option for the truck driver when the cost of fuel is above $1.25 per gallon. The NPV analysis does not include increases in costs per kWh because the truck owners were assumed to charge a consistent fee per hour of truck use. If the analysis were repeated with respect to costs to the stop owners, the results would be different due to fluctuations in kWh requirements and costs. However, the costs of the other technologies would not affect truck stop owners so their cost analysis was not factored into the NPV evaluation.

3.5.2.3. Emissions Savings Per Cost of Technology

In order to make a conclusion about the best option to reduce truck idling, the emissions savings per dollar must be evaluated. The NPV cost associated with the purchase of 30 units over a three-year time period at $1.50 per gallon was determined. This type of analysis is highly dependent on the price of fuel, which fluctuates regularly. However, $1.50 per gallon was used to show the methodology and a relative emissions savings, in kilograms, per cost analysis for each option. The emissions savings were calculated by subtracting the total emissions for each technology for three years from the total emissions from truck idling. The approximate results for the emissions are shown in Figure 20.

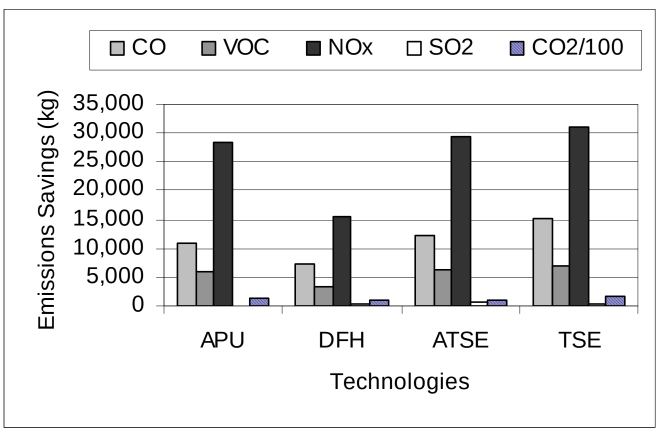

Figure 20: Emissions Savings in Kilograms for Each Option for Three Years

Figure 20 shows the emissions savings in kilograms for the production and use of each technology for a three-year time period. This table shows that TSE reduces emissions most significantly. The emissions savings were then divided by the NPV for three-years for each option at a fuel cost of $1.50 per gallon. The results are shown in Figure 21.

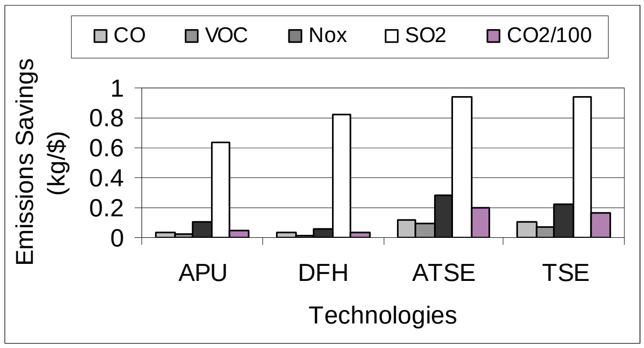

Figure 21: Emissions Savings per Dollar in kg/$, Based on Driver Costs

The results in Figure 21 show that ATSE reduces the most emissions per dollar spent by the truck driver, based on a hourly fee of $1.25 per hour. If this fee was increased by the rest area, TSE would surpass ATSE in emissions savings per dollar. The third best option based on savings per dollar would be Pony Pack, based on 30 unit retrofit and a fuel price of $1.50 per gallon. To date, DFH shows the lowest emissions reduction per dollar because there is currently no available independent cabin air conditioner. Once such a technology is produced, the Espar heater could be reevaluated for economic feasibility.

3.6. Conclusions

Idling HDDVs cause damage to the environment through excessive fuel consumption and emissions. It has been shown that of four evaluated technologies, Truck Stop Electrification and Advanced Truck Stop Electrification would be the best alternatives to idling. This is because electrification minimizes petroleum use, emissions of greenhouse gases, and emissions of CO, CO_2 and NO_x. TSE had the lowest ecological impacts and least amount of total emissions throughout the lifecycle. Due to additional materials production and increased electrical options, ATSE emissions and costs exceed those of TSE throughout the life cycle. However, the added options of ATSE causes additional production processing and energy use, resulting in increased environmental burdens throughout the life cycle. The Pony Pack APU showed considerable reductions in emissions and costs for the drivers. Since the APU is a more efficient diesel engine for idling, the fuel consumption rate is lower than idling the engine, and the emissions and ecological burdens are lowered as a result. Also, the APU proved to be the second most economical option, at a fuel price of $1.50 per gallon and above, by evaluating the net present value of each technology. However, the amount of emissions lowered due to the implementation of 30 APUs for three years is less efficient than both ATSE and TSE. This technology has been proven to be effective, and would benefit a fleet of trucks and its drivers. The Espar DFH alone did not show drastic improvement in idling emissions since the D1LC model provides only cabin heat during winter months. The technology did show emissions reductions and was determined to be most economical at a fuel price of $1.25 per gallon and below. Also, when comparing the overall emissions savings per dollar (at a fuel price of $1.50 per gallon), the DFH was least effective, but the APU only saved 24% more. Coupled with an air conditioner, the DFH would most likely surpass the APU in emissions reduction and economics.

By evaluating the emissions reduction and economic analysis for the driver and the rest area, the implementation of TSE would most benefit the state and the drivers in which the electrification structures were located.

4. Steady State Particulate Exposure Levels in a 1992 International School Bus

4.1. Introduction

The concentrations of breathable particles that can enter the cabin of a school bus have been an issue of public concern for some time. The purpose of this experiment is to methodically quantify particulate levels and determine factors that impact particulate levels in a 1992 International school bus. The test bus was instrumented and principles of experimental design were used to create a test for the steady state mobile testing of particulate matter. Three variables were studied: speed, window position and load. A Box-Behnken experimental design[42] was used to construct the experimental conditions space and set the levels of the tested variables. The particles inside the school bus were measured using the Dataram4 instrument with a pre-collector to remove particles greater than 2.5μm.

4.1.1. Particulates

In diesel engines, high temperatures and non-stoichiometric oxygen conditions result in incompletely burned fuel, and various concentrations of exhaust by-products, including carbon monoxide (CO), volatile hydrocarbons (HC), and particulates largely of carbon composition[43]. These particulates consist of elemental carbon (EC), organic carbon (OC), metals from fuel and engines wear, and sulfates with bound water. [44,45] The National Ambient Air Quality Standard (NAAQS) for particulates are divided into two size groupings. For particulate matter 10 μm and smaller the NAAQS annual average is 50 $\mu g/m^3$ and the 24 hour average is 150 $\mu g/m^3$. For particulate matter 2.5 μm and smaller the NAAQS annual average is 15 $\mu g/m^3$ and the 24 hour average is 65 $\mu g/m^3$. The reported values for particulates in Harford County, measured at the Edgewood Army

Base, for 2002 are 12.5 and 29 μg/m^3 for the 24 hr average maximum and annual averages.[46]

4.1.2. Health Effects

The effects of particulate matter on the human respiratory system are largely postulated. Although independent studies show a greatly increased risk in animal exposure studies, the EPA (Environmental Protection Agency) finds these cancer studies, “not clear for human hazard prediction.”[47] As long term studies on humans have not been conducted, an actual health risk figure is difficult to assess. However, diesel exhaust, as classified by the EPA, in its official statement, is "likely to be carcinogenic.” While only independent studies, and non-government organizations will assess a value to the cancer risk, the EPA and OSHA (Department of Labor Occupational Health and Safety Administration) alike recognize other more minor deleterious health effects ranging from headaches and nausea, to exacerbated preexisting respiratory conditions like asthma[48]. Children and elderly are especially at risk. According to a study by the NRDC (National Resources Defense Council) exposures to diesel exhaust particulates can cause as high as a 50% increase in lung cancer risk.[49]

4.2. Literature Review

While emissions standards have been evolving over the last several decades on gasoline-powered cars, comparable standards for Heavy Duty Diesel will be begin to take force in 2007 when stricter limits will be placed on emissions of hydrocarbons (HC), oxides of nitrogen (NO_X) and Particulate Matter (PM)[50] have been significantly reduced. However, potentially harmful PM is not only emitted by large trucks transporting goods, but also by school buses transporting children. Several reports have been published on studies conducted to assess the level of PM that children breathe riding in school buses, the most notable of which was *No Breathing in the Aisles*, by the NRDC. [49]

4.2.1. NRDC Study

Using a rented school bus currently in use to transport students in the Los Angeles area, the NRDC, a group of California doctors, and U.C. Berkeley Professors drove actual school bus routes. All measurements were taken with the DataRAM instruments Real-Times Aerosol Monitor and the Aethalometer Real-Time Aerosol Analyzer from Andersen Instruments.[49] The Aethalometer uses an optical transmission technique to measure particle concentration that is collected into its filtration system via a continuously drawn sample of air. This data is collected and displayed in near real time, reporting levels of carbon black in one-minute averages. The DataRAM, a two-wavelength nephelometer, measures the intensity of the light it emits and the intensity of diffracted light, which varies as it is deflected by particles drawn through the sensing region of the apparatus.[51] The intensity of the light is directly proportional to the amount of particulate passing through the sample cell. An impactor attachment on the DataRAM prevents particles less than 2.5μm from entering the detection chamber. Samples were taken inside the passenger compartment of the bus at both the back and front.[52] Additionally, measurements were taken in a car following the bus, noting varying levels of PM as a result of several factors including road grade, engine speed, and window position within the bus.

The study found that in the back of the bus with the windows closed the average exposure to diesel exhaust was 4 times greater compared to a passenger car immediately ahead of the same bus. The average exposure levels in the bus were between one and 14 micrograms per cubic meter (μg/m^3). This was more than the exposure the same child would get from walking or riding in a car on those same streets. Indeed, the California Air Resources Board estimated that the average outdoor concentration of diesel exhaust in California in 1995 was 2.2 μg/m^3. Thus, for the time a child is in a school bus, his or her exposure to diesel exhaust may be up to 8-1/2 times the average statewide air levels.[52]

While these conclusions were alarming to the public, the scientific community did not receive the study without skepticism. In fact, much of the study was considered unsubstantiated, and unfounded in scientific data. As a result, criticisms were published including the California Critique.

The California Critique questioned several aspects of the study.[52] In general, the NRDC report did not contain enough actual data from its study to make reasonable scientific claims as to the diesel exhaust present in the bus.

4.2.2. Connecticut Study

A study conducted by Yale University in Connecticut tracked the activity of 15 students from the time they left their home in the morning until the time they returned in the afternoon.[53] The students, each accompanied by a research assistant to assure proper device operation, wore 2 aethelometers to measure real-time airborne particulate, one from Magee Scientific Co and the other a personal DataRAM from MIE Inc measuring particles 2.5μm in diameter and smaller.

The study noted that diesel exhaust may enter the bus interior through an unsealed engine compartment, leaking exhaust systems, through windows and doors, and through unfiltered air and heating vents. With the windows open, more exhaust entered the bus.

Also, traveling behind another bus and idling at a bus stop cause a rise in levels.

The findings of the study were similar to those of the NRDC study. During 7 of the 27 experimental school bus runs, particulate levels in the bus where the students were riding exceeded 100 $\mu g/m^3$, as much as 10-15 times the levels in the Connecticut air to which they compared.

While the Connecticut study made no attempt to assess cancer risk, it did however relate some of the specific components in Diesel Particulate to a cancer risk. Benzene, 1,3-butadiene, soot, formaldehyde, are all know or suspected carcinogens, and according to the Connecticut study, present in diesel particulate matter.

4.2.3. Fairfax County Public School Bus Study

Fairfax County Public School District conducted a study to look at the concentration of PM in school buses. Twelve buses from the schools fleet were tested for the presence of diesel exhaust, by measuring the respirable particles, the organic carbon, and the elemental carbon inside the school buses. 10 of the 12 buses were fueled with diesel fuel, 1 used compressed natural gas, while one bus used both CNG and diesel fuel. The buses ranged in model year from 1987 to 2001. The samples were collected using a battery powered pump, with a 37mm PVC filter for respirable dust and a 37 mm quartz fiber filter for elemental and organic carbon. Each of the buses tested were driven on the same 19.9-mile route, with simulated bus stops. The analyses of the filters were performed by an independent laboratory following NIOSH 0600 and NIOSH 5040 standards. The study concluded that the concentration of respirable particles was not related to the concentration of elemental carbon or organic carbon in the air inside the bus. Furthermore, there was no age related difference in the bus cabin air quality.[54]

However, for several of the runs the quantities of elemental carbon were below the detection limit of 0.0041 mg/m^3 thus making it difficult to determine trends in the data.

4.3. Experimental Setup

4.3.1. Testing Plan

While the previous studies indicate increased levels of PM within the school bus interior, they do not address the factors which contribute to increased or decreased particulate level such as engine load, vehicle speed and ventilation of the interior. Accordingly, the present study attempts to utilize the techniques of experimental design to begin to address these factors. The main objective of the experimental design in this study was to obtain the maximum information from the minimum number of experiments.

Experimental design techniques are widely recognized to have many advantages over standard experimentation.[42] Experimental conditions that involve variation of more than one variable at a time to form an experimental conditions space are identified. Then the variable of interest is measured at these experimental conditions. The data are analyzed simultaneously using standard data analysis techniques.

To create a two-level factorial design, the building block of a Box-Behnken design, each factor is first determined to have a high and a low value. In this experiment the factors are speed, load, and window position. The high and low values for bus speed are 55 and 5 mph respectively. A table is created in which each factor is a column in the table. The first column (speed) is ordered by alternating high and low values as can be seen in Table 15. The second column (load) varies the high and low values in pairs. Each row of variables sets the conditions of one experiment.

Table 15: A 2-Level Factorial

Run Number	Speed Mph	Load
1	5	Flat Road
2	55	Flat Road
3	5	1.33% Grade
4	55	1.33% Grade

The Box-Behnken method expands on the two-level factorial designs, by introducing a third "middle" condition, or center point, to each factor. This design method then creates the test matrix by constructing 2-level factorials, while holding all other factors at their center points. This can be seen by the following shaded areas in Table 16. The center points represent the condition where all of the controlled variables are held in their middle values.

Table 16: Construction of a Box-Behnken Matrix

Run Number	Speed Mph	Load	Windows
1	5	Flat Road	1/2 open
2	55	Flat Road	1/2 open
3	5	1.33% Grade	1/2 open
4	55	1.33% Grade	1/2 open
5	5	0.67% Grade	All Closed
6	55	0.67% Grade	All Closed
7	5	0.67% Grade	All Open
8	55	0.67% Grade	All Open
9	30	Flat Road	All Closed
10	30	1.33% Grade	All Closed
11	30	Flat Road	All Open
12	30	1.33% Grade	All Open

Box and Behnken arrived at an efficient approach for studying the effects of three variables at three levels. Box-Behnken designs are described as rotatable, this is due to symmetry around the center point. Each point is equidistant from the center so that variance only depends on distance and not direction. When all points have the same radial distance from the center point they have the same magnitude of prediction error.[42]

This particular Box-Behnken design makes use of three 2^2 factorial designs, within each the remaining factor is held constant at its center point. Each 2^2 factorial can be visualized as below in Figure 22. The design creates three orthogonal two-dimensional planes within the experimental space known as blocks.

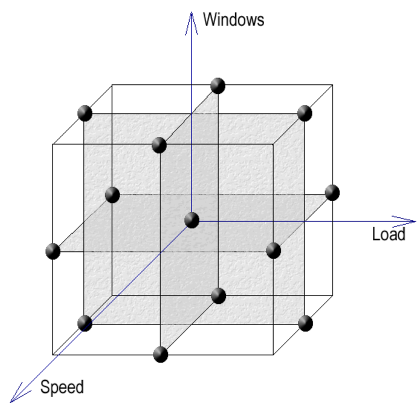

Figure 22: Experimental Design Space Indicating Separate Factorials

Upon inspection of the experimental spaces, it is apparent that due to the location of the treatment points (at the center of each edge of the experimental space) that the maximum or minimum conditions do not occur for all variables during any one treatment condition. This can make a conventional one factor at a time analysis difficult to perform. This paper will focus on using ANOVA techniques to extract the variation attributed to each variable independently from the other variables.

The first block can be constructed by holding the windows variable at its center point, which has been encoded as zero. The center point of the windows variable corresponds to all windows in the half open position. This results in the experimental space depicted in Figure 23.

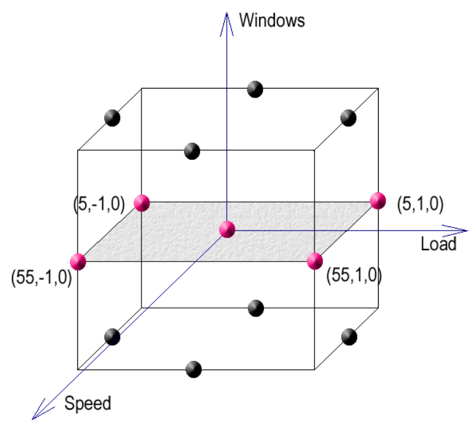

Figure 23: Resulting Factorial with the Variable Windows Held at its Center Point

Analysis of variance or ANOVA is a method to analyze means by using variances, and allows all the groups of data collected to be compared at the same time.[42]

Table 17: Run Order of Particulate Testing

Speed MPH	**Load % Grade**	**Windows Position**
30	0	Closed
30	0.66	1/2 open
30	0.66	1/2 open
Idle	0	Open
55	0	1/2 open
30	1.33	Open
5	1.33	1/2 open
30	0.66	1/2 open
55	1.33	1/2 open
55	0.66	Closed
55	0.66	Open
5	0.66	Open
55	0.66	Closed
30	0	Closed

Speed MPH	**Load % Grade**	**Windows Position**
5	0	1/2 open
5	0.66	Closed
30	0	Open
Idle	0	Closed
Idle	0	1/2 open
30	1.33	Closed
Idle	0	Open
30	0.66	1/2 open
30	0	Closed
30	0	Open
30	0.66	1/2 open
30	0.66	1/2 open
30	0.66	1/2 open
30	0.66	1/2 open
30	0.66	Closed
5	1.33	Closed
55	1.33	Closed
5	0	Closed
55	0	Closed
30	0.66	1/2 open

4.3.2. Equipment

The DataRAM 4, portable Real-Times Aerosol Monitor, is a two-wavelength nephelometer.[51] Using a diaphragm pump to draw air at a constant rate, sample air is pulled though an inertial coarse-particle pre-collector, or impactor, which removes particles typically larger than 2.5µm. As a result the DataRAM counts only particles 2.5µm or less since larger particles are excluded. The sample air is then drawn through the air duct where the beam from two light sources, 660 nanometers and 880 nanometers, emit alternately switching 27 times per second. The light is collected by two separate detectors operating alternately, in sync with the light sources. The detectors measure the intensity of the light, which varies depending on the deflection that occurs in the air duct sensing region. The intensity of the light is directly proportional to the amount of particulates passing through the air duct, based on the assumption that particle size and distribution remain constant. The DataRAM incorporates two wavelengths to distinguish particle size to correct for the constant particle size assumption. The data is reported and stored in real time in its internal computer for later downloading and analysis.

The DataRAM units were placed in the front, middle, and back of the bus. The front unit was placed on the front passenger seat centered from side to side. The impactor attachment and omni-directional probe put the sampling height just below the top of the seat back. The middle and back units were placed in a similar manner, with the back unit on the rear seat of the bus and the middle unit equidistant between the front and back.

The PM 300 is a portable particulate analyzer, which uses a light scattering technology to count particles[55]. A semiconductor-laser emits a beam of light through the air sample, which is carried via a heated hose to carefully control humidity and temperature and then diluted to a ratio of 1000:1, 2000:1, 5000:1, or 10,000:1, depending on the particle sizes being measured. The light is then detected by a photo diode at approximately 90° by way of mirror that is interrupted by passing particles. Each particle creates a pulse in the beam, which is directly proportional to its size. This signal is then classified into size categories and electronically stored. The PM 300 also collects the particulate on a PTFE filter that can be removed for analysis.

To assure that the bus was reaching the steady state conditions, the bus was instrumented and data was collected at a 10 Hz rate. The vehicle’s ground speed, engine torque, exhaust manifold pressure, intake air humidity and temperature, fuel temperature, three exhaust temperatures, engine oil temperature, and the fuel flow rate were measured and recorded using a ADOCS data bus system.

Table 17 shows the testing that was conducted on the 1992 International School Bus. The final test matrix includes the Box-Behnken matrix, 9 replicates of the center point (30, 0.67, ½ open), repeats of the other 30 mph conditions, a repeat of a randomly chosen 55 mph condition and of an idling condition.

4.4. Results

An average from each of the runs was computed after removing the outliers. The averages then had the background concentration subtracted to remove any effect that the background air particle concentrations had on the results. The background measurement was taken inside the engine compartment near the intake into the engine. Statistical calculations were made using the Statgraphics software package. An analysis of variance was performed on the instantaneous values recorded at the three locations inside the cabin of the bus. ANOVA results at the 95% confidence level indicated that bus speed, window location and load had a significant effect on the particle concentration in the bus (p values < 0.05). The duration of the experimental run did not have a significant effect on the particle concentration in the bus at the 95% confidence level (p = 1). This confirmed steady state operation during the tests. When an ANOVA was performed on the computed averages of the variables speed, windows and the interaction between speed and windows were found to be significant at the 95% confidence interval with p-values 0.0000, 0.0398, 0.0001 respectively. To compute the steady state averages several steps were taken. First, the statistical outliers from the data sets were removed. The outliers were determined to be any data points that were outside the range of the mean plus or minus 1.5 times the inter-quartile range of the data for a selected run.[42] Then the average background concentration was removed from the mean of the outlier free data. The background concentration was measured at the air intake to the engine. To verify that this measurement was an accurate representation of the background concentration, a DataRAM unit was placed off to the side of the test track during one day of testing. Figure 24 is a comparison of the unit placed from the side of the track to the unit in the engine compartment measuring the background concentration.

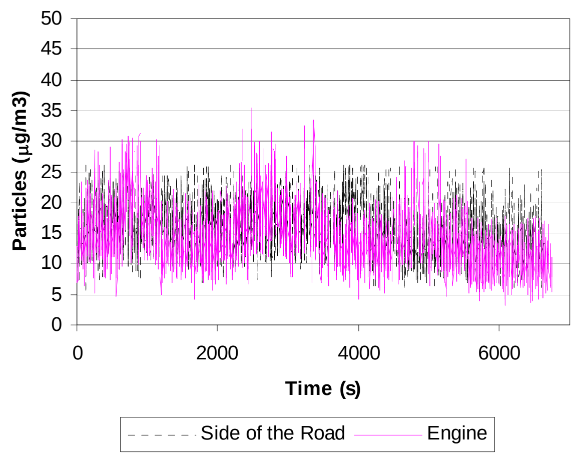

Figure 24: Comparison of Ambient Particulate Measurement to the Engine Compartment Air Intake Measurement

The effect of each variable on the particle concentrations in the bus was analyzed to ascertain the range of particle concentrations measured during the test independently from the other variables introduced.

4.4.1. Bus Speed

The speed was set at four constant velocity levels: 0, 5, 30 and 55 MPH. To analyze the data collected by the four DataRAM units several steps were taken. After the outliers were removed, several statistical parameters were calculated. Included in this analysis was a test for skewness and kurtosis. The skewness and kurtosis of the data with outliers removed is used as an indicator of data normality (parametric). Data normality is a requirement for the proper use of standard deviation as a measure of experimental error.[42] The data collected by the DataRAM units placed inside the school bus, showed standardized skewness outside the acceptable range (-2 to +2) to assume that the data is normal. Figure 25 shows the standardized skewness for each of the runs at each location of measurement performed during the study.

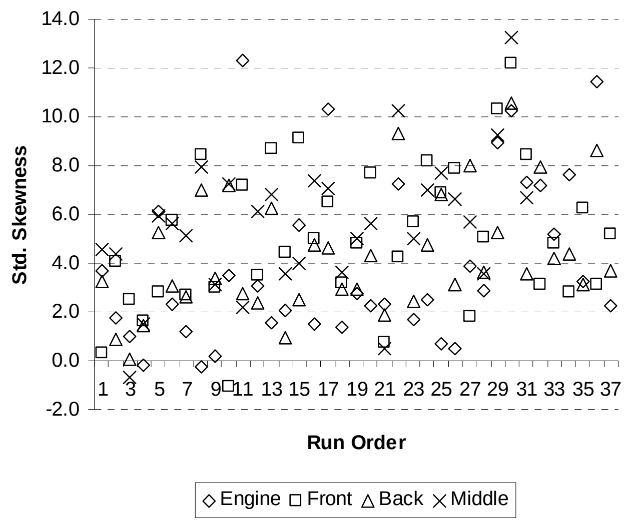

Figure 25: Standardized Skewness of Average Concentrations at Each Measurement Location in the Bus

The positive skewness seen in the data is believed to be a result of the method that the DataRAM uses to measure particles. To test this assumption one of the units was placed in an isolated room and the data recorded also showed positive skewness. Figure 26 shows the continuous data from one of the DataRAM units placed in an isolated laboratory. The unit had occasional increased spikes of particle concentration, but because the unit did not have corresponding decreased spikes the calculated standardized skewness is outside the excepted -2 to +2 range for the assumption of normally distributed data.

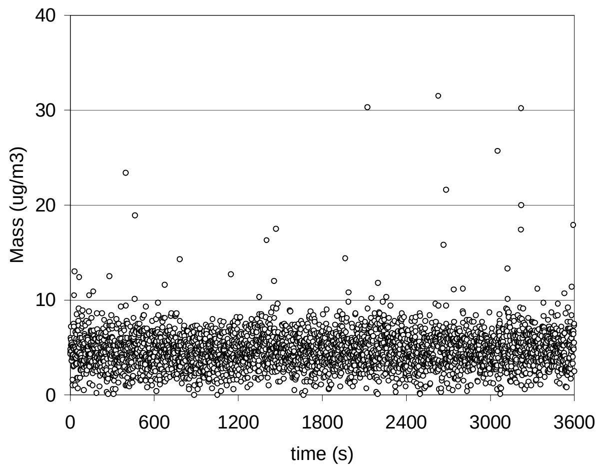

Figure 26: Example Data of a DataRAM Unit Placed in an Isolated Room

To show that the results of the test were insensitive to the data's non-parametric nature and that a steady state average could be used in the analysis, several statistical techniques were implemented. An ANOVA was performed on the instantaneous data recorded by the DataRAM units. As part of the ANOVA a multiple range test was performed on the variable speed. The Newman-Keuls LS mean was calculated for the speed conditions of 5, 30, and 55 mph. The Newman-Keuls method[42] is especially useful in non-parametric applications and was selected for this work. This test was performed at a 95% confidence interval, using this method there is a 5% risk of calling one or more pairs of data significantly different when they are in fact not. The test showed that there were three homogeneous groups and that there was a statistically significant difference between the 5, 30, 55 mph conditions independent of the other variables. When a multiple range test was performed on the steady state averages the same conclusion was reached. Figure 27 shows the mean concentrations represented in $\mu g/m^3$, and 95% confidence intervals for the instantaneous data set of each speed independent of the other variables without the average background concentrations removed.

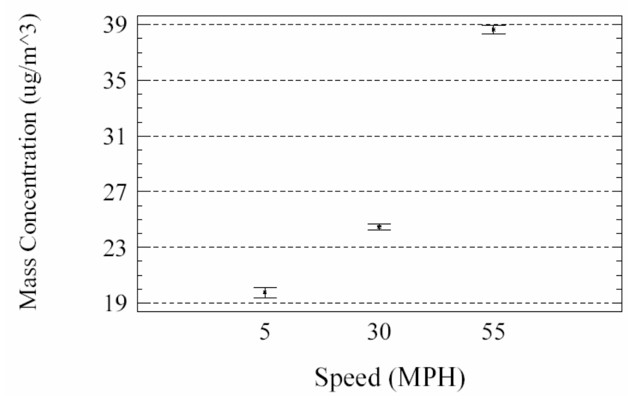

Figure 27: Mean Values and 95% Confidence Intervals for the Effect of Speed on Particle Mass Concentration Independent of Other Variables Based on Instantaneous Data Set

Figure 28 shows the effect of speed independent of all other variables for the calculated steady state averages for the entire test matrix. The figure shows that as the speed of the bus increased the number of particles inside the bus also increased.

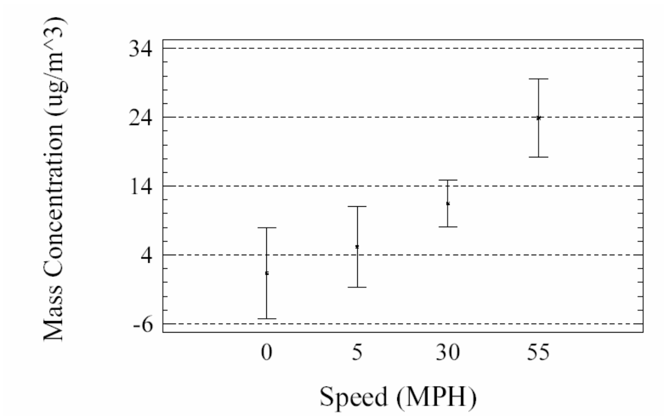

Figure 28: Mean Values and 95% Confidence Intervals for the Effect of Speed on Particle Mass Concentration for the Background Removed Steady State Averages

The PM-300 measuring the tailpipe emissions, groups the particles that it measures into 8 size bins. When an ANOVA was performed on each of the 8 size bins it concluded the at the 95% confidence interval that speed was the only factor that had a significant effect on the number of particles generated at the tailpipe, it was computed to be significant for all the bins except the bin measuring the largest particles (>2.5um). For that bin none of the tested variables were determined to be significant.

4.4.2. Windows

Using the same method that was used to analyze the speed data, the factor of windows was tested for significant effects on the concentration of particles inside the bus. When the computed averages were analyzed it was shown that windows had a significant effect on the particle concentration. Figure 29 shows the means and 95% confidence intervals for the computed averages of data for the different windows conditions.

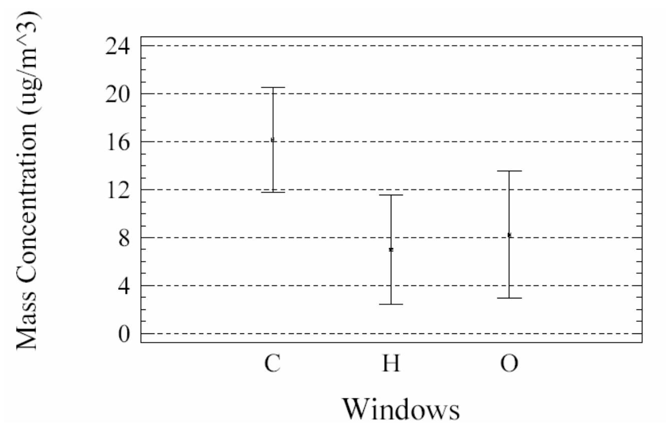

Figure 29: Mean Values and 95% Confidence Intervals for the Effect of Windows on the Background Removed Particulate Mass Concentration. (-1 = All Windows Closed, 0 = All Windows 1/2 Open, 1 = All Windows Open)

When the windows were closed the levels were the highest, while the open and ½ open conditions were similar. A multiple range test, an ANOVA tool to compare means of each level within a single variable, showed that there was a significant difference from closed to open and from closed to ½ open, but at the 95% confidence interval there was not a significant difference between the ½ open and open conditions. A Friedman ANOVA was also performed on the steady state averages to measure the effect of windows. Friedman ANOVA was chosen because its system of ranking the results allows for data comparison independent of the normality of the data. The Friedman statistic of 7.609 indicates at the 95% confidence interval that there was a statistically significant difference in the concentration inside the bus as a result of changing the window positions. Further the mean ranks calculated during the Friedman analysis indicate that the closed condition had higher concentrations than the half open and full open conditions. The difference in the particle concentrations with the windows in the half and full open positions was small. The limitations of the Friedman ANOVA prevent determining if the half open or full open condition was higher in particle concentration than the other.

It was also seen in studying the 2 factor interactions using the multifactor ANOVA that there is a statistically significant interaction between window position and speed. Figure 30 shows a plot demonstrating the effect that the window position and vehicle speed interaction had on the particulate concentration inside of the school bus.

Figure 30 shows a plot demonstrating the effect that the window position and vehicle speed interaction had on the particulate concentration had inside of the school bus, at idle and low speed with the windows closed the concentration of particles was lower than with the windows open. As the speed increased the concentration of particles inside the bus was greater with the windows closed than with the windows open all the way or half way. The half open and all open conditions follow similar trends. This analysis was performed with the computed steady state averages and includes the removal of background concentration; at idle with the windows closed the negative concentrations indicate that the concentrations inside the bus were lower than the background measurement taken at the air intake.

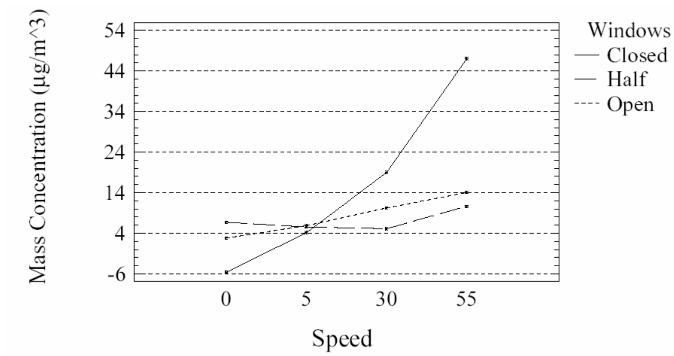

Figure 30: Interaction Plot of the Effect of Window Position and Speed on the Background Removed Particulate Mass Concentration

4.4.3. Load

The variable load did not have a significant effect of the results collected during the test. At the time of experimentation the decision was made to vary the simulated road grade rather than a percent load on the engine. The highest simulated road grade that the bus could maintain at 55mph was 1.67%. An analysis of the PM300 data indicated that a 1.67% grade did not have a significant effect on the concentration of particles measured at the tailpipe. Further analysis of the particulate concentration inside the bus also indicates that the load did not have an effect on the particle concentration inside the bus for the range of loads applied.

4.4.4. Location

Similar to speed and windows, the variable location was tested using analysis of variance. When both the instantaneous and computed steady state data sets were analyzed the variable location had p-values indicating that location had a significant effect on the particle concentration at the 95% confidence interval. Figure 31 is a plot showing the effect of location on particle mass concentration for the computed averages. Additionally, Figure 31 shows that the back and front of the bus showed very similar mean concentrations, and as verified by a multiple range test are from the same homogenous group at the 95% confidence interval. The middle location indicated lower particle concentrations than the other two locations.

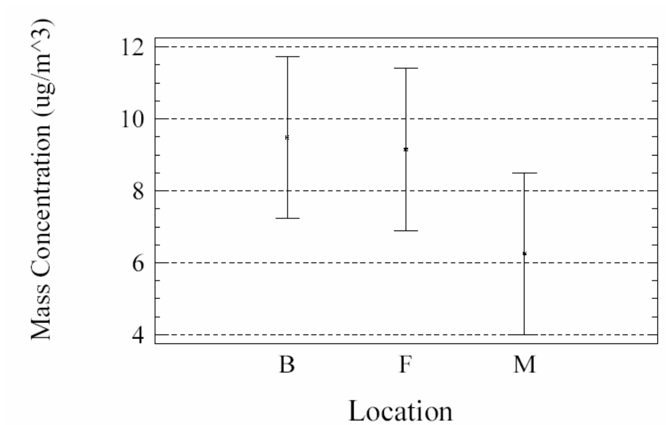

Figure 31: Mean Values and 95% Confidence Intervals for Location Effect on the Background Removed Particle Concentration Inside the School Bus (B= back, F= front, M=middle)

This result is not consistent with previous studies, showing that there was not variation in particle concentration throughout the bus.[49,52] A Friedman ANOVA was performed to elucidate the source of the inconsistency. The Friedman statistic of 0.2857 indicates that there is not a significant difference between the measurement locations inside the bus. The Friedman ANOVA, while providing less information, is insensitive to non-parametric data. Based on the results from the Friedman ANOVA it can be concluded that the location did not have an effect on the particulate inside the bus.

4.5. Conclusions

By calculating the expected mean squares based on the ANOVA calculations for the computed averages data, Table 18 shows the percentage of variation that each significant factor had on the total variation recorded during the tests.

Table 18: Expected Mean Squares Represented as Percentage of Total Test Variation

Factor	Percentage of Variation
Speed	52.8%
Windows	14.2%
Speed and Windows	28.1%
Residual	4.9%

At the 95% confidence interval 95.1% of the variation in the data can be attributed to the variables of speed and window position. 4.9% of the variation in the data is attributed to the residuals. Residuals are the random experimental error present in all experimentation. More than 95% of the variation in the concentrations of particles in the bus can be statistically attributed to the experimental variables.

The bus speed had the largest impact on the particle concentration in the bus. The speed was the only factor that affected the particulate concentration measured at the tailpipe.

As the speed increased from idle to 55 mph independent of the other factors the mean particle concentration inside the school bus ranged from 2.0$\mu g/m^3$ to 24.0$\mu g/m^3$ greater than the background concentration measured during the tests.

Independent of the other factors, when the windows were closed the particle concentration averaged 16$\mu g/m^3$ higher than the background concentration. When the windows were in the half open or full open position the concentration of particles measured an average of 8$\mu g/m^3$ greater than the background concentration measured at the engine air intake.

There was an interaction between the window position and the speed at which the bus was driving. At idle the concentration inside the bus was lower then the background concentration when the windows were closed. With the windows in the full open position the average concentration of particles was 4μg/m^3 higher than the background measurement. When the windows were half open the average concentration at idle was 8μg/m^3 higher than the background measurement.

At 5 MPH all three window positions had similar particulate concentrations averaging between 4 and 6 μg/m^3 higher than the background measurement. At 30 MPH the half open was the lowest at 6 μg/m^3, while the open increased slightly to 10 μg/m^3 higher than the background concentration. The closed position increased more than the open conditions to 20 μg/m^3 higher than the background measurement. At 55 MPH the closed window position reached the highest calculated average with the concentration of particles approaching 48 μg/m^3 greater than the background. The half open and full open positions average at 14 and 10 μg/m^3 higher than the background respectively.

5. Tailpipe Emissions from Diesel School Buses

5.1. Introduction

This section presents results of an experimental study aimed at evaluating emission reduction strategies for diesel powered school buses. Three school buses, which were purchased by NJDOT, were instrumented and tested at the U.S. Army Aberdeen Test Center (ATC). The most advanced mobile emission measurement equipment was purchased to measure the harmful emission levels from the school buses. The school buses were tested using a mobile test cycle, developed as part of the study.

There is currently a lack of mobile testing cycles for school buses, so a NJ composite school bus mobile testing cycle, the Rowan University Composite School Bus Cycle (RUCSBC) was created for the testing. A variety of fuel types were tested to determine the cleanest burning fuel type for the NJ school bus duty cycle (e.g. rural, urban, etc.) that was developed. Previous research in the heavy-duty diesel emission reduction field has been conducted in research labs on engine and/or chassis dynamometers. Testing for this project was conducted entirely with the vehicle mobile or on-road on a test track at the Aberdeen Testing Center running the RUCSBC. Another important aspect of this research is to gain an understanding on how temperature and humidity effects emissions, specifically NO_x.

5.1.1. Literature Search

In recent years several experimental and theoretical studies have been performed on diesel emission reduction strategies. Each of these studies has focused on emission reduction strategies by performing tests on a chassis or an engine dynamometer. The majority of previous studies were mainly performed on different HDDVs other than school buses. The few previous studies on school buses did not use testing cycles that were initially developed for school bus operation. This section presents the results of a new experimental mobile emission reduction study using a newly developed school bus mobile testing cycle. A review of several previous emissions studies is provided in the following sections.

As stated previously, there has been only a limited number of school bus emission studies ever reported in the literature. One of the first school bus emissions studies took place in 1978 and evaluated tailpipe CO emissions only. [56] In this earlier study, school buses were tested for CO levels over a 10-month evaluation period to determine whether or not there were any serious CO intrusion problems or indications of potential problems on a small sample of the nation's school buses. Test results from the study showed, based on a maximum safe exposure level of 20 ppm, that 7.2% of the buses tested exceeded this level, and 5.4% of the buses tested had maximum CO readings over 50 ppm.

In 1995, the Northeast Florida Regional Planning Council, together with the National Biodiesel Board compared four alternative fuel sources to # 2 diesel in one of the sector school bus fleets.[57] These tests did not consider varying weather conditions or any direct comparison of a bus running identical cycles. The alternative fuels tested in this study were: biodiesel (B20 and B100), compressed natural gas (CNG), liquefied natural gas (LNG) and liquefied petroleum gas (LPG). The study concluded that relative to diesel, each of the four fuels tested had significantly lower emissions. B20 reduced CO and PM by 12 % and HC by 20 %. B100 reduced CO and PM by 50 % and HC by 70 %. This study also showed biodiesel resulted in significant reductions of unburned HC, CO, and PM. NO_x emissions stayed the same or were slightly increased. The study concluded that biodiesel blends could compete effectively with other alternative fuels when life cycle, total fleet costs are considered.

Another study conducted in 1997, and followed up in 1999, evaluated diesel emissions, from a variety of vehicle classes several of which were school buses. The study evaluated the initial effects of a retrofitted diesel oxidation catalyst technology and also the effects of the device two-years later. In this study chassis dynamometer emissions testing and in-use emissions testing were employed with and without a retrofitted catalyst technology using the New York Composite and Central Business District cycles, further detailed previously.[58] The results of the study found that the diesel oxidation catalyst reduced total PM by 20 to 50 %, CO by 45 to 93 %, and HC by 50 to 90 %.

In another study, West Virginia University characterized the emissions of a fleet of school buses in Indio, Ca. In this fleet, both 8.3 L Cummins natural gas engines and conventional 8.3 L diesel engines were tested. Their results showed that the natural gas engines had lower emissions in PM and NO_x (46 % and 12 %, respectively), but higher emissions of HC (50 %) compared to the diesel engine.[59] A remote sensing study of CO and HC emissions from school buses was initiated to develop emissions factors but results of this study have not been reported.[60]

The most recent study involving school buses was completed by collaboration between ARCO, West Virginia University, Johnson Matthey, and Engelhard.[61] The program evaluated ultra-low-sulfur diesel fuels and passive diesel particulate filters (DPFs) in truck and bus fleets operating in southern California. In this study exhaust emissions, fuel economy and operating cost data were collected for the test vehicles, and compared with baseline control vehicles. The evaluation of exhaust emissions took place prior to testing and also one year after installation of the filters. For all fleets tested including school buses, the test vehicles retrofitted with the DPFs reduced PM emissions by more than 90% when operated on ULSD when compared to the control vehicles having factory mufflers and operated on a typical California diesel fuel.

The San Diego School Bus Pilot program is currently testing 30 school buses. Five of the 30 buses are equipped with the Johnson-Matthey CRT filter and the other five buses are fitted with the competing Engelhard DPX filter technology. The second part of the California school bus pilot program is using a test fleet of 39 school buses from the Los Angeles Unified School District, the Anaheim Union High School district, and the Hemet Unified School district. In this program, 13 buses have been retrofitted with Johnson-Matthey CRT filter system, thirteen buses retrofitted with Engelhard DPX filter technology and at least one with Ceryx Quadcat system. The remaining buses are using low-sulfur ECD diesel fuel and no filter system.[62]

5.1.2. Emissions/ Emission Measurement

This research focuses on the EPA regulated emissions from HDDVs: CO, NO_x, HC, and PM. In addition, the greenhouse gas CO_2 is also examined. The EPA has regulated HDDV emissions since 1970, and has since slowly reduced the allowable level of each pollutant to the future standards of 2007. School buses stay in a school district's fleet for a maximum of 13 years by law, so by 2007 school buses from as early as 1994 could still be operating in a district's fleet. All emission testing takes place using a testing system such as an engine dynamometer, chassis dynamometer, or mobile in-use emissions. When testing using these different systems the units used to analyze the experimental data becomes an important factor in developing conclusions. The research presented herein, focuses on experimental data taken from mobile in-use emissions testing, however it should be noted that the other two methods of testing (engine and chassis) have advantages and disadvantages that are relevant to consider when forming conclusions.

5.1.2.1.Diesel Emissions

Mobile sources contribute significantly to air pollutants such as carbon monoxide CO, carbon dioxide CO_2, nitrogen oxide NO, nitrogen dioxide NO_2, particulate matter PM, and hydrocarbons HC. A mobile source is defined as any variety of vehicle, engine, or equipment that generates air pollution and that moves, or can be moved, from place to place.[63] A school bus falls into the mobile source emission category under a heavy-duty diesel vehicle (HDDV). A HDDV is any diesel-powered vehicle with a weight over 8,501 pounds Gross Vehicle Weight (GVW). [63] HDDVs are divided into different classes (e.g. Class 7, Class 8, etc.) according to the weight of the vehicle, with Class 8 being the heaviest. School buses are typically rated as Class 7 or Class 8. The gross vehicle weight ratings (GVWR) according to class are shown in Table 19.

Table 19: Gross Vehicle Weight Rating (GVWR) for diesel trucks.

Vehicle	2B	3	4	5	6	7	8
GVWR (lbs.)	8,501 - 10,000	10,001 - 14,000	14,001 - 16,000	16,001-19,500	19,501-26,000	26,001-33,000	33,000+

Carbon monoxide (CO) gas has no odor and is colorless. CO is produced by the incomplete combustion of the fossil fuels – gas, oil, coal and wood used in boilers, engines, oil burners, gas fires, water heaters, solid fuel appliances and open fires. Automobiles are the primary source of CO pollution. Transportation sources are responsible for 77% of the nationwide CO emissions.[64] CO emissions increase when the weather is cold or when less oxygen is available in the air to burn the fuel (poor combustion). When the carbon in the fuel is fully oxidized rather than partially oxidized, the greenhouse gas carbon dioxide (CO_2) is formed. The EPA does not regulate CO_2 for HDDVs, however reducing the greenhouse CO_2 is still important for the environment. CO_2 could be reduced by making an engine's combustion process more efficient by regulating school bus idle time.

The emissions NO and NO_2 are often grouped into a single term as the EPA regulated emission NO_x, or oxides of nitrogen. The EPA regulates NO_x emissions as a whole and does not regulate individual oxides of nitrogen. NO_x emissions are produced during the combustion of fuels at high temperatures.[64] NO_x is formed from a variety of mobile highway sources (e.g. HDDVs), non-road sources (e.g. marine and locomotives) and stationary sources (e.g. factories and power plants). Prior research has shown that at higher ambient and combustion temperatures there is an increase in NO_x. Hydrocarbons (HC) are produced differently with increasing combustion temperature than NO_x; increasing combustion temperature will lower HC emissions. HC emissions result from when fuel molecules in the engine do not burn or burn only partially.

The final regulated emission by the EPA is particulate matter (PM). PM is microscopic particles or liquid droplets suspended in the air that can contain a variety of chemical components. Low combustion temperatures and non-stoichiometric oxygen conditions result in incompletely burned fuel, and various concentrations of particulates largely of carbon composition. These particulates consist of elemental carbon (EC), organic carbon (OC), metals from fuel and engines wear, and sulfates with bound water. [65,66] The National Ambient Air Quality Standard (NAAQS) for particulates are divided into two size groupings. For particulate matter less than 10 μm, the NAAQS limits the annual average of particulates to 50 $\mu g/m^3$ and the 24 hour average to 150 $\mu g/m^3$. For particulate matter 2.5 μm and smaller the NAAQS annual average is 15 $\mu g/m^3$ and the 24 hour average is 65 $\mu g/m^3$.

5.1.2.2. EPA Diesel Emissions Regulation History

Since diesel engine emissions have been classified by the International Agency for Research on Cancer as a Group 2A carcinogen (probably carcinogenic to Humans) the EPA began regulating emissions.[67] Since 1970 the EPA has been regulating certain emissions from HDDV (including school buses). The EPA regulates the following pollutants from mobile sources:

- Total Hydrocarbons (HC)
- Oxides of nitrogen (NO_X)
- Particulate matter (PM)
- Carbon monoxide (CO)

From 1970 to 1974 however, only opacity levels of smoke for acceleration and lugging (laboring the engine in too high a gear) were regulated. In 1974, CO and a combined HC + NO_x regulation were put into effect as well as tighter smoke standards. Combining HC and NO_x emissions were an attempt to ease the transition into regulated emissions for engine manufacturers. The CO limit was introduced at 40 g/bhp-hr and the HC + NO_x was introduced at 16 g/bhp-hr. The emissions standards again tightened in 1979 with CO emission levels tightened to 25 g/bhp-hr. Also in 1979, a choice of 5 g/bhp-hr HC + NO_x or HC of 1.5 g/bhp-hr combined with a 10 g/bhp-hr HC + NO_x was introduced for the first time.

In 1984 new regulations split NO_x and HC into individual standards. In 1988 particulate matter regulations were introduced for the first time and set at .60 g/bhp-hr. Starting in the early 1990's new engine technologies were needed to meet the tightening regulations. In 2004, HC and NO_x will again recombine to be regulated as one emission in an effort to make the most stringent emissions standards ever in 2007 possible for engine manufacturers and fleet owners to meet. Also it is important to note that in 2007, the sulfur content in fuel will be reduced from an average of about 500 ppm to 15 ppm, which will also be helpful when using particulate traps that require ultra low sulfur fuel.

Figure 32 and Figure 33 show the EPA emission standard timelines from 1974 to model year 2007 for NO_x, HC, and a HC and NO_x combination and a timeline for PM, respectively. A complete listing of emission regulations since 1970 is shown in Table 20.

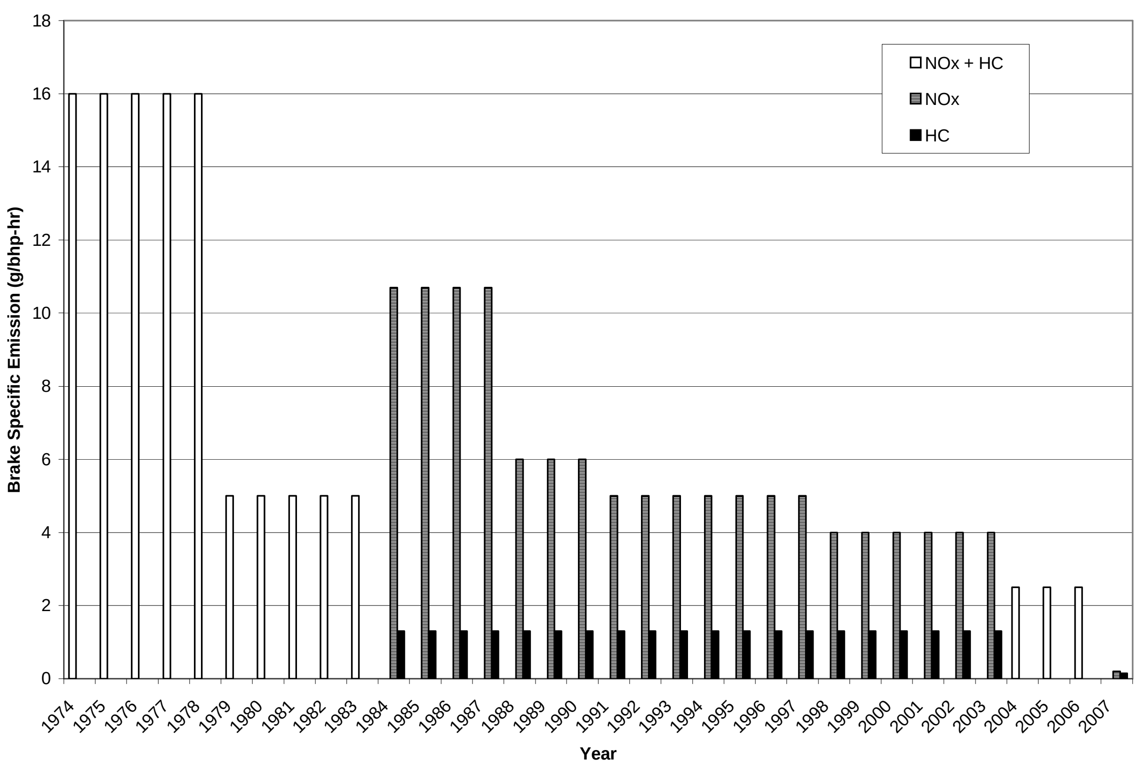

Figure 32: US EPA Emissions Standards Timeline for HDDVs for NOx and HC

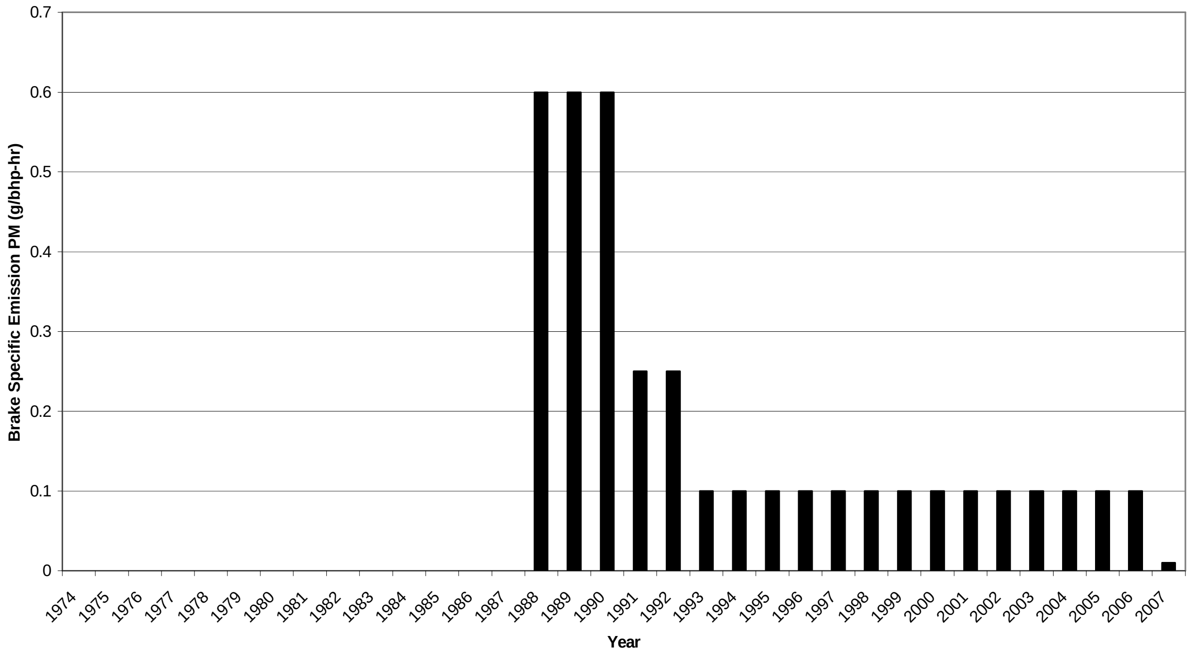

Figure 33: US EPA Emissions Standards Timeline for HDDVs for PM

Table 20: EPA Emission Standard History for HDDVs

Year	**CO (g/bhp-hr)**	**NO_x (g/bhp-hr)**	**HC (g/bhp-hr)**	**PM (g/bhp-hr)**
1974	40	16		-
1979	25	5		-
1984	15.5	10.7	1.3	-
1988	15.5	6.0	1.3	.60
1990	15.5	6.0	1.3	.60
1991	15.5	5.0	1.3	.25
1993	15.5	5.0	1.3	.10
1998	15.5	4.0	1.3	.10
2004	15.5	2.5		.10
2007	15.5	.20	.14	.01

5.1.2.3. Units of Measure for Emissions

Prior to presenting the results of this research, a few comments are provided on the units of measure that are typically used for reporting emissions measurements.

Results from emissions testing can be manipulated in several different ways based on how the emission units are reported. For example, the current EPA regulations specify heavy-duty diesel emission limits in terms of brake-specific emissions, with units of grams per brake horse power-hour (g/ bhp-hr) or equivalently in metric units of grams per kilowatt-hr (g/kW-hr). Total vehicle emissions in g/hr scales proportionally to engine size (hp). The g/bhp-hr emission unit allows for comparison between emissions from non-road sources (lawn mower, boat, etc.) to a class 8 truck. Other emissions units commonly used in prior research are g/mile and g/hour. For the purpose of this research, results will be reported in g/bhp-hr and g/mile for mobile testing or g/hr for school bus idling where the miles are always zero.

Brake specific emissions (g/bhp-hr) are the mass flow rate of the pollutant per unit power output. Time-specific emissions, or grams of pollutant per unit time, are required to compute these measurements. Emissions from an internal combustion engine are commonly measured as a concentration (corresponds to the mole fraction multiplied by 10^6 or the percent multiplied by 10^2, respectively) from a dilution tunnel in ppm or percent by volume.[68] Concentration is converted to mass using a mass balance on the gas being emitted from the exhaust pipe. Procedures for performing this calculation are given in the Code of Federal Regulations (CFR) by multiplying the mole fraction of the pollutant by the mixing volume measured in the dilution tunnel (device where the engine exhaust and dilution air are mixed together) and multiplying by the density of the pollutant and subtracting the background emissions measured during the test.[69] The work from the vehicle is obtained from the engine torque.

5.1.2.4. Emissions Testing

Emissions are tested by applying a known load to an engine or vehicle and by sampling the engine exhaust. Loads can be applied to an engine in a variety of ways, such as a dynamometer system or by mobile in-use testing of the engine installed in a vehicle. A dynamometer system is used to measure the mechanical power an engine can produce against known loads. There are two categories of dynamometers: engine and chassis. Each of theses types of emissions testing is described in the following section. The majority of testing in the present study was performed using mobile testing; however the past practice required by EPA was to certify a new engine on an engine dynamometer.

Engine Dynamometer Emissions Testing

An engine dynamometer is a dynamometer test system that is used to simulate road conditions and loads in stationary settings to gather data about the engine's performance under those conditions. With an engine dynamometer the engine is installed on a test system, which is more convenient to work with and has greater accuracy than if the engine were installed in a vehicle. In the engine dynamometer system, the engine is supposed to simulate performance characteristics as if the engine were actually being used in the vehicle. Power is usually measured at the flywheel (mounted at the rear of the crankshaft and used to store up rotational energy during the power impulses of the engine[70]) of the engine when using an engine dynamometer, which is difficult when using a chassis dynamometer or mobile testing. As described in the following sections, measuring the power at the flywheel gives the actual power produced by the engine however, because it results in no transmission or driveline losses to influence the results.

An engine dynamometer is typically operated with a specific software package provided by a vendor. A typical engine dynamometer test system is shown in Figure 34.

A disadvantage for the EPA inspectors when using an engine dynamometer is the need for the missing vehicle subsystems required for engine operation. Such subsystems including: fuel supply, electrical supply, exhaust extraction, air flow for cooling and for combustion air, coolant temperature control, and throttle actuation are required to maintain control over the engine.

Testing for emissions with an engine dynamometer significantly lacks some real conditions that influence emission results from a vehicle. The lack of real conditions on the engine dynamometer provides the engine manufacturer an opportunity to manipulate engine emissions. Emission influencing factors such as temperature and humidity, wind resistance, frictions from the tires and road, driveline losses, real vehicle accelerations and decelerations, etc. are almost impossible to simulate with an engine dynamometer. Installing emission reduction after treatment devices such as particulate filters is possible with an engine dynamometer, but installation of these devices when the engine is in the vehicle is more practical for emission testing. The engine dynamometer is currently used however, for HDDV emission certification in the United States.

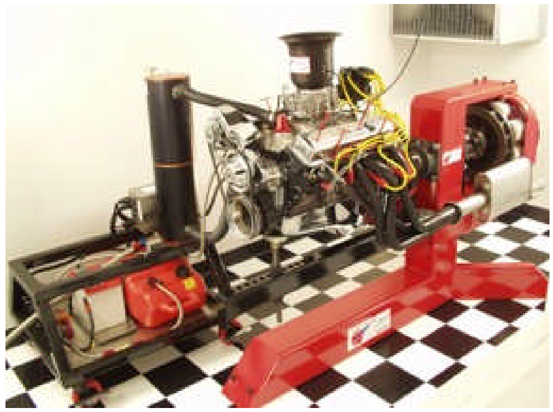

Figure 34: Engine dynamometer in–use[71]

Chassis Dynamometer Emissions Testing

A chassis dynamometer is a machine that can be used to simulate road conditions and test a vehicle's performance without actually putting the vehicle on the road. The chassis dynamometer system uses a series of rollers driven by the wheels of the vehicle. The rollers are connected to a power absorber system capable of controlling the load applied to the rollers. There are three primary types of chassis dynamometers, each characterized by the technology employed to absorb power: water brake, eddy current, and electric motor. Chassis dynamometers can be used for diagnostic purposes, as well as performing emissions and fuel mileage testing.

A variety of emissions test cycles have been created with the purpose of performing emissions testing on a chassis dynamometer. These test cycles make it possible to simulate road conditions, which will be explained in more detail. These cycles are used in conjunction with the dynamometer to perform emissions certification and testing. Certain types of dynamometers work better for each of these applications discussed. Chassis dynamometers have their advantages over engine dynamometers because no modification has to be done on the vehicle prior to testing (e.g. engine removal). Some disadvantages associated with using a chassis dynamometer include the inability to achieve repeatable measurements due to such factors as driveline losses or tire wear, pressure and temperature. Another disadvantage to the chassis dynamometer is that, although it includes some parameters that are not present in engine dynamometer testing such as driveline losses and wheel friction, it still lacks the real conditions (changing temperature and humidity, wind resistance, road conditions, etc.) mobile testing can provide.

In order for a dynamometer to simulate road conditions, it must have a means of applying load to the rollers, which the wheels of the vehicle ride on. The water brake is one type of braking system that is used for this purpose. The water brake produces a load by pumping water. The pump is driven from the rollers, which the tires of the vehicle being tested ride on. The characteristics of the pump can be changed to apply varying degrees of load to the rollers. The advantages of a water brake are that the system is easy to maintain and relatively inexpensive. The water brake dynamometer can also be operated for extended periods of time because the system is actively cooled.[72] The disadvantage of a water brake is that it cannot apply a load at zero RPM and is slow to respond to quick changes in load conditions. Another disadvantage is that it requires a significant amount of hardware installed on the premises in addition to the dynamometer itself. Since the water brake dynamometer uses a water pump to apply load, it requires an ample water supply and drainage to remove the used water. In many cases a cooling tower is needed to lower the temperature of the exhaust water before it is returned to the environment. The water brake dynamometer is intended for applications that require the dynamometer to be run for extended periods of time and have facilities that can accommodate the amount of hardware necessary for this type of dynamometer to be operated.[73] Water brake dynamometers are typically installed in–ground, but some companies have developed a more expensive above ground ramp system.

As part of the research study presented, a variety of chassis dynamometers were evaluated for potential use in school bus emissions testing. For example, the research team visited and operated the water brake system shown in Figure 35 at the Johnson Towers Truck Service Company in Mt. Laurel.

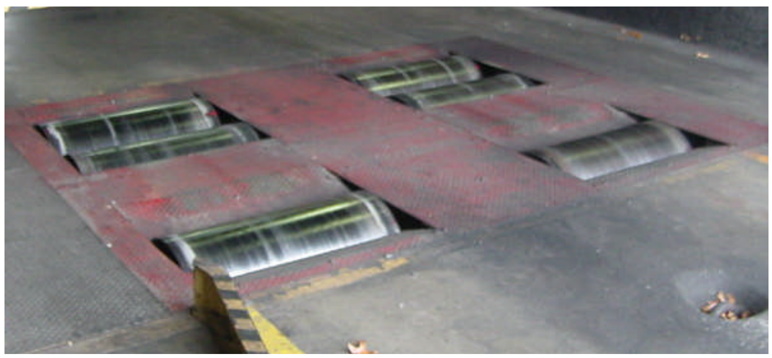

Figure 35: Water brake dynamometer installed in ground

The eddy current brake is another means of applying load to the rollers of the dynamometer. The eddy current brake applies load by creating a magnetic field, which applies a force to a shaft that is connected to the rollers. The eddy current dynamometer has many advantages; one being that the load is applied with a magnetic field so it is frictionless. Compared to the water brake system, the physical size of the dynamometer is much smaller, and requires much less hardware installed to operate the system. The eddy current dynamometer can easily be mounted either above ground or in a pit and is also relatively inexpensive. There are also some disadvantages of the eddy current. Since the eddy current is air cooled, there is a limit on how long it can be operated. It is primarily designed for shorter tests, but can be used for some longer tests.[74]

The third type of system used to apply load for a chassis dynamometer is the electric motor brake or AC dynamometer. The electric motor applies a load via direct coupling with the rollers on the dynamometer. The motor can then apply a load to the rollers by providing a resistive force on the axel of the rollers. The electric motor dynamometer is capable of running almost any test that has been created. It can apply a load to the rollers at zero RPM, which none of the other brake systems are capable of. The primary disadvantage of the electric motor dynamometer is that it is very expensive; almost eight times that of the water brake and over ten times that of the eddy current.[75] Electric motor dynamometers can perform complicated real-world driving cycles that the other chassis dynamometers cannot, however the electric motor dynamometers are so expensive that there are only two in the US.

Mobile In-Use Emissions Testing

The third and final type of emissions testing is mobile or in-use testing. A mobile emissions test includes an engine installed in the test vehicle while on the road running a prescribed test cycle. Mobile testing allows the school buses to be tested under conditions that cannot be reproduced on any dynamometer, or within an environmental chamber, but do allow for repeatable driving routes to be run.

Mobile testing was chosen as the research method for this project for several reasons. The main reason was that the EPA plans to switch to mobile testing by 2010 for all of their emissions testing.[76] Mobile testing provides a more accurate and realistic account of emissions actually from a vehicle while it is in-use, something an engine or chassis dynamometer system in a lab will never be able to reproduce. Another reason why mobile testing was chosen is due to the ease of installing emissions measuring equipment and emissions reduction devices. There were no modifications necessary prior to vehicle testing, the engine did not have to be removed, and the expense of a test system (engine or chassis dynamometer) was not needed. Mobile emissions measurement equipment is advanced enough to provide similar controls to those which were previously only available for dynamometer testing, such as vehicle interface and driver assist routing aid, which will be discussed later.

Previous research in the emissions field was done without the advantage of a test track for mobile testing often forcing the researchers to work in the lab on an engine or chassis dynamometer test system. At ATC there are several test track options for running test cycles uninterrupted from outside influences, such as traffic and pedestrians.

Another important factor when choosing mobile testing was the fact that engine manufacturers actually misrepresented emissions levels when testing their engines on engine dynamometers. In 1998 the Department of Justice and the Environmental Protection Agency found seven diesel engine manufacturers guilty of installing software that disables pollution prevention control devices after completing EPA standard tests. These companies are Caterpillar, Inc., Cummins Engine Company, Detroit Diesel Corporation, Mack Trucks, Inc., Navistar International Transportation Corporation, Renault, and Volvo Truck Corporation. Combined, these manufactures were ordered to pay fines totaling $83.4 million, which is the largest civil penalty ever for violation of environmental law.[77] This penalty was also the third in a series actions brought against engine companies that allow their ECMs to "selectively" prevent pollution. The first exposure of the defeat device came in 1995 when the EPA and the Department of Justice found GM guilty and penalized them $45 million. The American Honda Motor Co. was penalized $267 million and the Ford Motor Co. for $7.8 million to conduct environmental projects.[78] Mobile testing eliminates any cheating by the engine manufacturers, since the emissions being measured by the analyzer are after the certification tests and the manufacturer does not have the ability to change the ECM programming.

A disadvantage to mobile testing is that the weather cannot be controlled (snow, rain, heavy winds, etc.). Some emissions, particularly NO_x, have been shown to be a strong function of ambient conditions. Though these are real conditions HDDVs may undergo, it makes for a difficult time for researchers and the vehicle's driver (trying to follow a prescribed drive cycle) when testing for mobile emissions. Indeed, the human error associated with the driver is another disadvantage of mobile testing. Though mobile testing does not result in the wear and tear of chassis dynamometer on the vehicle, the driver cycle repeatability is inferior to what can be accomplished on the chassis dynamometer.

5.1.3. Diesel Emission Reduction Strategies

Several different emissions reduction technologies will be tested with mobile testing over the course of the school bus emissions testing project. The technologies that are going to be tested are the Johnson-Matthey CRT Particulate Trap, Engelhard DPX Particulate Trap, PFC crank case breather, the PFC flux wave cell, and other various technologies. Alternative fuels to be tested include #2 diesel, ultra-low sulfur diesel (ULSD), biodiesel/# 2 diesel blends, and biodiesel/ULSD blends. The results from the alternative fuel-testing portion of the project are presented in this research.

In an attempt to meet the stringent 2007 EPA emissions standards, all HDDV engines will need an emission reduction technology. In the past 30 years of EPA emission regulation engine manufacturers were able to meet the new standards by only changing their engine designs (e.g. fuel injection systems, exhaust gas recirculation, and electronically controlled engines). The most common types of emission reduction strategies are after treatment devices (e.g. particulate traps) and alternative fuels. Fuel additives and other reduction devices (e.g. Selective Catalytic Reduction, Diesel Oxidization Catalysts, etc.) are also used, but are not as common and widely available as particulate traps and some alternative fuels. In order to meet the new standards for HDDVs the emission reduction technologies needed will be costly and usually come with a fuel penalty.

5.1.3.1. Alternative Fuels

An alternative fuel is defined as a fuel other than petroleum diesel or gasoline.[79] The purpose of an alternative fuel is to have a cleaner burn and produce lower emissions. Alternative fuels will also reduce our reliance on imported oil. The most common alternative fuels such as biodiesel and ultra low sulfur diesel (ULSD) have been shown to reduce some diesel emissions significantly in cars and trucks. For this research, # 2 conventional petroleum diesel (low sulfur ~360 ppm), B20 (20% by volume biodiesel, 80% by volume #2 conventional petroleum (~360 ppm) diesel), ultra low sulfur diesel (~15 ppm), and a biodiesel-ultra low sulfur diesel (20% by volume biodiesel, 80% by volume ultra low sulfur diesel (~15 ppm)) mixture were examined.

Biodiesel is an alternative fuel that is a cleaner-burning diesel replacement to # 2 diesel. Biodiesel is made from natural renewable sources such as new and used vegetable oils and animal fats. The most common source of biodiesel in the US is soybeans. Biodiesel can be used pure or in different blends with #2 conventional petroleum diesel.

These blends are classified by percent volume of biodiesel. For example, a blend of 20 percent biodiesel and 80 percent conventional petroleum diesel is called B20. Research has shown that the best emission reductions for PM, HC, and CO come from higher percent biodiesel blends and pure biodiesel, B100.[85] One large obstacle in the widespread use of biodiesel as a permanent petroleum diesel replacement is availability. Biodiesel resources are estimated at about two billion gallons per year, which is considerably lower than the 60 billion gallons used annually by the USA distillate market.[80]

One tradeoff when using pure biodiesel, B100, is that it can significantly increase NO_x depending on the duty cycle.[81] The NO_x increases when using biodiesel could be caused by the higher fuel density and lower heating value of the fuel.[82] Increasing oxygen content in the fuel has caused significant increases in NO_x in previous research.[82] The NO_x tradeoff is not a large concern, due to the low sulfur content of biodiesel (~24 ppm), which will work with NO_x reducing technologies that require low sulfur fuel. Biodiesel blends higher than B20 however, can cause problems with deterioration of existing gaskets and could cause gelling in the winter. A basic mixing process called splash blending creates a mixture of biodiesel and conventional petroleum diesel. Biodiesel has a higher specific gravity (~. 88) than conventional petroleum diesel (~. 85), so splash blending should involve mixing the biodiesel on top of the conventional petroleum diesel.

Biodiesel has other advantages besides decreasing HC, PM, and CO emissions. Every unit of energy needed to produce biodiesel results in 3.24 units of fuel energy, while producing conventional petroleum diesel requires more energy to produce the fuel than is generated.[83] As far as safety factors are concerned biodiesel has a higher flashpoint than conventional petroleum diesel and is biodegradable and non-toxic. Also, since biodiesel is renewable, CO_2 reductions are indirectly created from the lifecycle of biodiesel. Biodiesel also has no known blending problems when being mixed with ULSD. Biodiesel also improves lubricity of the engine, where ULSD does not, and a combination of biodiesel and ULSD would offset the loss of lubricity when using just ULSD. ULSD and biodiesel both have higher cloud points than conventional petroleum diesel, which could be a problem with gelling in colder weather conditions. The cloud point of a clear distillate fuel is the temperature at which the fuel becomes hazy or cloudy because of the appearance of wax crystals.[84]

In a comprehensive review compiling several separate biodiesel studies, the EPA concluded that common blends of B20 reduced HC emissions by 20 %, PM emissions by 10 %, and CO emissions by 11 %.[85] NO_x emissions increased slightly in some engines (~ 2%) and CO_2 emissions showed little or no difference. Some school districts such as Medford Township in NJ are already using B20 in half of their 44 buses[86]. As part of the present study, tests were performed on some of the buses in the Medford conventional and biodiesel fueled fleet. The results from those tests will be presented.

Ultra low sulfur diesel (ULSD) is an alternative fuel made to have lees than 15-ppm sulfur. ULSD will be the only diesel fuel allowed in the U.S. after 2006. PM emissions have been shown to decrease slightly with the use of ULSD, however the real advantage of the fuel comes when combining it with an emission after treatment technology. Since sulfur has been known to poison catalysts it is required that ULSD be used for most particulate traps and catalytic converters. When combining ULSD with these technologies significant reductions in some emissions have been reported.

The USEPA classifies ULSD as having no more than 15-ppm sulfur content, with the current U.S. regulations allowing up to 500-ppm sulfur for diesel fuel used for highway transportation. Previous studies show that ULSD by itself reduces HC emissions by 13 %, PM emissions by 13 %, CO emissions by 6 %, and NO_x emissions by 3 %. With the addition of a particulate filter, ULSD can reduce HC and CO emissions by 90 %, PM emissions by 80%, and NO_x emissions by 15 % to 20 %.[83] Compared to conventional petroleum diesel, a B20 biodiesel blend costs an additional $0.12 to $0.20 and ULSD costs an additional $.05 to $0.15.[83]

5.1.3.2. Particulate Traps

Although exhaust after treatment tests have yet to be completed, a review of the current status of available devices was conducted as part of the present research study. A brief review is presented here. A diesel particulate filter or trap physically captures particulates from the exhaust and prevents them from entering the atmosphere. The Johnson Matthey Continuously Regenerating Technology (CRT) Particulate Filter and the Engelhard DPX Catalyzed Diesel Particulate Filter are the only two diesel particulate traps approved by the EPA for HDDVs as part of their verified after treatment technology list[87]. A diesel particulate filter incorporates a filtering device to trap liquid and solid particulates. Materials used to construct diesel particulate filter include ceramic monoliths, wire mesh, woven silica fiber coils, ceramic foam, etc. A catalyst is used to promote combustion of the carbon inside the filter, producing carbon dioxide.

The three types of particulate filters are “catalytic, “fuel-borne catalyst,” and “continuously regenerating” particulate filters. In a catalytic filter, the catalyst is applied directly to the filter material. In a fuel-borne catalyst filter, the catalyst is added directly to fuel. A continuously regenerating filter uses a catalyst in front of the monolith to oxidize NO to NO_2, which absorbs the particulate matter and causes combustion in the second catalyst chamber. The combustion of the particulates is the “cleansing” or regeneration step of the process. A design schematic of a typical diesel particulate filter is shown in Figure 36. Similar to other exhaust after treatment technologies, the reduction capabilities of this technology depend on the amount of sulfur in the diesel or alternative fuel used and the exhaust temperature. Studies show that most diesel particulate filters can achieve from 90 to 99% reduction of particulate matter, hydrocarbons, and carbon monoxide.[88] However, particulate traps have shown only slight reduction of NO_x. Diesel particulate filters are not available for all families of engines. However HDDVs newer than 1994 that are electronically controlled will generally meet the retrofit guidelines provided by the filter manufacturers.

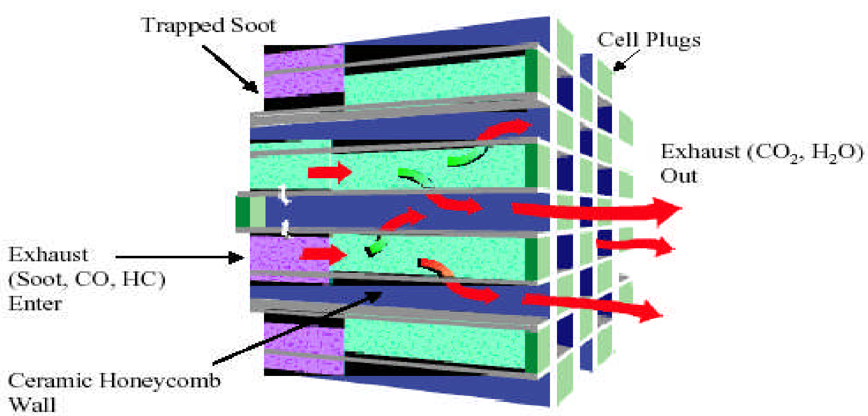

Figure 36: Schematic of a diesel particulate filter[89]

In order for an effective regeneration to occur, the exhaust temperature must reach a temperature between 350-400 °C. If this exhaust temperature is not reached, the soot collected in the filter is not combusted and the particulate trap becomes clogged. Another disadvantage when using a particulate filter on an HDDV is the effect of sulfur in the fuel. Sulfur inhibits the active sites on the catalyst, which results in a less active catalyst and a higher exhaust temperature requirement for regeneration. The oxidation of SO_2 to SO_3 over the platinum oxidation catalyst takes place in preference to the oxidation of NO to NO_2[90]. Therefore, the NO oxidation reaction is inhibited, and the NO_2 is less available to burn off the trapped soot.

Johnson Matthey's EPA approved particulate filter provides its diesel particulate retrofit in the form of a continuously regenerating technology (CRT), which is a trade name for a catalytic, two-stage, passive particulate filter system. The CRT system (shown in Figure 37) regenerates at temperatures below 300 °C, using ultra low sulfur diesel fuel. Johnson Matthey has recently patented this principle of using nitrogen dioxide to oxidize diesel particulate matter.

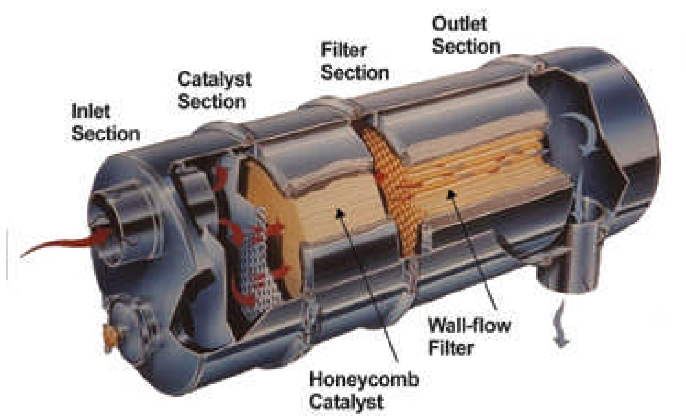

Figure 37: Johnson Matthey CRT diesel particulate filter

The CRT diesel particulate filter system consists of two separate chambers. The first chamber is a ceramic monolith, coated with the platinum catalyst. In the ceramic monolith chamber, carbon monoxide and hydrocarbons are combusted to form carbon dioxide and water. The first stage also increases the proportion of nitrogen dioxide to nitrogen oxide. In the second chamber the exhaust passes through another monolith, which forces the exhaust through the pores. The remaining soot is trapped and burned off by the nitrogen dioxide from the first stage.[91] Restrictions do exist for this technology however, such as the exhaust gas temperature, the NO_x to PM ratio, and sulfur content in the diesel fuel. The restrictions are as follows: the exhaust gas temperature for the CRT must be at least 275 °C, the sulfur content in the fuel must not exceed 50 ppm (ULSD has a sulfur content of less than 15 ppm), and the exhaust NO_x to PM ratio must be between 8:1 and 25:1 by weight. The minimum exhaust temperature has been determined by studies such as the California Air Resources Board for post-1994 engine retrofits, and the Diesel Emission Control - Sulfur Effects (DECSE) study on a CAT 3126 engine. The high exhaust temperature is required for the filter regeneration to take place, which according to California ARB must have a temperature of 270 °C for 40% of the operating time of the filter. According to the DECSE report, the filter has shown to regenerate as low as 300°C, provided that ultra low sulfur diesel fuel (15ppm) was used. ULSD must be used with the CRT because the sulfur deteriorates regeneration.[92] Sulfur is an inhibitor, which strongly competes with NO_x in the exhaust. Thus, the active sites in the catalyst become blocked by a competitive adsorption between sulfur dioxide and nitrogen oxide. The result is a lower NO_2 generation, and in order to obtain generation, the exhaust temperature must be raised.[93]

Engelhard's EPA approved particulate filter provides its diesel particulate retrofit in the form of a DPX catalyzed particulate filter. The DPX filter is a platinum and base metal oxide catalyst-coated ceramic wall-flow filter. The catalyst coating is embedded into the porous filter walls and oxidized the collected particulate matter, hydrocarbons, and carbon monoxide from the exhaust.[94]

According to Engelhard Corporation the DPX filter delivers 70-98% PM reduction and 70-98% carbon monoxide and hydrocarbon reductions.[95] The DPX particulate filter is effective when used with sulfur fuel ranging from 5 PPM to 500 PPM, and no fuel additives are required. Under such circumstances, oxidation catalyst technology in the form of a muffler replacement would be more suitable and would deliver 25-50% PM reduction, 50-80% hydrocarbon reduction, and 40-90% carbon monoxide reduction. Engelhard Corporation also claims that the DPX Soot Filter requires an exhaust gas temperature of 375°C for at least 25% of the time. [96]

5.2. Experimental Procedure and Equipment

5.2.1. Introduction

The purpose of this section is to describe the test vehicles, the test facilities, and the equipment used to measure emissions for mobile and idle school bus testing. This section will also provide information on how data collected from various instruments was compiled and managed.

5.2.2. Rationale for School Bus Selection

An early challenge for the project was to choose three diesel engines typically found in school buses across New Jersey for diesel emissions testing. Among the criteria considered for the selection was availability of the buses, frequency of use of a particular bus type in New Jersey, and popularity of engine type with respect to previous school bus emission studies. Another important factor in bus selection was the age of the school bus. Since school buses are replaced from a school districts fleet every 13 years, it was important to stay in the scope of the project and chose a bus that would still be in service for a significant time after completion of this study.

5.2.2.1. School Bus Types in NJ

One criteria for the selection of the school buses was developed after determining the types of buses that are commonly used in New Jersey school systems. NJDOT provided a comprehensive study of the engines used in school buses across the entire state. As shown in Table 21, specific engine types were used in the study done by Polk Automotive Intelligence of Detroit to organize buses from all NJ school districts. The three buses that were ultimately chosen for emissions testing are shown in bold in Table 21. In addition to the informal survey compiled by NJDOT staff, a survey was taken by

Rowan University students in the townships of Washington, Middletown, Medford, and Glassboro to see which buses they were using. Medford, and Washington townships both use International engines in their buses (T-444E and DT466), while Glassboro use Caterpillar engines in their buses. Middletown also uses Caterpillar and International, along with GMC, Detroit Diesel, and Cummins.

Table 21: Engine types used in NJ School Districts[97]

Engine Manufacturer	**Engine Model**	**Total Number of buses in New Jersey**
Caterpillar	3116	581
Caterpillar	3126	1356
Caterpillar	3406	1
Caterpillar	3208	13
International	**T-444E**	**2232**
International	DTA 466	15
International	DTA 360	891
International	**DT 466**	**1113**
International	DT 408	151
International	DT 360	258
International	7.3 L	1184
Detroit Diesel	8.2 L	126
Ford	7.8 L	20
Ford	6.6 L	99
Cummins	**5.9L B series**	**1816**
General Motors	7.0 L	9
General Motors	7.4 L	84
General Motors	6.0 L	494
General Motors	5.7 L	2
General Motors	8.1 L	19
Unknown	Unknown	409
Total Buses in NJ	-	10873

Previous school bus emissions studies were reviewed to help aid in the school bus selection to see what types of engines were commonly being tested. An SAE study in 1999, used a Navistar International T-444E engine to study the effects of alternative fuels on emission levels.[98] The T-444E was also used in another steady state comparison test of biodiesel and conventional petroleum diesel by FEV Engine Technology, Inc.[99] Further biodiesel testing was done on two Cummins B Series engines, which were fueled with 100% biodiesel for a 48 month period by the Agricultural Engineering Department at the University of Missouri-Columbia.[100] Also, as mentioned previously, beginning in early 1998, the Medford (New Jersey) Township Public Schools voluntarily started a 4-year demonstration program for B20 (20% biodiesel made from soybeans, 80% conventional petroleum diesel). In its fleet of 44 buses, 22 are operated on B20; the rest are operated on conventional petroleum diesel. Medford used International DTA360 and DT-466E for the testing of the biodiesel fueled buses.

Another factor in selecting a bus engine for testing was availability for purchasing. Though the Caterpillar 3126 was the third highest most commonly used bus type in NJ, there were no buses equipped with this engine available for purchase within the constraints of this study. The final selection of the three buses upon reviewing the specifications for selection was an International T-444E and DT-466E along with the Cummins B Series engine. School bus engine specifications for the three engines selected are shown in Table 22.

Table 22: Engine selection for school bus emissions testing

Engine	Year	Chassis/Body	Engine Hp	Rated Speed	Miles
T-444E	1997	98' International	190	2300	73,471
T466	1997	98' International	190	2300	47,862
5.9L Cummins	1996	97' Ford	190	2200	85,516

5.2.2.2.Engine Specifications

1997 International T-444E

The International T-444E is a four cycle, 8-cylinder (V-8) diesel engine and is commonly used in truck and bus Vehicle Classes 2 through 8 trucks and buses. This engine is available at 175-230 hp and has a 7.3 L displacement (the engine tested is rated at 190 hp). The T-444E idles at approximately 700 rpm, which is not adjustable for this engine. The DT-466E engine lug curve is shown in Figure 41. The combustion system for the engine is direct injection and it is turbocharged with a wastegate (a valve that allows the exhaust to bypass the turbine blades). The wastegate senses the boost pressure allowing some exhaust to bypasses around the turbine blades if the pressure gets too high.[101] The T-444E engine is air-to-air intercooled and has a 17.5:1 compression ratio. Among its many features include an electronic control module (ECM), electronic glow plugs, and an electro-hydraulic fuel system or HEUI (hydraulically actuated, electronically controlled unit injectors). The T-444E used by Rowan University for emissions testing is shown in Figure 38.

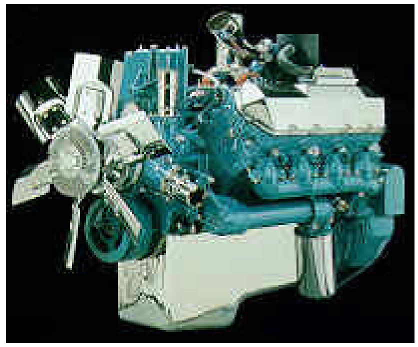

Figure 38: International T-444E diesel engine

1997 International DT-466E

The DT466 is a four cycle, in-line 6-cylinder diesel engine. This engine is available at 195-230 hp and has a 7.6 L displacement (the engine tested is rated at 190 hp). The combustion system for the engine is direct injection and it is turbocharged with a wastegate. The DT-466E idles at approximately 700 rpm, which is not adjustable for this engine. The DT-466E engine lug curve is shown in Figure 42. The engine is air-to-air intercooled and has a 16.4:1 compression ratio. Among the engines many features include an ECM and an electro-hydraulic fuel system. The DT-466E used by Rowan University for emissions testing is shown in Figure 39.

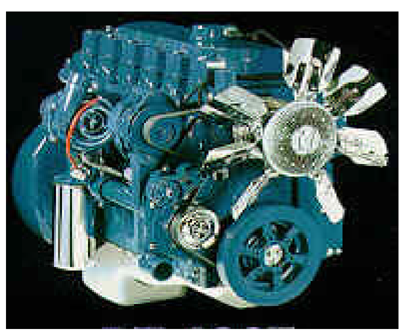

Figure 39: International DT-466E diesel engine

1996 Ford Cummins 5.9 L ISB Series

The ISB engine is a four cycle, 6-cylinder diesel engine. This engine is available at a range of about 185-300 hp with a 5.9 L (the engine tested is rated at 190 hp). The combustion system for this engine is direct injection and is turbocharged a wastegate. The B series idles at approximately 800 rpm, which is not adjustable for this engine. The Cummins 5.9 L B Series engine lug curve is shown in Figure 43. The ISB engine is air-to-air intercooled and has a 16.5:1 compression ratio. The 96' Cummins B Series is not equipped with an ECM. The Cummins 5.9 L B Series engine used by Rowan University for emissions testing is shown in Figure 40.

Figure 40: Cummins 5.9 L B Series diesel engine[102]

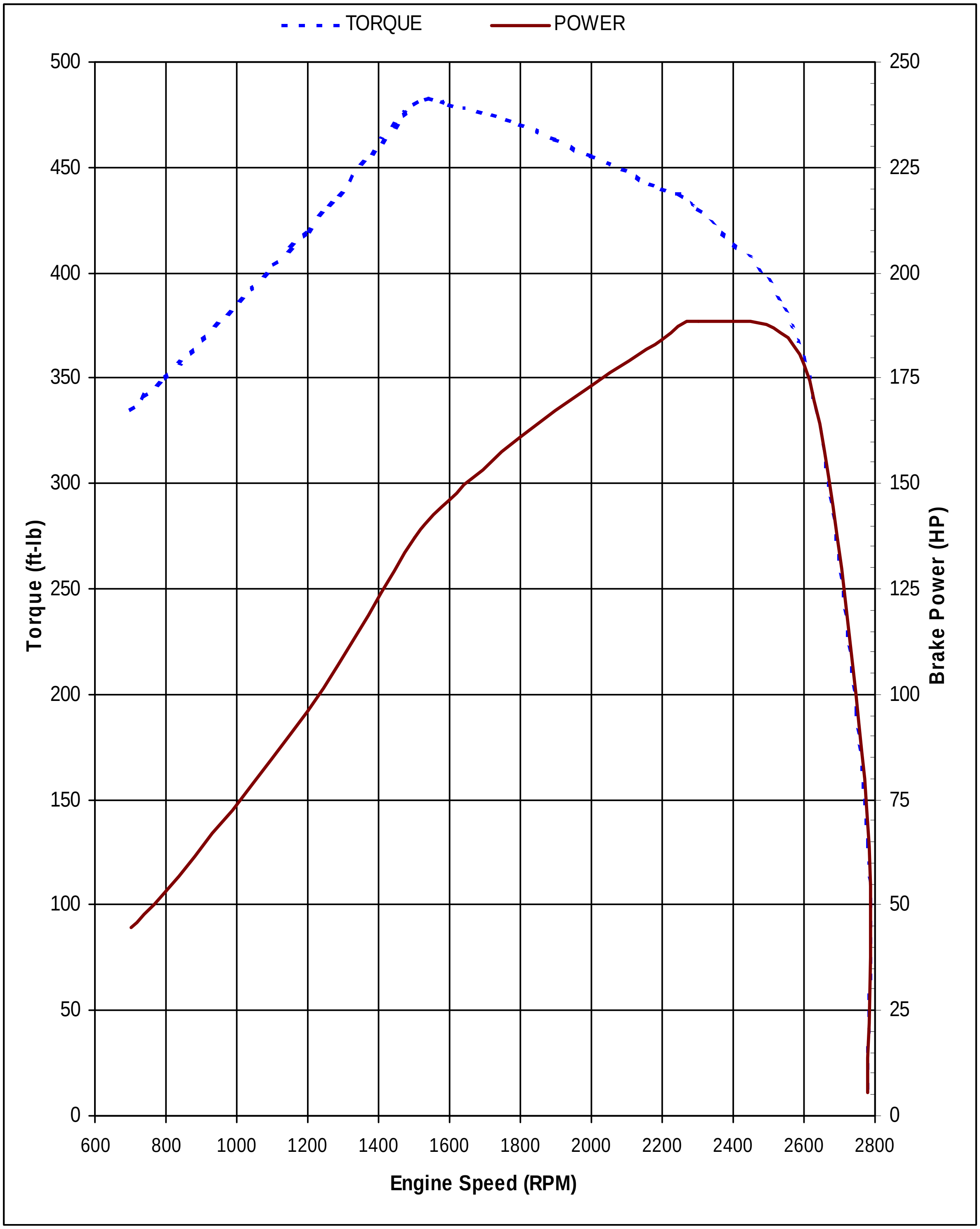

Figure 41: T-444E engine lug curve

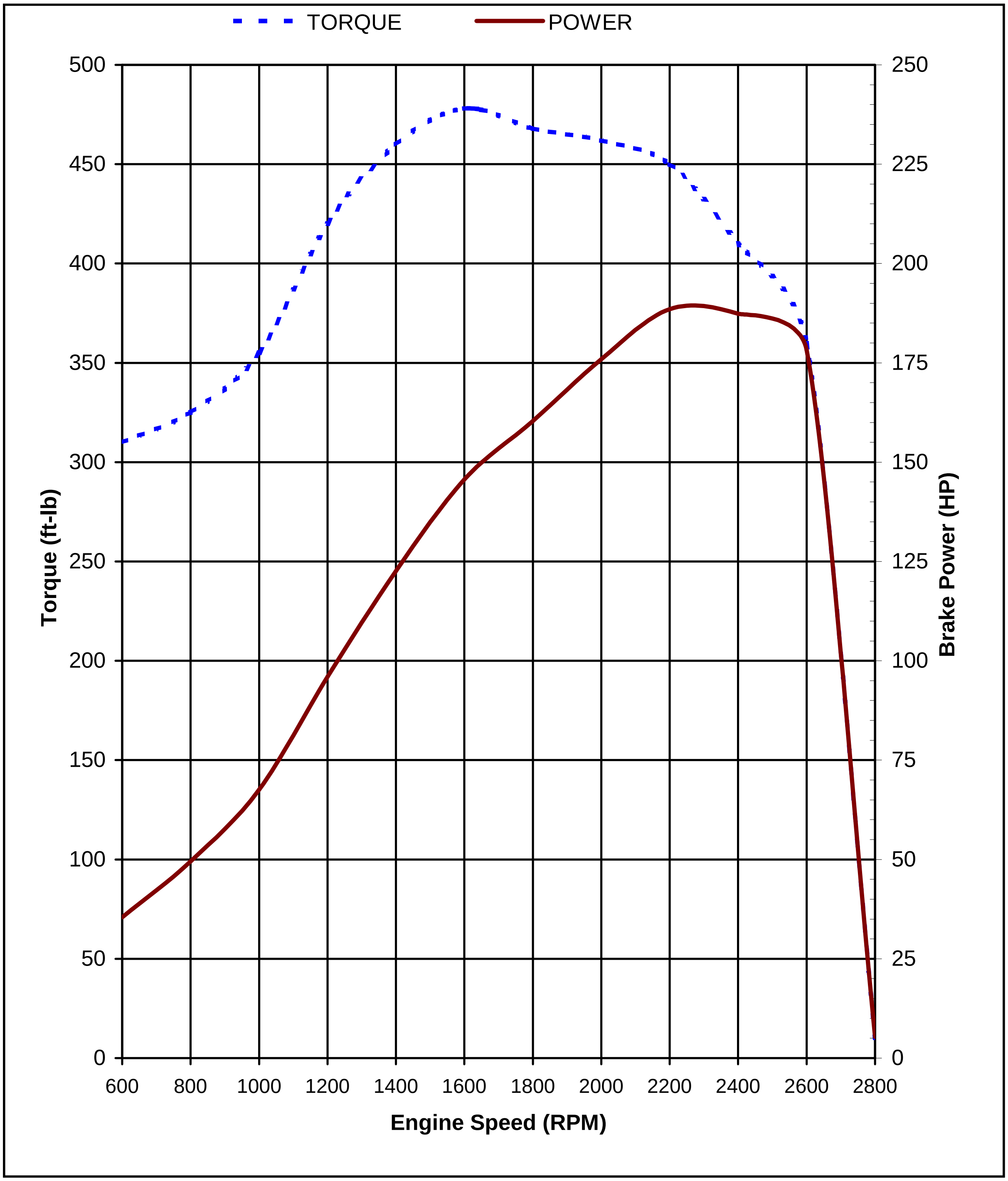

Figure 42: DT-466E engine lug curve

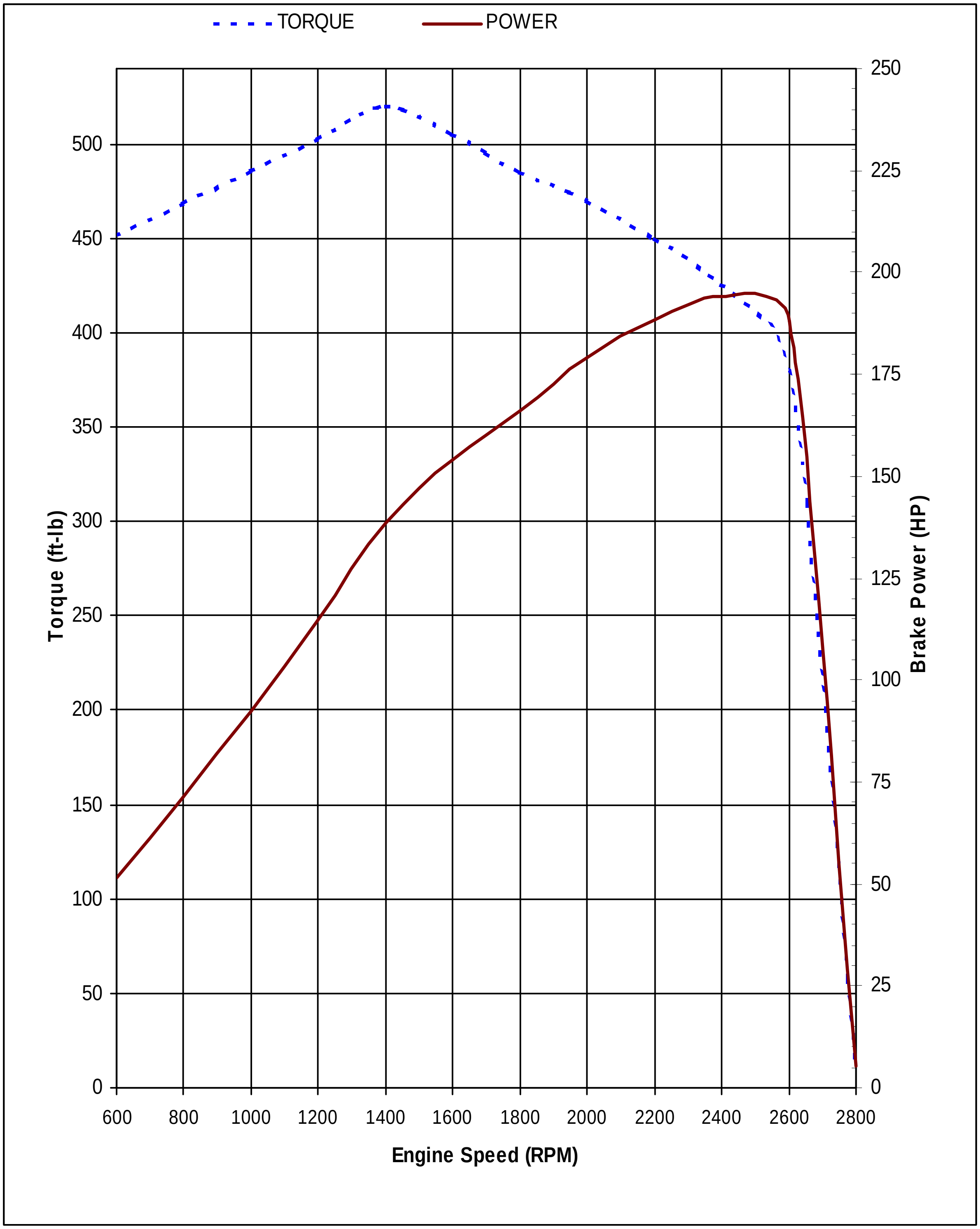

Figure 43: Cummins 5.9 L engine lug curve

5.2.3. Aberdeen Test Center

The Aberdeen Test Center (ATC) in Aberdeen, Maryland (50 miles North of Baltimore) is where the majority of school bus emissions testing for this project took place. ATC is a government owned and operated facility encompassing over 56,000 acres of various landscapes. For the purpose of this project, the main facilities used at ATC were their independent test track, an environmental chamber, and their precision fabrication machine shop. The ATC chemistry lab also provided fuel analysis for the various types of alternative fuels tested.

5.2.3.1. Test Track

A composite school bus testing cycle was conducted on the 1-Mile Loop Course at the Aberdeen Test Center. The testing course consists of a continuous asphalt surface with level, parallel 1/4-mile segments connected by 1/4-mile flat semicircular sections at each end. Use of the test track was employed with no other outside interruption, so the testing cycles were run smoothly with no outside interference.

5.2.3.2. Environmental Testing Chamber

School bus idle tests were also conducted at ATC. These environmentally controlled experiments were conducted in Environmental Chamber No. 4 at ATC. The environmental chamber is capable of controlling multiple climatic variables, including temperature, humidity, solar radiation, dust, icing, fog, and thermal shock. The test chamber has dimensions of 75 ft x 40 ft x 24 ft and can be divided equally into two smaller independent climatic compartments. One of these two independent climatic compartments was used for school bus testing. Temperature can be varied from –70 to 170 ºF, and relative humidity can be raised to 98 %. Data acquisition and control instrumentation are located in a separate room adjacent to the environmental chamber[103]. Various views of chamber 4 are shown in Figure 44. [103]

Figure 44: Environmental testing chamber 4

5.2.3.3. Chemistry Lab

The ATC Chemistry Fuels Testing Laboratory provided analysis on several properties of diesel fuels. The ATC Chemistry Team Laboratory is certified by the Army Petroleum Center as a fuel-testing laboratory.[103] The lab followed ASTM D975-01, Standard Specification for Diesel Fuel Oils, for the fuel testing. Properties of the fuels tested and the ASTM Method in which they were tested are as follows:

- Distillation range: The range of temperature, usually determined at atmospheric (Boiling Range) pressure by means of standard apparatus, over which boiling or distillation of a liquid proceeds., tested using **ASTM D 86.**

- API gravity: An arbitrary scale expressing the gravity or density of liquid petroleum products, tested using **ASTM D 287.**
- Flash point (closed and open cup): The temperature at which a combustible liquid gives off just enough vapor to produce a vapor/air mixture that will ignite when a flame is applied, tested using **ASTM D 93.**
- Cetane index %: A calculated value, derived from fuel density and volatility, giving a reasonably close approximation to cetane number, tested using **ASTM D 4737.**
- Particulate contamination
- Sulfur Content, tested using **ASTM D 4294.**
- Cloud point: The temperature at which wax first becomes visible when diesel fuel is cooled under standardized test conditions.
- Pour point: The temperature at which the amount of wax out of solution is sufficient to gel the fuel when tested under standard conditions.
- Freeze point
- Fuel Viscosity, tested using **ASTM D 445.**
- Density or specific gravity, tested using **ASTM D 4052.**

5.2.4. Bus Instrumentation

Table 23 is a summary school bus emission testing instrumentation proposed for these tests. If a measurement was taken following an SAE standard testing measurement method, the method is noted in Table 23. Exhaust gas emissions measurements will include oxygen, CO, CO_2, NO_2, NO, SO_2, unburned hydrocarbons, and particulate matter. In addition to tail pipe emissions, the intake air, ambient air, school bus interior, and engine operating parameters were also monitored. The data was acquired using several systems as described below.

5.2.4.1. Instrumentation Table

Table 23: School bus emissions testing instrumentation.

Sub-System	**Measurements**	**Measurement System**	**SAE Standard**	**Sensor**
Intake Air	Temperature	ADOCS	Yes J244	Thermo-couple Type K
	Humidity	ADOCS		Thermo-hygrometer
Ambient Atmospheric Conditions	Temperature	Semtech-D		
	Humidity	Semtech-D		
	Barometric pressure	ATC Post-Wide Meteorological System		
School Bus Exterior	Ambient Temperature Just Outside Bus	Semtech-D		Thermo Couple Type K
	Ambient Humidity Just Outside Bus	Semtech-D		Thermo-hygrometer
Engine	Crankcase temperature	ADOCS		Thermo-Couple on Dipstick Type K
	Vehicle Speed/ Distance	Semtech-D		GPS
	Engine Speed, RPM	Semtech-D	Yes J1003	ECM
	Exhaust Temperature 1	ADOCS		Thermo Couple Type K

Sub-System	**Measurements**	**Measurement System**	**SAE Standard**	**Sensor**
	Exhaust Temperature 2	ADOCS		Thermo Couple Type K
	Exhaust Temperature 3	ADOCS		Thermo Couple Type K
	Throttle Position	Semtech-D		ECM
Exhaust Gas (Tail Pipe Emissions)	Oxygen	Semtech-D		Electrochemical sensor
	CO	Semtech-D	Yes J177	Non-Dispersive Infrared (NDIR)
	CO_2	Semtech-D	Yes J177	Non-Dispersive Infrared (NDIR)
	NO_2	Semtech-D	Yes J177	Non-Dispersive Ultraviolet (NDUV)
	NO	Semtech-D	Yes J177	Non-Dispersive Ultraviolet (NDUV)
	THC	Semtech-D	Yes J215	Heated Flame Ionization Detector (FID)
	PM	PM300		Photo Diode
Fuel	Mass flow rate Supply	ADOCS/ Cummins	Yes J1003	Flowmeter
	Mass flow rate Return	ADOCS/ Cummins		Flowmeter/ECM
	Chemical analysis of liquid fuel	ATC Chemical Lab		--
	Boost Pressure	Semtech-D		ECM

5.2.4.2. Electronic Control Module (ECM)

The Electronic Control Module (ECM) is an on-board computer system that controls the opening and shutting of the intake and exhaust valves of an engine. The ECM is generally mounted near the engine in the engine compartment and reads a variety of signals. An ECM can also control engine performance parameters such as fuel metering, ignition spark advance, air-fuel mixture, and the engine-cooling fan. There are five individual parts to an ECM, the main one being the microprocessor. The microprocessor consists of Random-access memory (RAM), Read-only memory (ROM), Keep-alive memory (KAM), and several inputs and outputs.

Using an analog to digital converter, the ECM first converts information from the input sensors to a form that it can use to process the data. The information is then sent to the microprocessor where specifications that are stored in the memory chips are used to form an assessment of vehicle conditions based upon the engine's performance. This assessment is then sent to an actuator and an action occurs based upon the input of information. The final information can then be uploaded onto a device (such as the Semtech-D emissions unit read out screen) where the engine parameter information can be processed and analyzed. Several parameters can be read from the ECM microprocessor's RAM and KAM such as road speed, engine load, engine rpm, and fuel consumption. The main difference between the RAM and KAM is that KAM will store information even after the ignition is turned off.

Engine manufacturers have different service tools to access information from the ECM through a data link. A data link provides a physical means for transmitting and sorting electric signals. A data link consists of special electronic circuitry and electrical connections. Connection points for electronic service tools are also part of the data link. A data link adapter is a device that converts the SAE J1587/SAE J1708 or the SAE J1939 data link messages from the ECM into a message that a personal computer can understand. The Sensor's Inc. Semtech-D emissions analysis equipment connects to the ECM in a similar manner. The NEXIQ Corporation SDM network interface for heavy-duty diesel engine interfaces is used to connect the ECM to the Semtech-D. The SDM interface has been developed and validated on all SAE-J1708/SAE-J1587 equipped diesel engines, which comprises the majority of the fleet.[104]

5.2.4.3. Sensors Inc. Semtech-D

The Sensors Inc. SEMTECH-D (Sensors EMissions TECHnology-Diesel) mobile emissions analyzer was chosen as the main emissions measuring device for this project. The Semtech-D is a portable Windows PC based data acquisition system capable of measuring emission levels along with several vehicle and engine parameters. Installing the unit on a school bus takes less than half an hour and requires very few installation tools. The Semtech-D unit incorporates a variety of stand-alone emissions measurement devices to monitor THC, NO, NO_2, O_2, CO, and CO_2 emissions. Since the Semtech-D is a portable unit (78 lb. approximate weight), all of the emissions sensors were modified by Sensors, Inc. by either some or all of the following ways: a reduction in size or weight, decreased power consumption, or reduced sensitivity to vibration and changes in ambient temperature, pressure and humidity.[104] A front panel display of the Semtech-D mobile emissions analyzer can be seen in Figure 45. An important quality of the Semtech-D unit is the vehicle interface that allows the unit to retrieve engine and vehicle information from the ECM. A heated line is used to collect emissions from a probe located in the tailpipe with the following sensors (the internal sensors can be seen in layout format in

Figure 46).

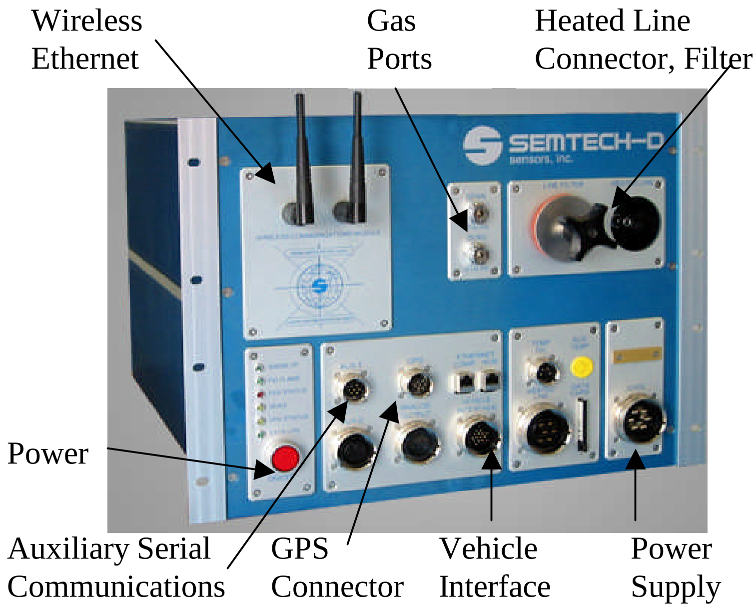

Figure 45: Sensors inc. Semtech-D mobile emissions analyzer

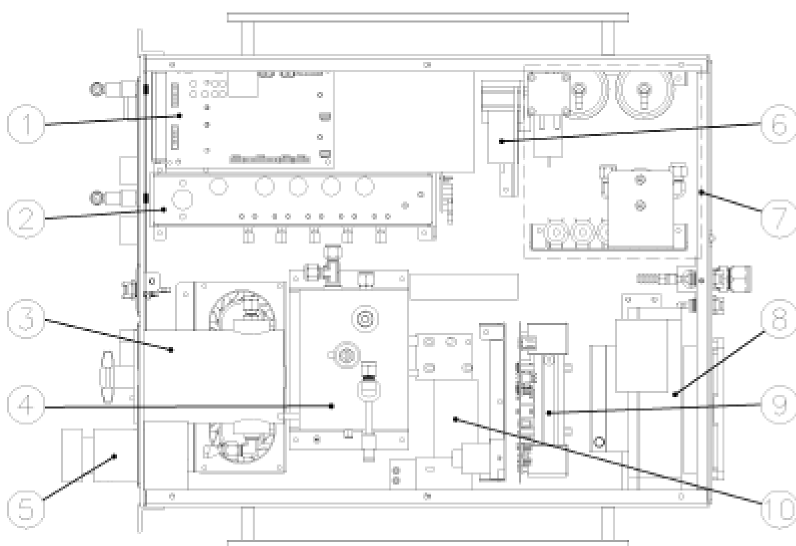

Figure 46: Internal layout of Semtech-D unit[104]

Provided below is the layout description in conjunction with Figure 46:[104]

1. Non-dispersive ultraviolet NO/NO2 analyzer.

2. Pneumatic control panel. This contains pressure regulator, solenoid valves, and needle valves that control the sample to the analytical instruments.
3. Internal Heated Filter. This chamber is heated and controlled to 190 ºC, and holds a replaceable, 0.1 micron filter element to remove particulates from the exhaust stream. The filter is accessed from the front panel.
4. Heated FID chamber. This assembly houses the FID chamber and solenoid valve. The entire assembly is heated to 190 ºC and insulated.
5. Heated line connection.
6. Sample and drain pumps. These pumps provide a cooled, dry sample to the CO2/CO, O2, and NO/NO2 analyzers. The two drain pumps remove water and by-pass sample from the chiller and coalescing pre-filter.
7. Filtration. Two Carbon filters remove hydrocarbons from the ambient air port on the rear panel, and from the FID combustion air. A coalescing pre-filter removes excess moisture from the sample before it enters the chiller. In-line particulate filters protect the pumps and analytical instruments. All filters are disposable.
8. Thermo-electric chiller. This device cools the sample in order to condense water and heavy hydrocarbons before entering the CO2/CO, O2, and NO/NO2 analyzers. The chiller cold-plate is controlled at 4 ºC.
9. Non-dispersive infrared CO/CO2 analyzer
10. FID heated sample pump

Most mobile emissions analyzers on the market are composed of a network of stand-alone sensors. The emissions needed for collection are NO, NO_2, O_2, CO_2, CO, and total Hydrocarbons (THC). Each chemical detected has an important function for data recording, calculations and consequences when released into the atmosphere. The Semtech-D uses a heated, insulated sample line to reduce the loss of THC. The heated line is twelve feet in length and operates at 191 °C. Teflon is used as the wetted surface of the line because of its high heat resistance and low absorbing properties. A heater is wrapped around the Teflon line, which is molded inside a larger insulated flexible tube.[104] The heated line is filtered at the inlet to prevent contamination from particulates.

Oxygen (O_2) is one of the two important reactants for internal combustion in air. O_2 concentration is read using an electrochemical sensor by the Semtech-D gas analyzer. Electrochemical sensors require the sample to be dry before passing over them. The sensor detects the partial pressure of O_2 in the stream and reports it electronically. This technology is used in prior emission measurement devices and gas analyzer companies are attempting to produce products that can continuously give accurate data. Other emissions can also be measured using electrochemical sensors, but more advanced techniques have been developed and are being used by the Semtech-D.

Sensors Inc.'s Non-Dispersive Ultraviolet (NDUV) system is currently the newest technology for NO_x. Sensor Inc. employs a dual NO and NO_2 detection system based on a plasma powered ultraviolet light to detect NO and NO_2 separately. Previous attempts at ultraviolet detection were hindered by the life of the ultraviolet light. The NDUV sensor does not deteriorate like the electrochemical does over time. The most important condition of NO_X detection is the removal of water before the sensor where the exhaust sample is dried with an ambient temperature coalescing filter followed by a thermoelectric chiller. The heavy hydrocarbons found in the diesel exhaust sample are removed from the sample along with a small amount of NO_2 (about 5% of sample) with the water removal process to prevent contamination of the optics.

The NDUV operates at a rate of 2 Hz to collect the continuous concentration measurements for NO and NO_2 to the Semtech-D data collection software via an internal EIA-232 serial connection.[104] The NDUV has an accuracy of 15 ppm, or 3 % of the reading for NO, whichever is greater, and 10 ppm, or 3 % of reading for NO_2, whichever is greater, when properly calibrated at a range of 0 – 5000 ppm and 0 – 500 ppm, respectively, and zeroed prior to a test. [104] Sensors Inc. conforms to the CFR 40 86.1342-90 standard for measuring NO_x, using the following equation. [69]

$$NO_{X\,mass} = K_H \times \sum_{i=1}^{n} \left[\frac{(NO_{X\,dry})_i}{10^6} \times (V_{mix})i \times \rho_{NO_2} \times \Delta T \right] - K_H \times \frac{NO_{X\,d}}{10^6} \left(1 - \frac{1}{DF}\right) \times V_{mix} \times \rho_{NO_2} \qquad 1$$

where $NO_{x\ mass}$ is the oxides of nitrogen emissions (grams per test phase), ρ_{NO2} the density of oxides of nitrogen (1.913 kg/m^3 assuming they are in the form of nitrogen dioxide at 20 °C and 101.3 kPa pressure), and $NO_{x\ dry}$ the oxides of nitrogen concentration of the dilute exhaust bag sample as measured (ppm). For flow compensated sample systems $(NO_{x\ dry})_i$ is the instantaneous concentration. $NO_{x\ d}$ is the oxides of nitrogen concentration of the dilution air as measured (ppm), V_{mix} the total dilute exhaust volume (cubic feet per test phase corrected to standard conditions 293 °K and 101.3 kPa, ΔT the change in temperature, and K_H the humidity correction factor. To obtain the KH to convert from wet NO_X to dry NO_X the 1973 SAE standard[105] is utilized:

$$NOcorr = \frac{NOwet}{K_H} \qquad 2$$

$$NOwet = NOdry(ppm)[1 - \alpha(F/A)] \qquad 3$$

$$K_H = 1 + 7 * A(H - 10.714) + 1.8 * B(T - 29.444) \qquad 4$$

$$A = 0.044(F/A) - 0.0038 \quad 5$$

$$B = -0.116(F/A) + 0.0053 \quad 6$$

where NO_{dry} is the measured NO_x emissions (ppm), α the atomic hydrogen to carbon ratio (y/x in fuel with formula C_xH_y), F/A the fuel to air ratio (Dry Basis), H the specific humidity (grams of H_2O/kg dry air), and T the intake air temperature (°C). The temperature range for this correlation to work effectively is 70-115 °F. Ambient and intake temperature and humidity are measured mainly for this reason. A new correction was developed specifically for use with the school buses tested here.

The AMBII Non-Dispersive Infrared (NDIR) analyzer is used by the Semtech-D to measure CO and CO_2 emissions. This sensor also needs the incoming gas dried to remove heavy hydrocarbons and water vapor that cause interference with the sensor. The gas is dried in the same manner as the NO_x analyzer with an ambient temperature coalescing filter followed by a thermoelectric chiller. If the gas were not dried interference would occur in the infrared channels. Unlike the NO_x emission, the CO_2 and CO emissions do not require humidity corrections. The AMBII NDUV operates on a continuous .83 Hz (1.2 second) data rate to collect concentration measurements of CO and CO_2 to the Semtech-D data collection software via an internal EIA-232 serial connection.[104] The AMBII NDUV has an accuracy of 50 ppm, or 5 % of reading, whichever is greater, when properly calibrated at a range of 1200 – 1500 ppm and zeroed prior to a test. [104]

While infrared and electrochemical cells may work for HC detection, the Flame Ionized Detector (FID) employed in the SEMTECH-D is superior in measurement sensitivity. While keeping a flame lit with hydrogen, a sample is passed over and combusted. The concentration of the HC is then determined by the amount of sample that burns. The FID fuel used for FID flame ignition is a 40/60 mixture of hydrogen/helium. The user can also select a data rate of up to 4 Hz through the Semtech-D application software. The AMBII NDIR has an accuracy of 5 ppm, or 1 % of reading, whichever is greater, when properly calibrated at a range of 0 – 100 ppm and zeroed prior to a test. [104]

In order to calculate the widely accepted emissions units of grams per mile and grams per brake horsepower, fuel flow rate is needed. Using injector pore size, the ECM can measure fuel flow rate, which is the procedure used by Sensors Inc for Semtech-D.

Semtech-D relies on the ECM to provide fuel flow information in order to calculate fuel flow rate and time specific mass emissions. The ECM determines the fuel flow rate based on the real-time pulse width of the fuel injectors.[104] Transient mass emissions are thus calculated by multiplying the fuel specific emissions by the fuel flow rate (NO_2 for example) as follows:

$$NO_2\ (g/s) = NO_{fs}\ (g\_NO_2/g\_fuel) \times Fuelflow\ (g/s) \qquad 7$$

The total fuel consumption can then be calculated instantaneously from the volumetric fuel flow rate and fuel density, which is supplied by the user. The ATC Chemical lab provided fuel density of the fuels tested for this purpose. The fuel flow method of computing mass emissions, CFR40 part 86.345-79 describes the fuel flow method for mass emissions computations for diesel engine dynamometer testing, which is what was used here. The Semtech-D unit also calculates torque to use for calculating emissions in g/bhp-hr. Direct torque output is not available for any of the school buses used in this project, so engine torque was computed by applying the percent load parameter with an engine lug curve (maximum torque curve). The percent-load parameter is defined as:

% Load = (current engine torque)/ (maximum engine torque)

where the maximum engine torque is defined at the current engine RPM provided by the ECM. The engine lug curves for the three buses tested were supplied by the engine manufacturers International and Cummins. The lug curves define the maximum engine torque for all engine speeds. Examples of engine lug curves for the engines tested can be seen in Figure 41, Figure 42, and Figure 43. Using the fuel flow rate and torque measurement it is possible to provide g/bhp-hr emissions units.

The Semtech-D unit is equipped with a compact flash reader, 2 Ethernet connections, 3 RS-232 connections, an RS-485, and two wireless connections. The two wireless connections are designed for use with a laptop computer, and a personal desktop assistant (PDA). The Semtech-D uses a graphical user interface (GUI) for control, monitoring, and analysis of the data collected by the unit. The GUI is displayed on both the laptop screen and the PDA screen while the unit is in use. The data collected is stored in two locations in the Semtech-D. At the end of the test, the run data is loaded onto the laptop and a copy of that data is saved on the compact flash card located on the front panel of the Semtech-D. To validate vehicle speed from the ECM, an external GPS device accompanies the Semtech-D. This device mounts outside of the vehicle to maximize reception. When the data is processed, both ECM speed and GPS speed are represented as columns in Microsoft Excel.

The Semtech-D can be calibrated at any time prior to actually running a test. The unit contains 4 inputs for gas: the ambient port, span/audit port, the sample port, and zero air port. The audit gases are run before and after a test is performed to ensure the sensors are still reading accurately. The user has the option of recording the audit at all times. The span gas is used before a test to calibrate the CO, CO_2, NO, NO_2, and/or THC sensors. The zero air port (pressure regulated) and ambient port (unregulated) is used before a test to calibrate the O_2 sensor. The sample port audits gas through the heated sample line and can be used for any gas channel. For this project the span and zero air ports were used for calibration. The procedure used for the sensors for start-up of the unit is as follows:

1. A zero calibration is performed after the equipment has been properly warmed up. A zero is performed at the beginning of every test day.
2. An audit is performed at the beginning and end of every test to ensure analyzer accuracy. Gas bottles with known concentrations are used for the audit, where the all sensors must meet specified tolerances for a successful test.
3. If any gas channels fail the audit, a span is necessary. A gas bottle of known concentration is used and programmed into the Semtech-D unit. The unit uses the known value to recalibrate the sensor.
4. After the zero, audit, and span if necessary operations are completed a test is ready to be performed. After the test it is useful to perform another audit to check the sensors for drifting. If any audit fails, the test will be discarded.

The Semtech-D uses a Vehicle Interface (VI), which is not always common in emission gas analyzers. However, communicating with the engine's ECM through the VI allows the user to calculate the emission rates in grams per brake horsepower-hour, and grams per mile, which are currently the emissions units used by the EPA. The Semtech-D has the capability of connecting to the ECM, providing the vehicle has one, and reading the data the ECM sends out. Common measurements read from the ECM include vehicle speed, engine RPM, and fuel flow rate. All ECMs must meet SAE programming standards, which enables gas analyzer companies to connect to all engine manufacturer's ECMs with very few connectors.

The VI is also important for Semtech-D to allow the user the ability to follow a prescribed drive cycle on the PC screen. The user inputs a prescribed driving cycle into the Semtech-D software. The target vehicle speed vs. time curve from the prescribed drive cycle is graphically displayed as a line along with the actual vehicle speed, which is shown as a large dot. The driver of the bus attempts to line up the instantaneous dot (actual speed) with the prescribed line (target speed) in order to accurately follow the drive trace. A digital display is also included on the screen that shows the vehicle's actual speed, target speed, time elapsed and remaining, as well as the total drive cycle time.

5.2.4.4.Sensors Inc. PM-300

Particulate Matter was measured using a Sensors Inc. PM-300. The PM-300 is a portable particulate analyzer, which uses a light scattering technology to count particles.[106] A semiconductor-laser emits a beam of light through the exhaust sample, which is carried via a heated hose to carefully control humidity and temperature and then diluted to a ratio of 1000:1, 2000:1, 5000:1, or 10,000:1, depending on the particle sizes being measured. The light is then detected by a photo diode at approximately 90° by way of mirror that is interrupted by the passing particles. Each particle creates a pulse in the beam, which is directly proportional to its size. This signal is then classified into size categories and stored for later download to a computer for analysis. The PM-300 also collects the particulate on a PTFE filter that can be removed for analysis. The PM-300 unit uses a similar twelve-foot heated line as the Semtech-D unit to preserve the integrity of the sample out of the tailpipe and into the unit. The PM-300 can be seen in Figure 47.

Figure 47: Sensor's Inc. PM-300 particulate analyzer

Unlike the Semtech-D, the only pre-test requirement for the PM-300 is to allow the heated sample line to reach a desired temperature of 200 ºF. As stated earlier the PM-300 measures particulates in bins relating to the size of the particulate measured (0.3 micron to 2 micron in 8 bins (0.3, 0.4, 0.5, 0.65, 0.8, 1.0, 1.6, 2.0 microns)). Each bin is recorded on 1-second intervals and is time stamped. The PM-300 measures particulate by the total number of particulates per liter for the particular bin size. To convert from number of particulates per liter (#/L) to g/hr, number of particulates per liter is multiplied by the particulate density (g/m^3), volume (m^3/ #) (assuming spherical geometry =

4/3(Pi) r^3), and dilution ratio (L) of the given particle. The PM-300 uses a dilution ratio of 1000 L. An example of an Excel graph of PM data from the PM-300 is shown in Figure 48.

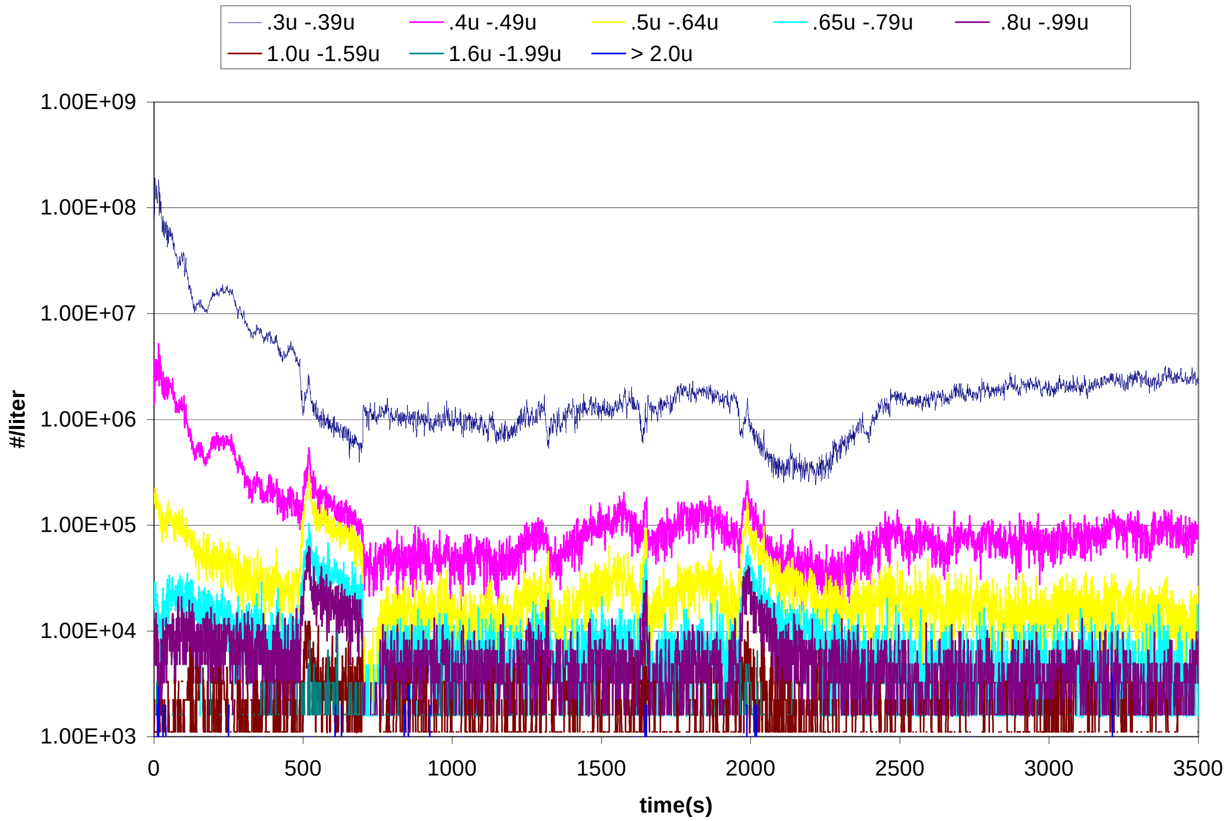

Figure 48: Excel graph of PM data separated by bins

5.2.4.5. ADOCS ATC Data Acquisition System

The ADvanced Onboard Computer System (ADOCS) data acquisition system was used by ATC to combine 32 inputs into one continuous stream. ADOCS was designed by ATC for testing parameters off of any vehicle particularly army type vehicles. Due to the military application ADOCS was built to be very rugged. The system is based on the 32 bit Motorola family of processors and 3U size VME bus circuit cards.[107] ADOCS was used to measure vehicle and engine parameters not provided by the ECM or the Semtech-D unit. ADOCS data is formatted in ATC's Universal File Format (UFF), which can be easily converted to an Excel spreadsheet. ADOCS operates using a Windows based user interface for easier interaction. An ADOCS Signal Conditioning System (ASCS) is used to condition each of the 32 ADOCS channels being used. The ASCS accepts inputs from pressure sensors, thermocouples, and displacement sensors as well as outputs from pulse instrumentation and provides signal amplification, filtering, and calibration.[107] The complete ADOCS and ASCS system weighs approximately 32 lbs. and dimensions of 9 inches width, 10.3 inches high, and 17 inches deep. A complete ADOCS unit is shown in Figure 49.

Figure 49: ADvanced Onboard Computer System (ADOCS)

For the purpose of school bus emissions tesing, ADOCS was used for only a few parameters. The Cummins bus had a fuel flow rate meter installed due to the lack of an ECM. The fuel flow rate was recorded by ADOCS. Three thermocouples were used in conjunction with ADOCS to measure the exhaust temperature at three distinct locations along the tailpipe. The temperature at these locations are pertinent when designing particulate traps where temperature can be an important factor.

5.2.4.6. Data Management

An important part in analyzing the data collected from up to three separate instrument platforms is making certain the data is correctly referenced in time. All three units were started at approximately the same time and all three units report data at 1 Hz. The Semtech-D reports all of its data by exporting it directly into a single Excel spreadsheet. The PM-300 provides a text file, which can be turned into a comma delimited Excel file rather easily. ADOCS data is reported in Universal File Format (UFF), which also can be quickly converted into an Excel spreadsheet. Since, for example, percent load (reported by Semtech-D) is important in the concentration of particulates (PM-300) it was important to have all data in a single Excel spreadsheet. All three pieces of equipment provide time stamping, which is a definitive way to reference all three Excel files compiled from the equipment into one single file for the analysis.

Data collected by ATC personnel during testing was sent electronically to Rowan for analysis. Included with all data was a running log file that was up to date with the current data being forwarded. Every log consisted of the following data: day of test, time of test start and end, daily run number, fuel type, school bus type tested, equipment used, school bus driver, success of audits, and any additional comments to describe the test run. The data was then separated into folders named according to date and then data type (e.g. PM-300, Semtech-D, audit, etc.).

5.3. Development of a New Mobile Emissions Test Cycle for School Buses

5.3.1. Introduction

Federal regulation requires that all heavy-duty diesel vehicles (HDDV) complete an engine certification process using the Transient FTP engine dynamometer cycle.[108] Several emission-testing cycles, such as the Transient FTP, have been developed for federal and private emission testing purposes. These HDDV testing cycles are based upon speed versus time traces. Traditionally, diesel engine emissions are measured using a cycle in a stationary position with the engine either in a vehicle on a chassis dynamometer or the engine alone using an engine dynamometer. Mobile emissions' testing consists of the engine emissions being measured from the mobile vehicle being tested on the road. There are presently emission test cycles developed for transit buses and delivery trucks, which are not approved or adopted by the EPA, using a chassis dynamometer for the testing, but no cycles have been created for mobile testing.

Prior to the present study there existed a scarcity of emission test cycles developed specifically for school buses. Moreover, mobile-on-road or in-use emissions testing is relatively new to the emissions testing field, so a standard test cycle for mobile school bus emissions testing was not available. Accordingly a new standard test cycle for mobile school bus emissions testing was developed as part of the present study. The Rowan University Composite School Bus Cycle (RUCSBC) was developed using actual global positioning system (GPS) data from a variety of prototypical New Jersey school bus routes. The school district routes were chosen based upon the population density of the district, school age children population of the district, the total number of the district's buses, and the total number of students in the district. The RUCSBC can be broken down into three sections to represent the three common areas of the state: rural, suburban, and urban. As described below, the RUCSBC was used to simulate a typical New Jersey school bus route in order to compare baseline emissions to emissions with a variety of fuel types.

5.3.2. Literature Review

The 2007 HDDV emission standards have lead to extensive testing of the vehicles and their engines on both chassis and engine dynamometers. The extensive testing has led to an increasing number of test cycles being created to represent some type of driving pattern for the HDDV industry. Only a few test cycles have ever been created using actual data collected from the vehicle during its normal operation. To date there has also been no test cycle known created specifically for school bus mobile emissions testing. This literature search is provided to show the function of current emission test cycles, how the cycles were developed, and what the cycles were developed for.

West Virginia University (WVU) developed a route for delivery trucks using data from actual delivery truck routes. The City Suburban Heavy Vehicle Route (CSHVR)[109] was designed to consider power-to-weight ratio of the vehicle running the route. A route differs from a cycle in that a route allows the full power of the vehicle being tested to be employed.[109] In a route the vehicle follows a speed vs. distance trace allowing vehicles with the ability of more rapid accelerations to finish the route in less time. A cycle is a speed vs. time trace and should be completed in the same amount of time by every vehicle regardless of its power or size.

The CSHVR was developed from data collected from Classes 7 and 8 delivery trucks (from two different trucking companies, one based in Akron, Ohio and one from Richmond Virginia). Speed vs. time data along with video recordings were collected for the trucks for a total of approximately 60 hours. The data was broken down into a total of 130 microtrips. The definition of a microtrip for this route was defined typically as driving from one delivery site to another. The 130 microtrips were further separated into categories: interstate freeway, suburban, city, and yard with the aid of the video taped data.

All of the microtrips from the CSHVR were analyzed to determine the percentage of time when the vehicle was accelerating, decelerating, and cruising. The idle time and average velocity for each microtrip was also taken into account. The microtrips were then randomly selected and concatenated using a computer program yielding 10,000 possible combinations. The constrained time range of the cycle was 1000-1600 seconds. The most representative cycle was then determined using a route mean squared (rms) approach using the following parameters: standard deviation of speed, average speed, and percent cruise time. Each of the parameters chosen for the most representative cycle was weighted evenly. These were all compared to the desired database values for each category. The cycle with the lowest rms was chosen as the most representative cycle. When performing the analyses, the idle time was removed and then added back in at the end so that only the vehicles motion was characterized. In the WVU, individual driver habits determined the amount of idle time the vehicle would incur (whether or not they would leave his/her vehicle on during deliveries, etc.). The CSHVR is shown in Figure 50.

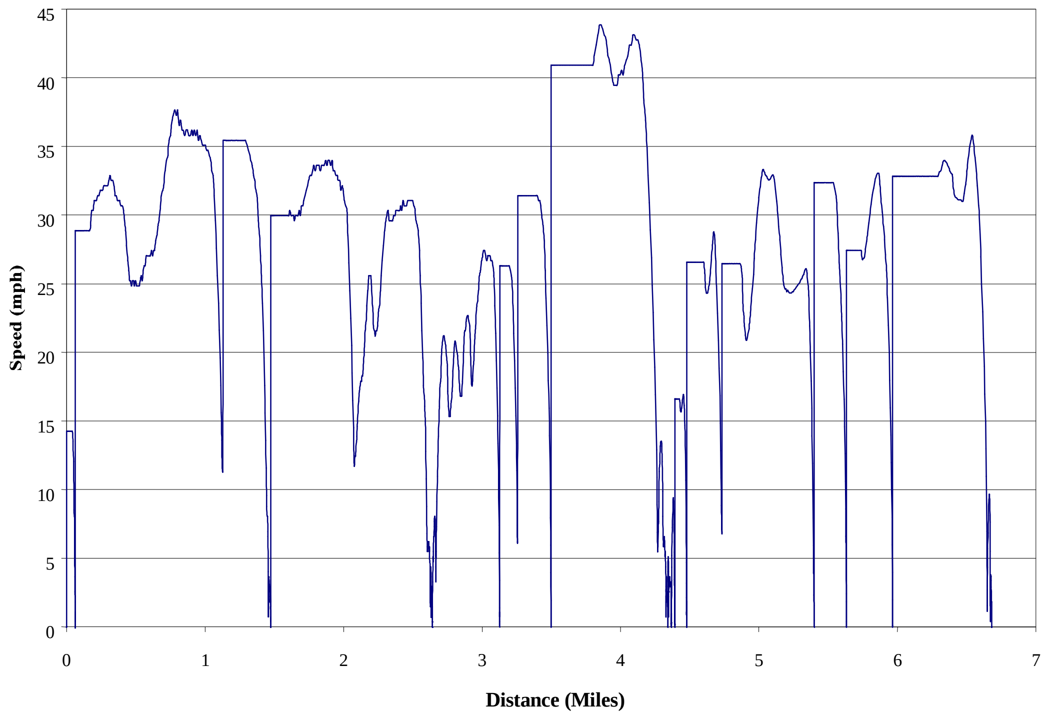

Figure 50: City Suburban Heavy Vehicle Route

Three additional cycles were developed by WVU using the same procedure discussed for the CSHVR: the Yard, City-Suburban, and Freeway cycles. There is also a discussion of driver repeatability and positive comparison between different drivers performing the same cycle in reference to output emissions. These results include discrepancies of 11.1% for CO and 14.8% for PM, which were the emissions most influenced by using various drivers (NO_x emissions varied slightly).

National Environmental Protection Council Service (NEPCS) presented a method used to take real driving data and construct a representative cycle. In creating a representative cycle, the trips (velocity vs. time data collected) were separated into microtrips similar to the WVU study. The definition of a microtrip is a period of idle, followed by a period of driving activity until it again comes to rest, whereupon a new microtrip begins.[110] The idle periods at the ends of a driving trip were not analyzed as microtrips, but were factored into the representative cycle at the end. The two most important variables chosen in classifying road trips were average speed and idle time.

Some statistical information was then calculated for each microtrip and they were separated into the following categories: congested, residential/minor, arterial, and freeway/highway. In the NEPCS study, the most representative microtrips were those that spent time at speeds and accelerations in similar proportions to those of all the microtrips combined. The chosen microtrip was the one that minimized the empirical distribution function between it and all of the microtrips. However, the length of the idle period was also factored into and weighted heavily into representative microtrip selection.

One of the earliest and a well-documented heavy-duty vehicle cycle was developed for city buses. The "Central Business District" (CBD) Cycle (SAE recommended practice J1376) was developed to simulate heavy-duty buses during inner-city operation. This test is well established and, arguably, accurately accounts for the exhaust emissions from heavy-duty inner-city buses (Clark et al., 1994). The CBD Cycle consists of 14 accelerations and 14 steady state operation periods at 20 mph each followed by a deceleration and an idle period, as depicted in Figure 51. Total traveled distance for the CBD is 2 miles. There are a few disadvantages of the CBD that tend to limit its use beyond inner-city buses. One of these disadvantages of the CBD is the high acceleration rates with the cycle. A typical class 8-road tractor with an unsynchronized transmission could not follow the CBD acceleration ramps successfully (Clark et al., 1994). The Central Business District (CBD) Cycle is a chassis dynamometer testing procedure for heavy-duty vehicles (*SAE J1376*). The CBD cycle represents a "sawtooth" driving pattern, which includes 14 repetitions of a basic cycle composed of idle, acceleration, cruise, and deceleration modes.

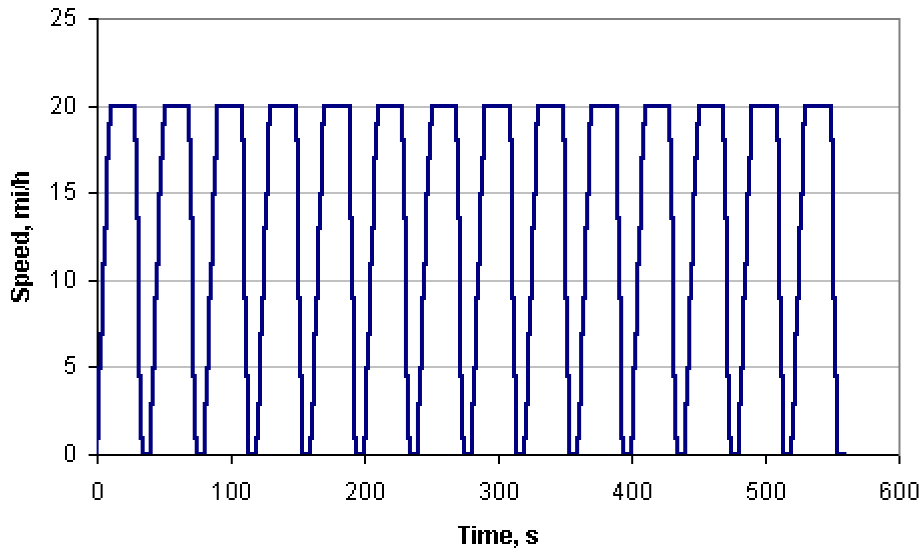

Figure 51: Central Business District Cycle

5.3.3. Procedure for Generating a New Mobile Cycle

The first step in generating the mobile school bus cycle was to take actual GPS data from a variety of prototypical school districts in NJ. In each case, a Garmin GPSMAP 765 Global Positioning System was placed on the school bus and activated at the beginning of a normal bus route and stopped when the bus returned to school. There were a total of five school bus districts examined from three different counties. These districts were as follows: Deptford (Gloucester County), Pittsgrove (Salem County), Medford (Burlington County), Washington Township (Gloucester County), and Glassboro (Gloucester County).

In total, data from 11 different school bus routes (each referred to as a single "trip") were acquired. Each trip was then separated into microtrips (sometimes called a sequence). Each microtrip (or sequence) consists of a period of idle, followed by a period of acceleration and deceleration, until the bus again comes to a complete stop at which time the next microtrip starts.[111] A total of 135 individual microtrips were generated from the data. In addition, most of the trips contained a period of idle at the end. For simplicity, the idle times were not included in any of the statistical analyses, but were later factored into the developed cycle to accurately represent the typical idle a school bus would incur.

5.3.3.1. Types of School Districts /Regions

The microtrips were separated into three categories based on the average speed of the microtrip. Category A included the microtrips with a mean speed range of 0-20 mph, category B a range of 20-35 mph, and category C a range of 35+ mph. Since idle is very important in characterizing school bus driving behavior (typically many stops for child pick-up/drop-off), idle were used in calculating the mean values of microtrip speed, thus slightly reducing the averages.

Each of these categories (A, B, and C) were designed to represent a different type of region in NJ: urban, suburban, and rural. An urban area would be considered to be most densely populated and would reside predominantly within category A. Glassboro and Washington Township (both located in predominately urban Gloucester County) are classified as urban areas according to the NJ State Data Center 2000 report.[112] These urban area microtrips therefore have the lowest mean speed, the shortest duration, shortest distance, and the largest percent of idle time at the beginning of each microtrip (signifying more stops, made more often, with more children at each stop).

Category C microtrips represented the rural area in NJ, which are the least densely populated areas. The rural areas of NJ were characteristic of having the highest mean speeds, the longest duration, the longest distances, and the shortest idle times (signifying fewer stops that are further apart with less children at each stop). Pittsgrove, located in predominately rural Salem County, has the lowest population density of the data taken and is classified as mostly rural by the NJ State Data Center 2000 report. [112]

Those microtrips belonging to category B were considered suburban and its statistical characteristics fell in between categories A and C. Deptford is classified by the NJ State Data Center as mostly urban, however statistical data from the school bus routes places the Deptford runs mainly in the suburban category for the cycle development purpose. Medford, which is located in the mixed, urban and rural, Burlington County also contains some urban and some rural population. Medford also has the second lowest population density of the GPS taken and was classified as suburban for the purpose of the RUCSBC development. A breakdown of the rural and urban districts are shown in Figure 52, which is provided by the U.S. Census Bureau, with the urban areas shaded. A population and demographic breakdown of the five districts for which data was collected is shown in Table 24.

Table 24 Prototypical NJ School Bus Districts[112,113]

District	**Medford**	**Washington Twp.**	**Glassboro**	**Pittsgrove**	**Deptford**
Population	22,253	47,114	19,068	8,893	26,763
Population Density People/Sq. Mile	561	2091	1898	195	1414
Amount of Rural Population	2,690	0	252	5,907	0
Amount of Urban Population	19,563	47,114	18,816	2,986	26,763
Number of Students	2949	9761	2518	1878	4107
Number of Schools in District	5	11	5	4	9
Number of Buses in District	30	73	23	27	41

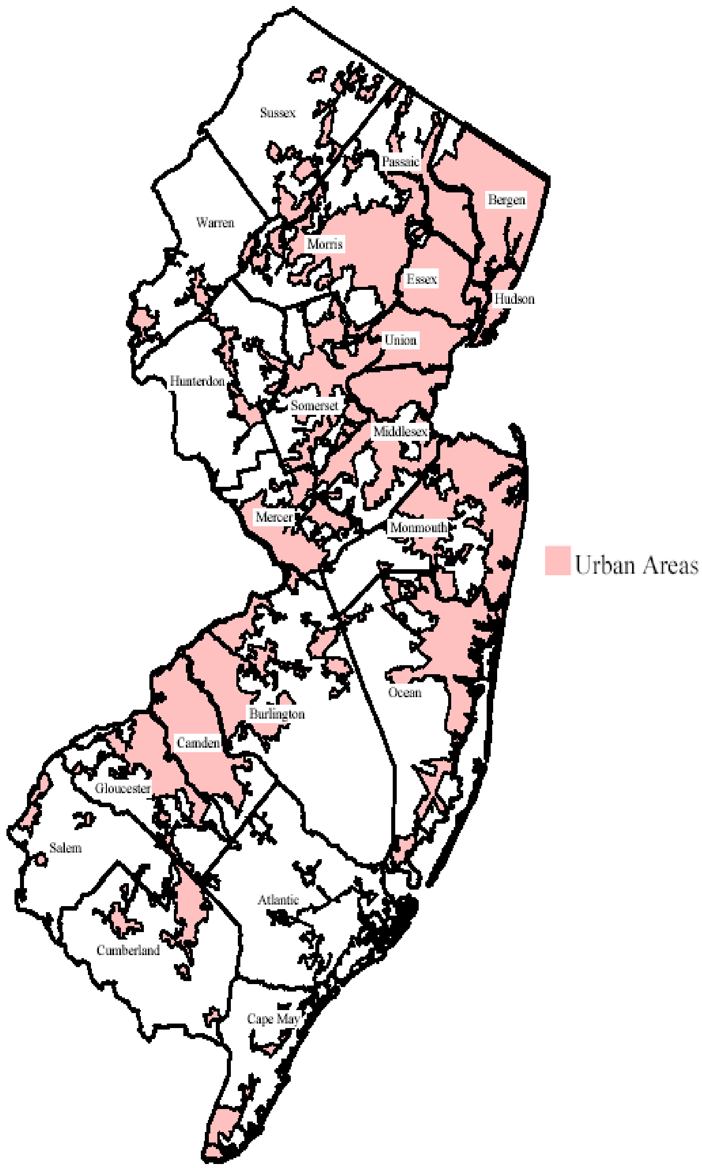

Figure 52: New Jersey Population Breakdown by Urban and Rural Regions[112]

5.3.3.2. GPS Mapping: Experimental Procedure

The Global Positioning System (GPS) used for school district route data acquisition was a Garmin GPSMAP76S. The GPS used for data acquisition is capable of acquiring up to 500 waypoints and about one hour of data before loading the data onto a computer. The unit has a position accuracy of approximately 15 m and a velocity accuracy of 1.15 mph. Data is processed using Excel and the Garmin supplied software Map Source. The GPS transfers data to a PC in the form of an Excel file, which includes the following information: position, altitude, time, leg length, leg speed, leg time, total time, average speed, and leg course. The Garmin GPSMAP76S unit is shown in Figure 53.

Figure 53: Garmin GPSMAP76S

The GPS was placed on the school bus for each respective district. Data acquisition started when the school bus driver started the bus for their route and ended when the school bus was turned off for the same route. Waypoints were taken at specific locations to mark the route and the school bus stops. The GPS was then connected to the serial port on the computer through a PC cable and data was transferred in text format for analysis. Data to create the cycle was taken in the form of a speed vs. time drive trace. The speed vs. time drive traces for the Medford, Washington Township, Glassboro, Pittsgrove, and Deptford school districts are shown in Appendix A.

In a similar format to the drive traces, data was transferred to the Map Source software provided by the Garmin Company, which created an actual map of the school bus route. The map created by the Map Source Software is similar to a common road map except the drive trace of the school bus is highlighted and the school bus stops are marked. Two maps are shown for the Washington Township and Pittsgrove school districts Appendix A. Note that the Washington Township map contains three separate runs consisting of an elementary, middle, and high school route. Figure 54 and Figure 55 are examples of typical map and speed vs. time traces acquired during testing, respectively.

Figure 54: Pittsgrove Township GPS Map

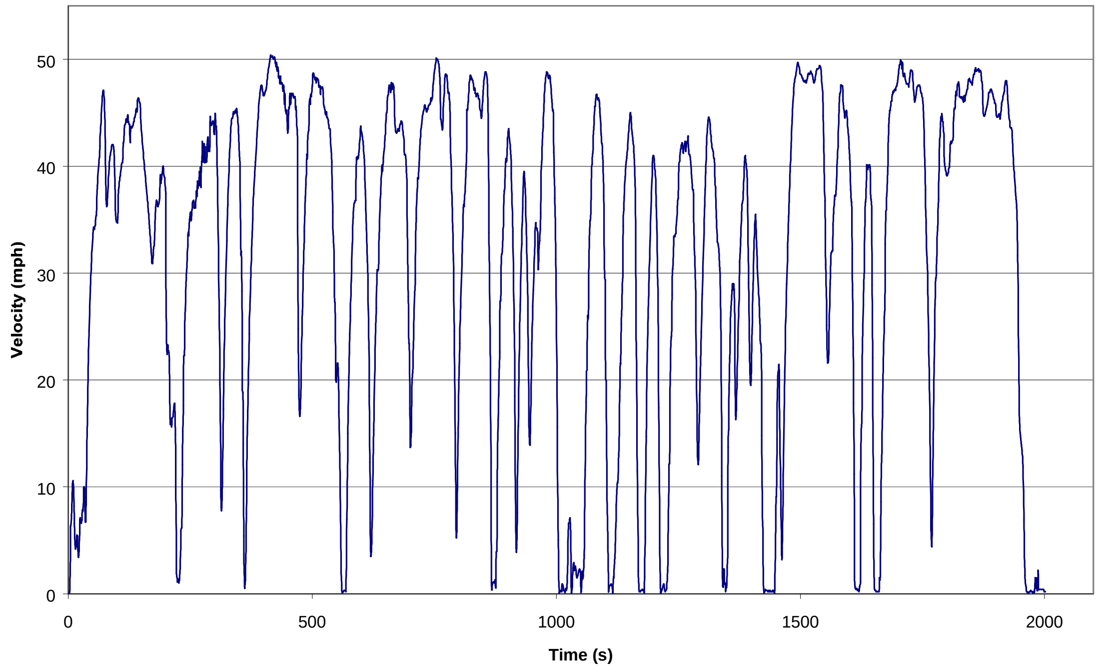

Figure 55: Pittsgrove School District velocity vs. time profile

5.3.3.3. Data Reduction/Cycle Development

Statistical information from the GPS data was first calculated for each microtrip. The following metrics were calculated for each microtrip for further data analysis:

- maximum microtrip velocity (mph)
- average velocity (mph)
- standard deviation of velocity
- total time (s)
- total distance (miles)
- percent idle (%)

The same statistical calculations were performed on all 135 individual microtrips and averaged over all of the microtrips within each of the three categories. Table 25 provides statistical information on the microtrip characteristics of urban (A), suburban

(B), and rural (C) areas, respectively. As mentioned previously, urban areas have the lowest mean speed, the shortest length of a microtrip in time and distance, and the longest average idle time (more students at each stop). Rural areas generally tend to have more pick-up stops and only one or few students to pick up at each stop. The total numbers of microtrips in each category were 71, 57, and 7 for categories A, B, and C respectively.

Table 25: Statistical Information on Microtrip Categories

Microtrip Category	**Mean Speed (mph)**	**Average Time (seconds)**	**Mean Distance (miles)**	**Average Idle Time (%)**
Urban (A)	12.7	65.9	0.2	22.5
Suburban (B)	28.7	130.5	1.1	8.0
Rural (C)	38.3	192.0	2.1	3.6

One final check to make sure that the categorical separation makes sense was to look at specific bus trips. Washington Township and Glassboro were considered the most urban of the areas tested. All trips from these areas were made up primarily of category A microtrips. The Pittsgrove runs were considered the most rural and were composed mostly of microtrips from categories B and C, containing only a few microtrips from category A. The Medford and Deptford trips were a mixture of microtrip types and are classified as suburban.

Once the microtrips were separated into categories, the most representative microtrips in each category were chosen. The most representative of the microtrips were those that had the closest relationship between the average speed, standard deviation of velocity, and % idle as compared to that of the total values for each category. To determine the closest microtrips, a root mean squared calculation (performed using MATLAB) with these parameters, equally weighted, was performed. The root mean squared equation used to determine the closest microtrips is as follows:

$$rms = \sqrt{(V_T - V_{m_i})^2 + (Std_T - Std_{m_i})^2 + (\%I_T - \%I_{m_i})^2} \qquad 8$$

where V_T is the mean velocity, Std_T the standard deviation of velocity and $\%I_T$ the percent idle time of all of the microtrips in a certain category. The terms V_{mi}, Std_{mi}, and $\%I_{mi}$ are the mean velocity, standard deviation of velocity, and percent idle time of each individual microtrip from a certain category, respectively. Accelerations, decelerations, and cruise time were not considered in the determination of the most representative cycle due to the time lag that is associated with the GPS device.

Once each representative microtrip was selected, its empirical cumulative distribution function (ECDF) was graphed and compared to the total ECDF for all microtrips to ensure that they passed a visual inspection and that they followed similar trends. The "ECDF" was plotted using the Matlab statistical toolbox.

To construct the most representative cycle, parameters such as time length, number of each type of microtrip, and duration of end idle needed to be determined. A minimum length of 20 minutes was chosen because it was within the range of the length of the bus trips analyzed and could be comfortably executed by a driver at ATC. To determine the number of microtrips to use from each category, the percentage of the total time of all trips that each type of microtrip and idle period composed was calculated. The representative cycle was then developed with similar time proportions.

The representative microtrips were concatenated until these desired parameters were fulfilled. The composite cycle was obtained by choosing the 6 most representative category A microtrips, the 6 most representative category B microtrips, and the one most representative category C microtrip. Once the microtrips were pieced together, an average idle was added to the end of the representative cycle consisting of 47 seconds, which was the average duration of “end of run” idle time for all of the 11 bus routes. The total duration of the RUCSBC cycle is 1241 seconds.   See Table 26 for a breakdown of category percentages pertaining to the desired time length of each category and the actual length of each category in the RUCSBC.

Table 26: Microtrip Times for a Cycle with a Minimum of 20 Minutes

Microtrip Category	**Time Desired (seconds)**	**Time Obtained (seconds)**	**% Difference**
A	400.9	445	8.8
B	636.8	658	1.31
C	115.0	74	36.9
Idle Time	47.3	47	2.66

To ensure that the cycle was easy for a driver to follow and perform, an additional idle period (10 seconds) was added at the beginning of the cycle and all of the idle periods were zeroed (the GPS has an accuracy of 2mph).   The velocity vs. time profile of the RUCSBC can be seen in Figure 56. The RUCSBC (velocity vs. time) is also shown in Figure 57 broken down into the three-microtrip categories urban (A), suburban (B), and rural (C).

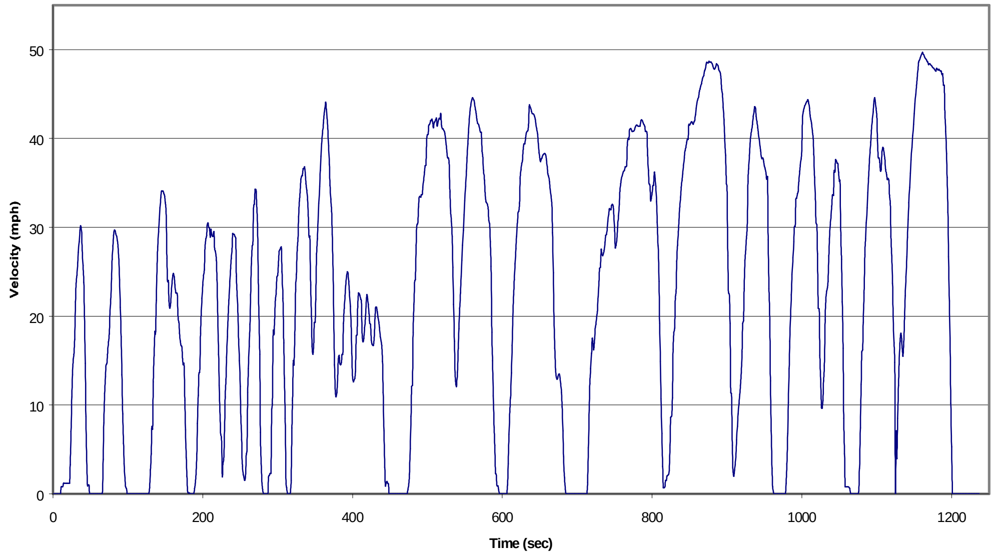

Figure 56: The Rowan University Composite School Bus Cycle

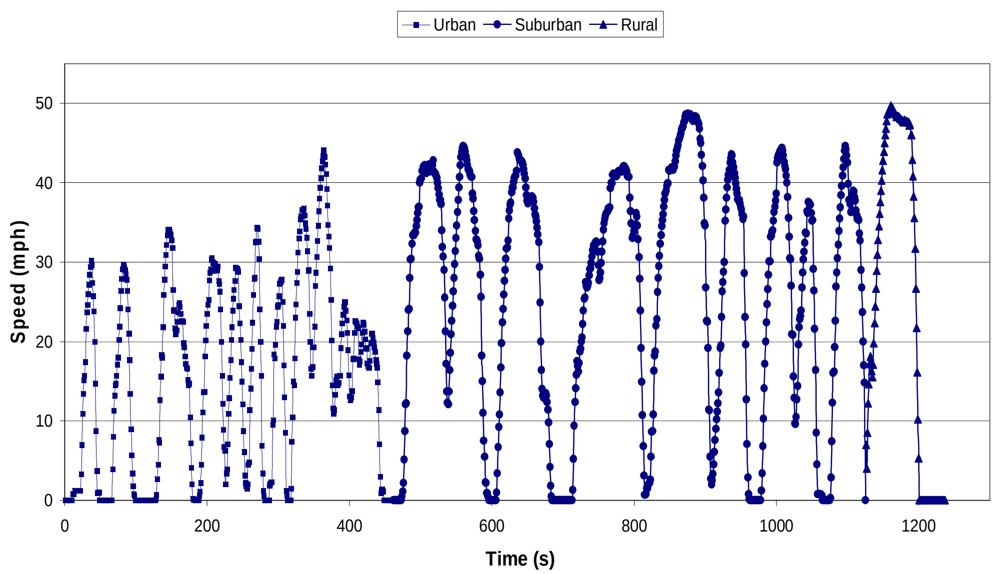

Figure 57: Rowan University Cycle Separated by Representative Regions

A visual inspection of the cycle illustrates an apparent distinction between the urban, suburban, and rural components. Finally, because prior mobile test cycles created and tested by Rowan using GPS data contained some considerably harsh accelerations and decelerations (due to GPS lags), the velocity gradient of the RUCSBC was graphed (using Matlab) and inspected. The areas with high accelerations and decelerations were manually smoothed such that the maximum value was adjusted from approximately 10mph/s to 7mph/s. This adjustment allowed the driver to follow the Semtech trace provided by the ECM more smoothly and accurately.

An initial driving test of the cycle was performed successfully at the ATC 1-mile loop. During the driving test it was shown that the same driver could execute the cycle with adequate repeatability. The close repeatability of the driver following the Semtech speed trace is shown in Figure 58, and again in Figure 59, which is a speed vs. time trace of the RUCSBC driven on the 1-mile loop by the same driver using the DT466 bus. The processed data also showed close comparison between the same two runs with respect measured emissions, further proving the cycle's repeatability. Figure 60 and Figure 61 show the instantaneous NO_x concentration measured during the two runs shown in Figure 58 and Figure 59. From Figure 60 and Figure 61 it is evident that during the idle periods of the RUCSBC the NO_x levels always returned to the same concentration and peaked at similar positions during the cycle. From the emission and GPS data it was concluded that the RUCSBC is a repeatable cycle when executed at conditions of similar temperature and absolute humidity.

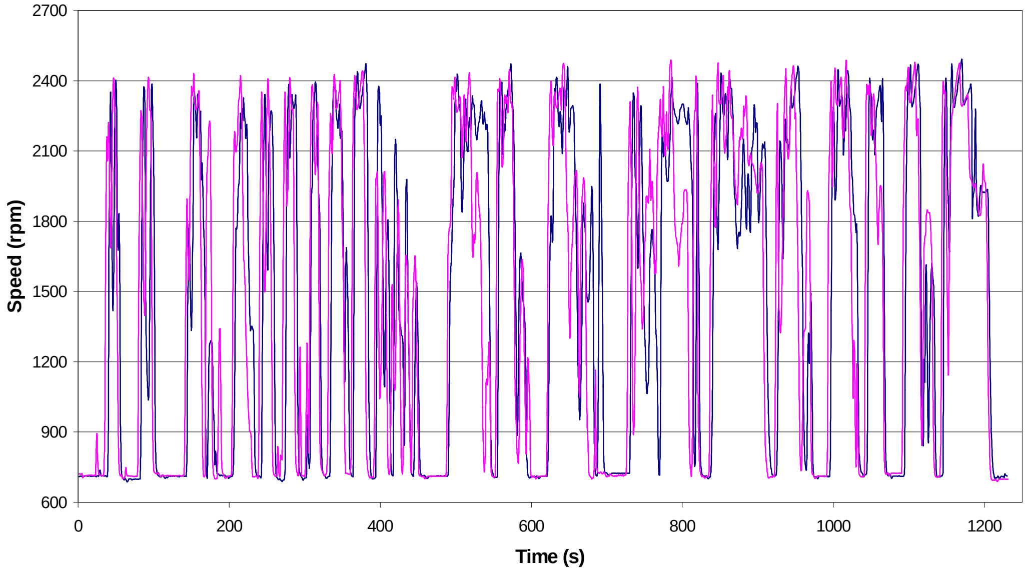

Figure 58: Speed Trace of Two Separate Runs of the RUCSBC

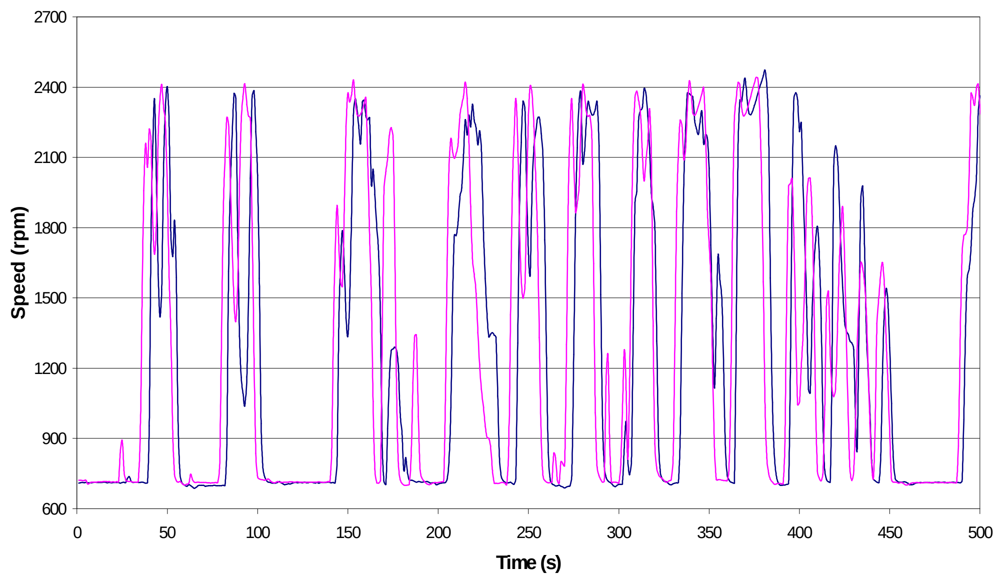

Figure 59: Speed Trace of Two Separate Runs of the RUCSBC (Reduced Axis)

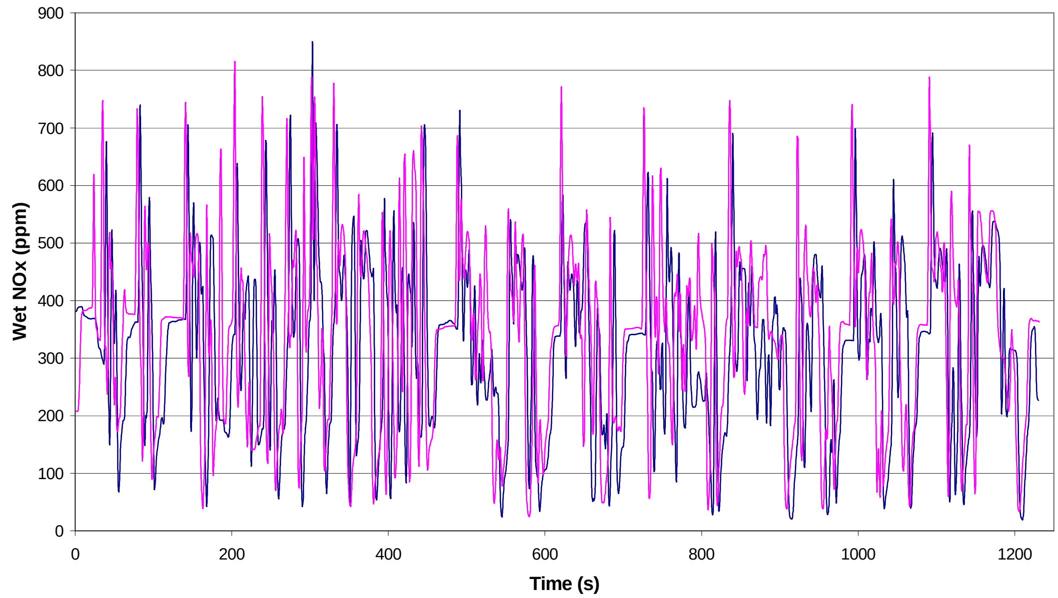

Figure 60: NO_x Concentration Trace of Two Separate Runs of the RUCSBC

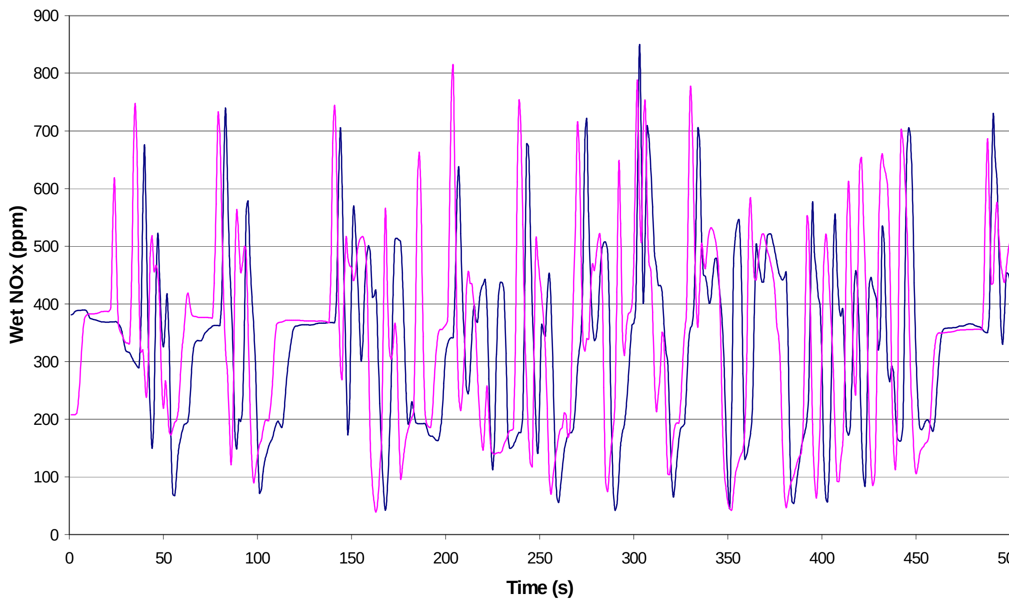

Figure 61: NO_x Concentration Trace of Two Separate Runs of the RUCSBC (Reduced Axis)

5.4. Rowan On Road Medford Township School Bus Testing

5.4.1. Introduction

This section provides emissions data taken from school buses in the Medford Township School District running on #2 diesel and biodiesel. In conjunction with the school bus emissions reduction study being performed at ATC, Rowan University performed emissions testing at a local school district already running biodiesel. Since a local school district (Medford, NJ) currently employs a B20 biodiesel blend to fuel 50% of their fleet, actual on-road emissions data were acquired in addition to the tests performed on the test track at ATC. The on-road tests were performed at the Medford Township School District in Medford, NJ on four of the districts 44 buses. Over the past five years, Medford has converted half of their 44-bus fleet to a blend of 20 percent biodiesel and 80 percent petroleum (B20) purchased from World Energy Alternatives. Since converting Medford has had no known problems with running biodiesel even at temperatures of 11 degrees below zero[86].

5.4.2. Purpose of Medford Study

In recent emission reduction programs for heavy-duty diesel engines, biodiesel has become a popular alternative fuel for testing. In an effort to acquire as much emissions data as possible, Rowan tested at the only school district in NJ and the surrounding area running school buses on any mixture of biodiesel. Tests were performed in Medford in the month of January on two separate occasions. Since 1997, Medford has run biodiesel in almost half of their buses, but they had never had them tested for emissions to see if their efforts in running on biodiesel were worthwhile. Rowan was able to provide Medford with emissions data that could only otherwise be acquired by purchasing or renting expensive testing equipment. Medford was able to provide Rowan with buses that have been running on biodiesel for many years, which is in contrast to the other results presented, which present the immediate results of switching from one fuel to the next.

5.4.3. Medford School District Biodiesel Program

Medford Township, located in mainly rural Burlington County in central New Jersey, received a grant in 1997 to convert half of the fuel used in their school bus fleet of 44 buses (which can be seen in Figure 62) to a B20 mixture of biodiesel. The U.S. Department of Energy provided the New Jersey Board of Public Utilities, Division of Energy $115,000 for the project under a 1997 grant. Since 1997, Medford school buses have logged over 400,000 miles on buses operated by biodiesel. Medford school district director of operations and technologies Joe Biluck, Jr. spearheaded the movement to biodiesel in the districts buses. Biluck has noticed only positive results since switching,

> "We've had no down time as a result of this fuel. We've seen no drop in miles per gallon, which means the engines aren't working any harder." "We've never had a fuel system gel up on us," Biluck said. "We've run down to temperatures of 11 degrees below zero and haven't experienced any problems."[86]

Medford Township School District is the oldest account held by biodiesel supplier World Energy Alternatives. The only added costs for Medford in running with biodiesel has been the slightly higher cost for the fuel (~$0.15) and the addition of a biodiesel storage tank, which is shown in Figure 63.

Figure 62: Medford Township's biodiesel operated school bus fleet

Figure 63: Medford biodiesel storage tank

5.4.4. Experimental Setup: Test Procedure

All four buses tested in Medford used International DT466 engines. The specifications of the school buses tested can be seen in Table 27. Buses 76 and 80 have been operated using B20 fuel for four years while Bus 84 has been operating for only one year. Bus 77 has been operating entirely on #2 petroleum diesel, since it was put into the Medford school bus fleet in 1998. The 2002 and 1998 DT466 series engines were similar in all aspects (displacement, power, etc.) except total number of miles (about ¼ of the miles on Buses 76, 77, and 80). The same school bus route was performed twice on each school bus using the Semtech-D and Garmin GPS equipment to measure the vehicle parameters and emissions. Note that the Medford cycle was used as one of the 11 cycles to create the RUCSBC.

Table 27: Vehicle and engine data for Medford school buses investigated.

Medford Bus #	**Engine**	**Fuel**
76	’98 International DT466	B20
77	’98 International DT466	#2 Petroleum Diesel
80	’98 International DT466	B20
84	’02 International DT466	B20

The Medford school bus route shown in Figure 64 is approximately 8.25 miles in length and has a duration of approximately 25 minutes. The tests were performed in January at the same approximate temperature of 35 °F and absolute humidity of 9 grains/lb.-dry air. The same driver was used for all Medford school bus data collected. All of the bus routes had approximately the same average engine and vehicle speeds of 1480 rpm and 20 mph, respectively.

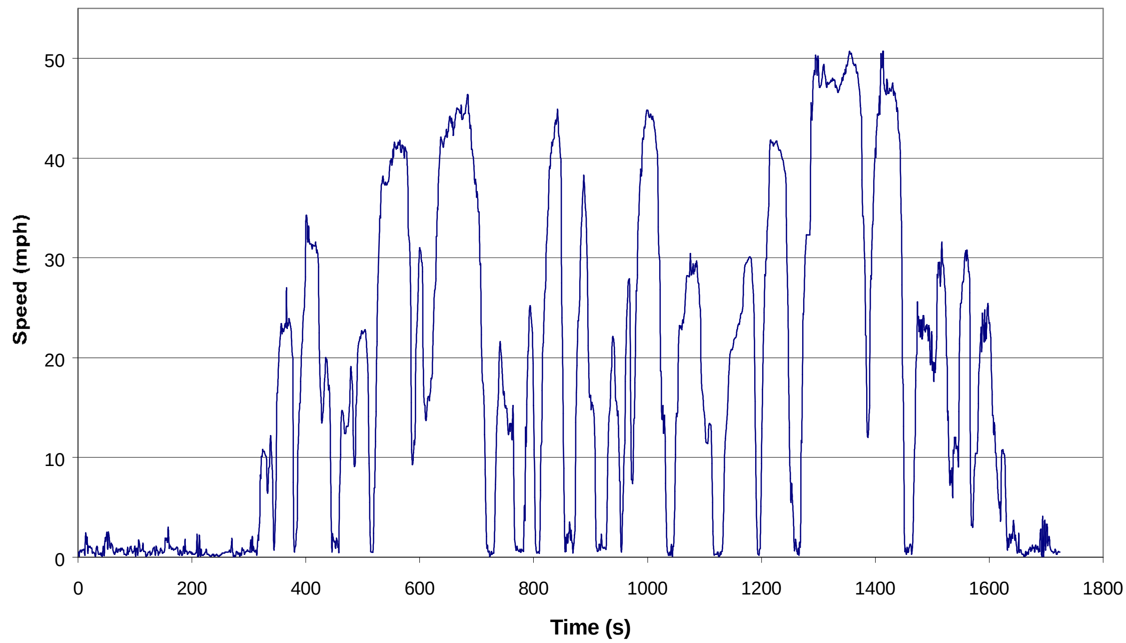

Figure 64: Speed Trace of Simulated Medford School Bus Route

5.4.5. Test Results

5.4.5.1.Medford Fuel Consumption/Total Work

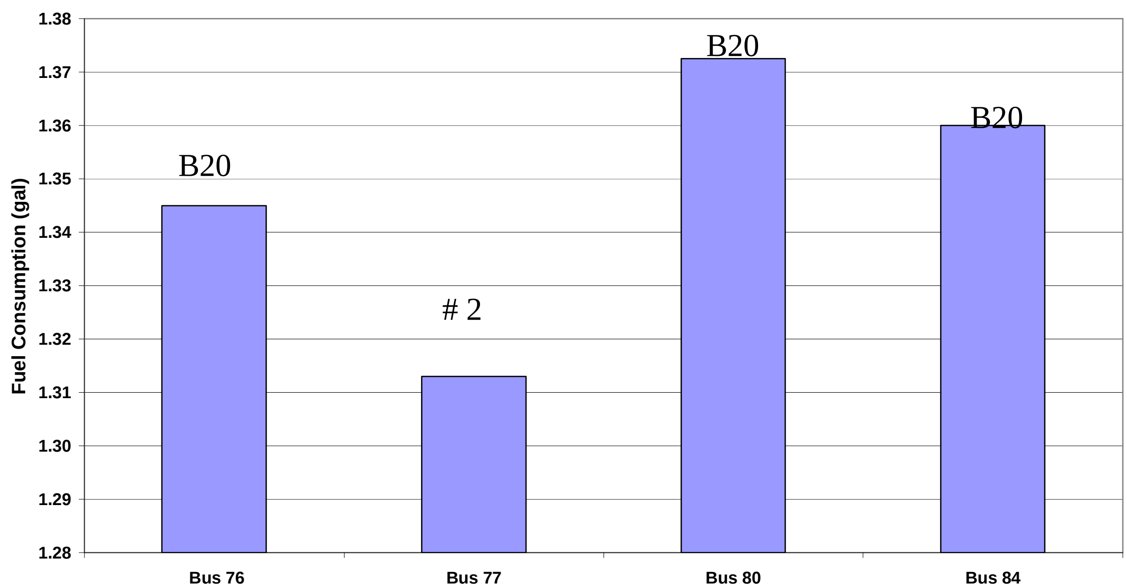

Figure 65: Fuel Consumption for Medford school buses tested

As described in previously, Semtech-D relies on the ECM to provide fuel flow information in order to calculate fuel flow rate and time specific mass emissions. The ECM determines the fuel flow rate based on the real-time pulse width of the fuel injectors.[104] The total fuel consumption is then calculated instantaneously from the volumetric fuel flow rate and fuel density, which is supplied by the user. There was no fuel analysis completed on the Medford fuels so the standard value of .85 g/cm^3 was used for fuel density of # 2 petroleum diesel and .86 g/cm^3 was used for B20 (estimated based on B20 used for ATC Fuels test).

Biodiesel is expected to increase fuel consumption due to its 8 % lower calorific value by volume when compared to conventional diesel. [85] Previous studies have found that a B20 blend produced a 1.6% reduction in fuel economy when the biodiesel was produced from soybeans or rapeseeds. [85] Figure 65 shows that for all Medford buses tested operating on a B20 blend there was an increase in fuel consumption. The B20 fueled buses increased fuel consumption slightly 2.4 % for Bus 76, 4.5 % for Bus 80, and 3.6% for Bus 84.

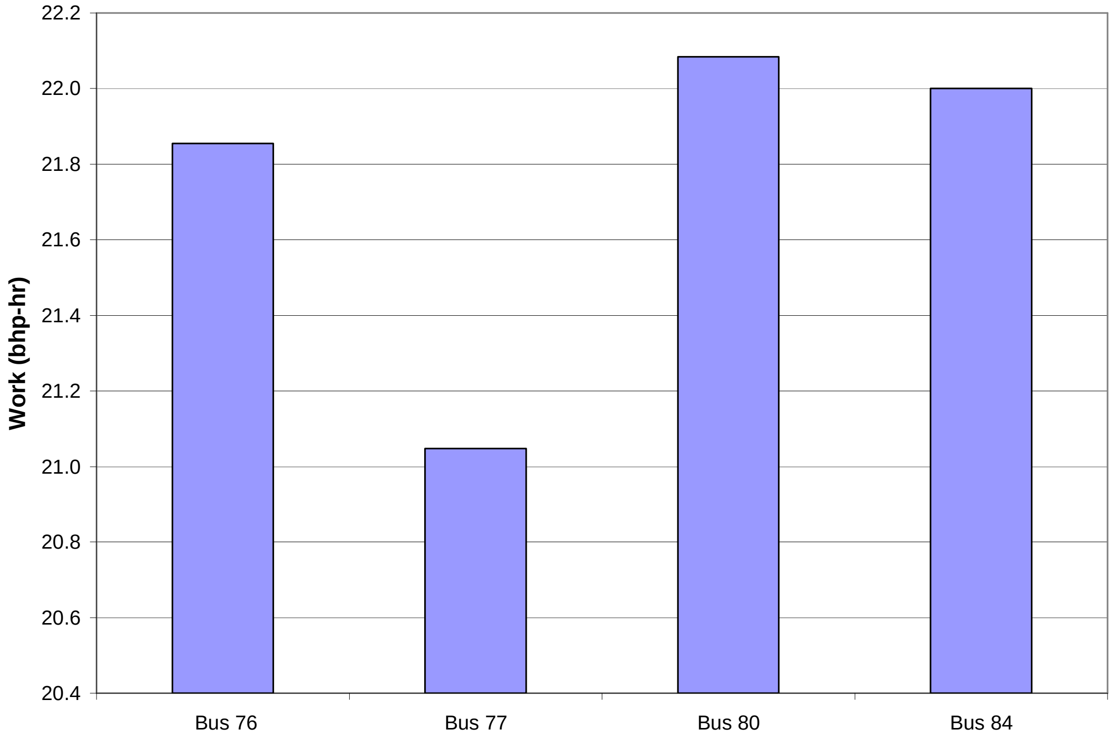

Figure 66: Work for Medford school buses tested

The engine torque is computed by Semtech-D using the engine's known lug curve and vehicle parameters such as engine speed and % load. The torque is then used to calculate the total work done by the engine for each second of the test and integrated over the total time of the test. Figure 66 shows the total work for the Medford school buses tested. Variations in traffic patterns may account for the variations in total work for the same route. As shown in Figure 67, fuel consumption is proportional to the total work the engine undergoes to complete the cycle. The same driver using the same route performed the Medford school bus emission runs. However, the tests were not run under controlled conditions, so factors such as stop lights and pedestrian traffic influenced the consistency of the runs and thus may have affected the work and fuel consumption. The experimental values for fuel consumption and work can be seen in Table 28.

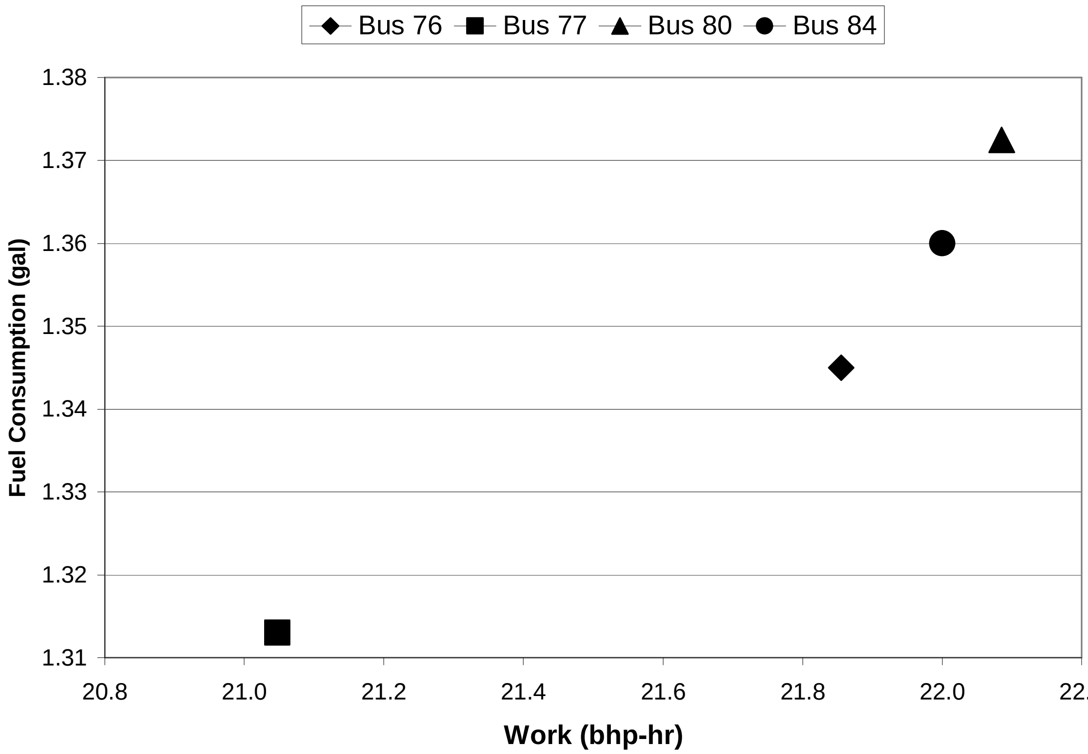

Figure 67: Fuel Consumption as a function of work for Medford school buses tested

Table 28: Medford fuel consumption and work

Bus #	Fuel Consumption (gal)	Total Work (bhp-hr)
Bus 76	1.35	21.9
Bus 77	1.31	21.0
Bus 80	1.37	22.1
Bus 84	1.36	22.0

5.4.5.2. Medford Emissions

Figure 68 shows a representative breakdown of all emissions data collected in Medford from the Semtech-D unit. As shown in Figure 68, the buses operated on B20 produced slightly higher CO_2 emissions levels and lower CO, NO_x, and HC emissions then the bus powered on the #2 conventional petroleum diesel.

Bus 84 had only operated on B20 for approximately one year prior to the tests conducted for this study, while the other two buses had operated on B20 for almost four years. The same driver tested all four buses under similar conditions (ambient temperature and humidity) under the same route. Similarities in vehicle (% load, oil temperature, and engine and vehicle speed) and testing conditions parameters are shown in Table 29. From the data provided in Table 29, it is concluded that Medford testing was repeatable and can be justly compared. Average Medford school bus emission values are quantified in Table 30 and Table 31.

Table 29: Vehicle and testing condition parameters for the four different Medford buses tested

Bus #	Load %	Oil Temp. (F)	Ambient Temp. (F)	Absolute Humidity (gr./lb air)	Total Distance (miles)	Engine Speed (rpm)	Vehicle Speed (mph)
Bus 76	36.5	177	32.3	9.9	8.15	1518	20.4
Bus 77	34.7	178	31.9	8.4	8.27	1463	19.9
Bus 80	34.8	180	37.2	10.2	8.36	1429	18.9
Bus 84	35.6	170	35.4	7.6	8.33	1464	19.6

Table 30: Average emissions results for the four different Medford buses tested measured in g/mile

Bus #	CO_2 (g/mi)	CO (g/mi)	NO_x (g/mi)	kNO_x (g/mi)	HC (g/mi)
Bus 76	1708	1.78	12.14	12.02	0.69
Bus 77	1574	1.89	13.97	13.36	0.95
Bus 80	1690	1.54	13.27	12.71	0.88
Bus 84	1650	1.78	13.84	13.01	0.87

Table 31: Average emissions results for the four different Medford buses tested measured in g/bhp-hr and ppm concentration

Bus #	Wet NO_x (PPM)	kNO_x (PPM)	Wet HC (PPM)	CO_2 (g/bhp-hr)	CO (g/bhp-hr)	NO_x (g/bhp-hr)	kNO_x (g/bhp-hr)	HC (g/bhp-hr)
Bus 76	**316**	**270**	**55**	**637**	**0.69**	**5.23**	**4.48**	**0.26**
Bus 77	**368**	**314**	**81**	**616**	**0.77**	**6.13**	**5.22**	**0.37**
Bus 80	**325**	**278**	**73**	**640**	**0.59**	**5.63**	**4.81**	**0.33**
Bus 84	**348**	**297**	**71**	**622**	**0.67**	**5.46**	**4.77**	**0.33**

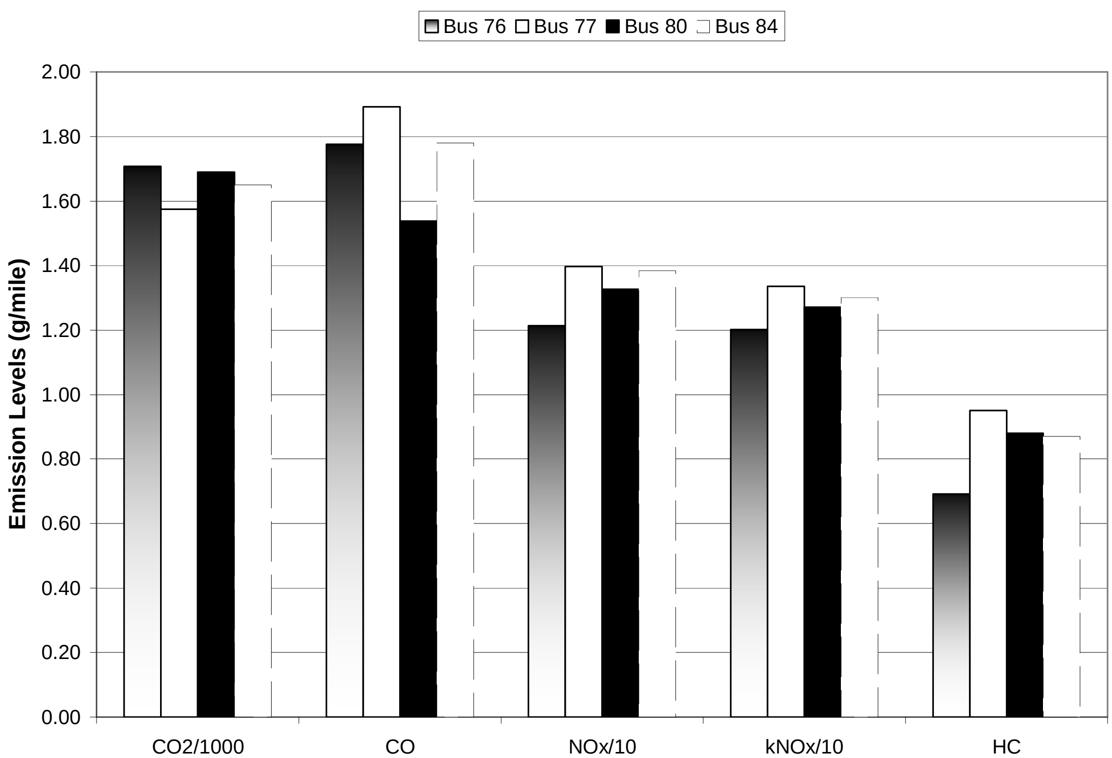

Figure 68: Average emissions results for the 4 different Medford buses tested.

As stated previously, the EPA concluded (from a variety of previous studies performed mainly on engines dated before 1997) that, on average, B20 reduced HC emissions by 20%, PM emissions by 10%, and CO emissions by 11%. NO_x emissions increased slightly in some engines (~ 2%) and CO_2 emissions showed little or no difference.[85] In the present study, HC emissions showed some significant reductions with the use of B20, particularly in Buses 76, which showed a reduction of 27.2 % when compared to the baseline #2 diesel bus (Bus 77). These reductions are higher then those found by the EPA cumulative study. However, Bus 80 and Bus 84 reduced HC emissions by only 7.4 % and 8.4 %, respectively, which was slightly lower than given by the study. CO emissions were slightly decreased by 6.1 % and 5.9 % with the use of B20 in Buses 76 and 84, respectively, when compared to the baseline #2 diesel bus (Bus 77). Bus 80 showed a much higher CO decrease than the other buses of 18.7 %. These decreases in CO emissions were expected since the EPA report claimed that B20 was expected to slightly reduce CO emissions.

NO_x emissions showed slight reductions between 1.0 % and 13 % with the use of B20. Semtech's corrected NO_x (kNO_x) also slight reductions between 2.6 % and 10 %. An SAE NO_x correction factor for temperature and humidity was not used for the Medford data because all tests were conducted within a close range of 5 ºF and 2 gr./lb-dry air, respectively. Previous work has found however, that NO_x emissions generally increase slightly with biodiesel. [82, 85] The NO_x increases when using biodiesel could be caused by the higher fuel density and lower heating value of the fuel.[82] Increasing oxygen content in the fuel has caused significant increases in NO_x in previous research.[82] The NO_x tradeoff is not a large concern however, due to the low sulfur content of biodiesel (~24 ppm), which will work with NO_x reducing technologies that require low sulfur fuel.

The slight reduction of NO_x emissions from the Medford biodiesel buses could be a result of the B20 being mixed with kerosene for winterization. It is a common practice for cold weather areas to mix kerosene with biodiesel to lower the cloud point of the fuel to prevent gelling. Kerosene has a lower relative density (~0.80 g/cm^3) when compared to B20 (~0.86 g/cm^3) and #2 petroleum diesel (~0.85 g/cm^3). Kerosene also contains a slightly higher heating value (20,000 btu/lb) when compared to biodiesel (17,500 btu/lb). A previous study on the effect of kerosene in #2 petroleum diesel fuel found that the addition of kerosene slightly reduces NO_x and PM emissions and slightly raises CO and HC emissions.[114]

The Medford data concurred with the EPA study that there was little change in CO_2 emissions (between 2.4 % and 4.5 %) from using B20. However, the real savings in CO_2 emissions comes from the fact that biodiesel is renewable, meaning the CO_2 emission released into the atmosphere when biodiesel is burned is recycled by growing plants, which are later processed into fuel. A small percentage of tailpipe fossil CO_2 produced from operating on biodiesel can be attributed to the methanol contribution, however almost 95 % of the biodiesel created CO_2 emission is tailpipe biomass CO_2.[115] A recent government study shows that the use of biodiesel can reduce CO_2 emissions by 78.45% on a life cycle basis, which include emissions in the production of the fuel.[115].

5.5. School Bus Mobile Emissions Testing (ATC)

5.5.1. Introduction

Alternative fuels such as biodiesel and ultra low sulfur diesel (ULSD) have been shown to reduce some diesel emissions in cars and trucks. The final phase of testing was mobile testing of various alternative fuels to evaluate the emissions reduction advantages and disadvantages. The RUCSBC developed was used as the mobile emissions testing cycle for the research. NO_x emissions data collected during mobile testing was corrected for temperature and humidity using the NO_x correction factor. Finally, mobile emission results using various alternative fuels, including B20, were compared to the test results from the Medford Township School District.

5.5.2. Experimental Procedure: Test Matrix

Experiments were conducted on the 1-Mile Loop Course at the Aberdeen Test Center in Aberdeen, Md. The course consists of a continuous asphalt surface with level, parallel 1/4-mile segments connected by 1/4-mile banked semicircular sections at each end. Data acquisition and control instrumentation were located inside the school bus. Three separate school buses were acquired and tested each with four different fuel combinations. The vehicle and engine specifications for each school bus tested are listed in Table 22. Each of the vehicles was tested with four fuels under the RUCSBC as seen in the test matrix in Table 36. Each test consisted of a single RUCSBC cycle, which has a duration of approximately 20 minutes during which HC, NO, NO_2, CO, CO_2, and PM emissions were monitored.

The Sensors Inc. SEMTECH-D mobile emissions analyzer and the Sensors Inc. PM-300 particulate measuring device were used to acquire the above exhaust constituents during each test.

5.5.3. Test Results

Medford Township school bus emissions tests were performed on school buses that had been operating on a certain fuel for an extended period of time. The mobile emissions testing on school buses at ATC consisted of testing alternative fuels that had just been placed into the school bus fuel system. The same three school buses were used for all four fuels tested. It should be noted that the ULSD /20% biodiesel blend was not tested for the Cummins engine due to time constraints. The procedure for switching fuels consisted of draining the fuel tank, adding the new fuel, idling the bus for ½ hour, and driving the bus for an additional ½ hour. Figure 69 is an example of raw emissions data collected during a run of the RUCSBS comparing NO_x and HC emissions over a 400 second portion of the RUCSBC.

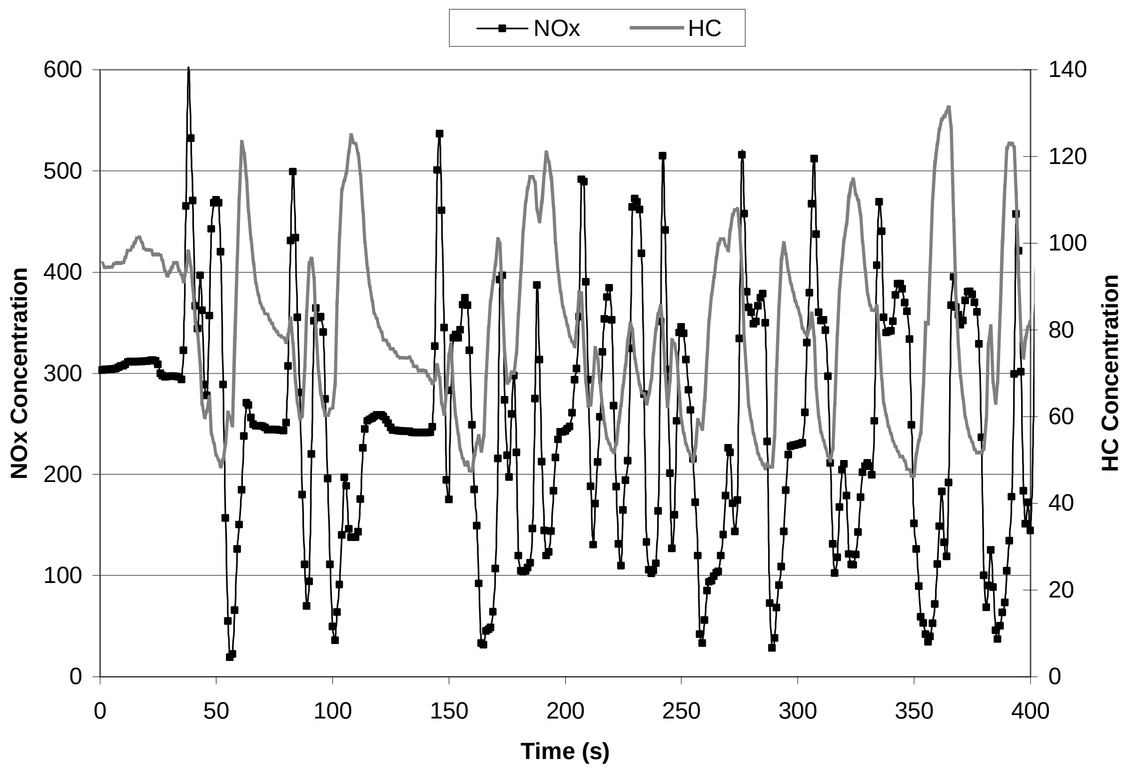

Figure 69: Raw emissions data from RUCSBC

The following fuels were tested at ATC using the RUCSBC described above: # 2 petroleum diesel, ULSD, #B20, and ULSD/ 20 % biodiesel mixture. Fuels were analyzed by the chemistry lab at ATC for density, cetane index #, viscosity, and sulfur %. Results from the fuels tests are shown in Table 32.

Table 32: Fuel properties for fuels tested at ATC.

Fuel Type	**#2 Diesel**	**B20**	**ULSD**
Density (g/cm^3)	.8521	.8592	.8243
Cetane Index	45.2	46.5	42.5
Sulfur %	.0431	.0409	.0049
Viscosity (mm^2/s)	2.40	2.60	1.60

5.6. Development of a New NO_X Correction Factor

5.6.1. Introduction

This section of text contains the method taken to develop a unique engine specific NO_X correction factor that will be used to analyze the data from the mobile tests.

5.6.2. Background

Ambient temperature and humidity have an effect on NO_X emissions from both gasoline and diesel engines. In order to correct for the effects of temperature and humidity, correction factors exist to standardize the NO_X emissions to a set of standard conditions. The existing correlations however, are unable to correct for the range of temperatures and humidity that occur during the timeframe of outdoor testing. This led to the school bus idle study. The school bus idle tests were performed for two main reasons, to quantify emissions at idle, and to develop the Rowan University NO_X Correction Factor (rNO_X).

5.6.3. Procedure

Three school buses were tested at the Aberdeen Test Center (ATC) in Aberdeen, Maryland inside an environmental chamber. The environmental chamber is capable of controlling multiple climatic variables, including temperature, humidity, solar radiation, dust, icing, fog, and thermal shock.[116] The full climatic chamber dimensions are 75ft x 40ft x 24ft. However, only half of the chamber was used for this testing. To simulate a wide variety of idling situations, tests were conducted at four different ambient temperatures (20°F, 40°F, 65°F and 85°F) and relative humidity ranging from 37 to 90%. In total, 34 tests were performed. Engine data for each of the school buses utilized in the testing are shown below in Table 33.

Table 33: Engine Data for the School Buses Tested

Chassis	Engine	Rated Power
1998 International	'97 International T-444E	190 at 2300 RPM
1998 International	'97 International DT466	190 at 2300 RPM
1997 Ford	'96 Cummins 5.9L B Series	190 at 2200 RPM

The test matrix of temperatures and corresponding humidity shown in Table 34 were chosen based on typical weather conditions experienced by a New Jersey school bus during the course of a school year.[117] Each of the 3 buses were tested at each condition listed in Table 34. The 85° F and 40 % relative humidity (~75 grains/lb. dry air absolute humidity) condition is the current standard condition for stationary emissions testing to correct for NO_x and all other data points collected will be corrected to that value.[118]

Table 34: Environmental Test Matrix for Each Bus

Test	Temperature °F	Relative Humidity %	Absolute Humidity (grains H_2O/ lb. dry air)
1	20	65	11.19
2	40	40	15.63
3	40	65	25.45
4	40	90	35.31
5	65	40	39.52
6	65	65	64.56
7	65	90	89.87
8	85	40	75.00
9	85	65	127.64
10	85	90	178.59

Each test was approximately one hour in length. During this period, the temperature and humidity were held constant in the environmental chamber. After 1 hour, the time rate of change of the oil temperature was generally 0.2°F per minute for the last 10 minutes. Steady state values of emission levels and fuel consumption were obtained by computing time averages over the final 10 min. Figure 70 is an example of the NO_x emissions and oil temperature from a typical test conducted on the DT466E bus at 40°F and 40% relative humidity. Figure 70 shows that the measured NO_x emissions vary as the engine warms up. The higher NO_x emissions during the transient startup period are a result of increased engine load as evidenced by the increased fuel flow rate during this same period. The increased engine load during the transient period is a result of increased engine oil viscosity and battery charging requirements.

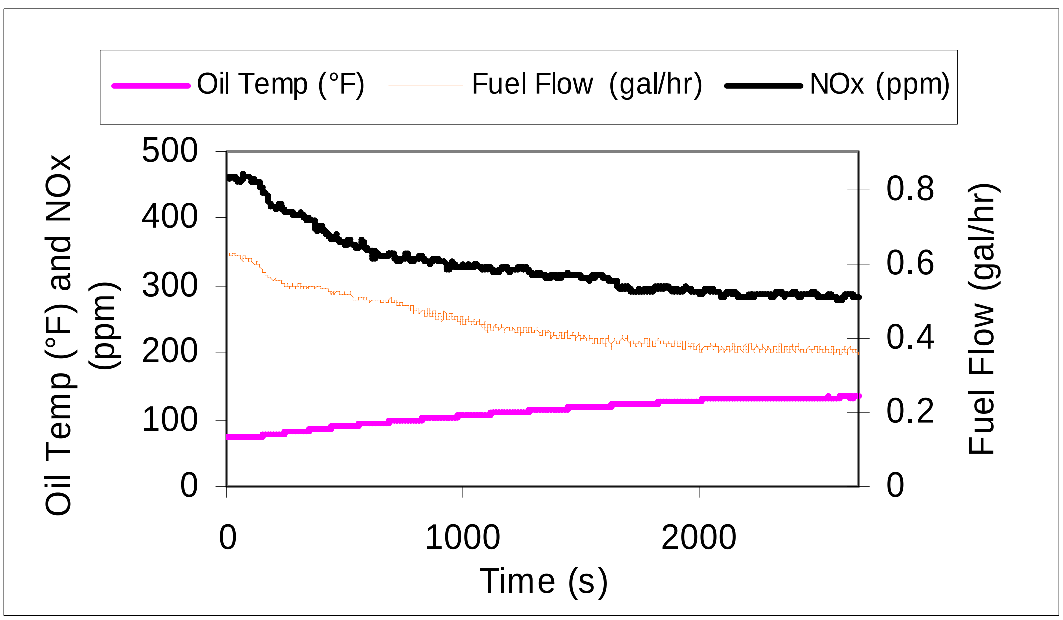

Figure 70: Transient NO_x Concentration, Oil Temperature and Fuel Flow Rate for DT466E at Ambient Temperature of 40 ºF and 40% Relative Humidity.

5.6.4. Experimental Results – NO_X emissions

Figure 71, Figure 72, and Figure 73 show the NO_X emissions in g/hr from the three buses tested. As shown in the figures, emissions vary not only with temperature and humidity, but also with engine type. The Cummins B Series engine produced the highest NO_x emissions of the three buses tested. It should be noted that the Cummins engine is the oldest engine tested and does not contain an ECM.

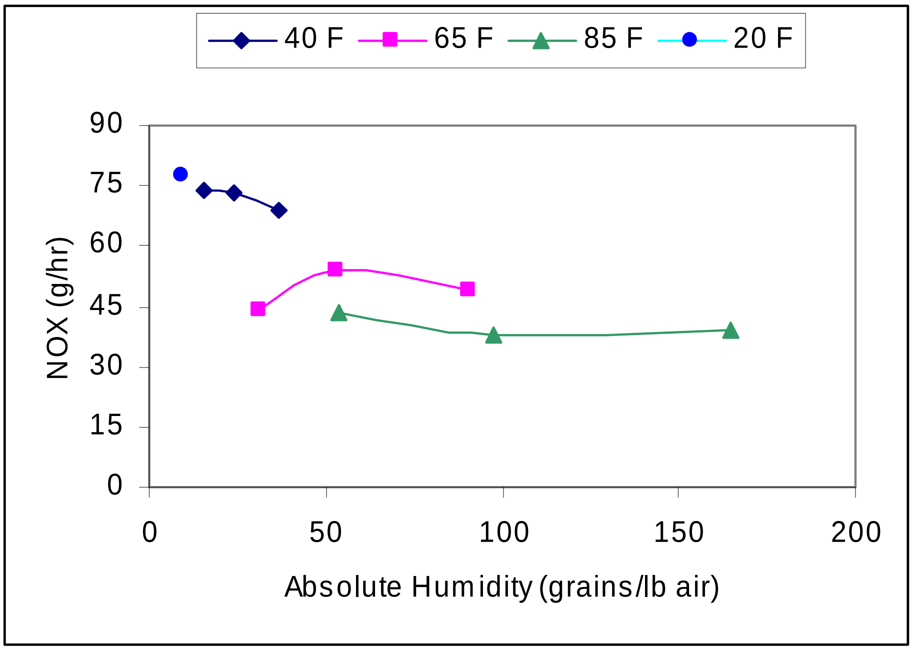

Figure 71: NO_x Emissions During Idling Conditions for School Bus with T444E Engine.

The NO_x emissions shown above in Figure 71 demonstrate the effect of humidity on NO_x emissions. As expected, the results showed that for each of the buses tested, as humidity increases, NO_x emissions decrease. Since a higher inlet temperature should result in a higher cylinder temperature, it might be expected that NO_x would increase with increasing inlet temperature due to the well-known thermal NO_x mechanism. However, for each of the three buses tested in this study, NO_X emissions generally was found to decrease with increasing ambient temperature.

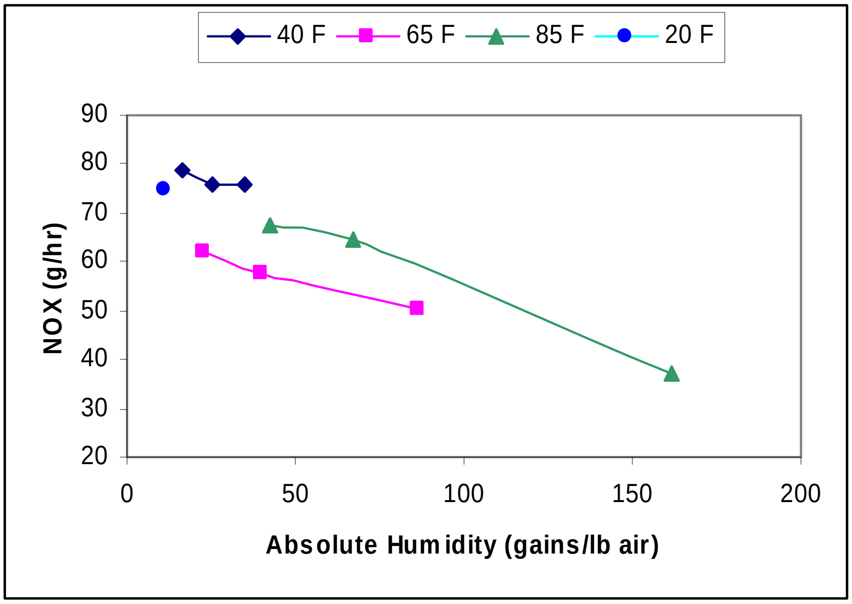

Figure 72: NO_x Emissions During Idling Conditions for School Bus with DT466E Engine.

Figure 72 also shows a decrease in NO_X emissions as humidity increases. For the DT466E, the measured NO_X emissions were slightly lower than those measured for the T444E engine. The DT466E engine showed a slight increase in NO_X when the ambient temperature was increased from 65 °F to 85 °F.

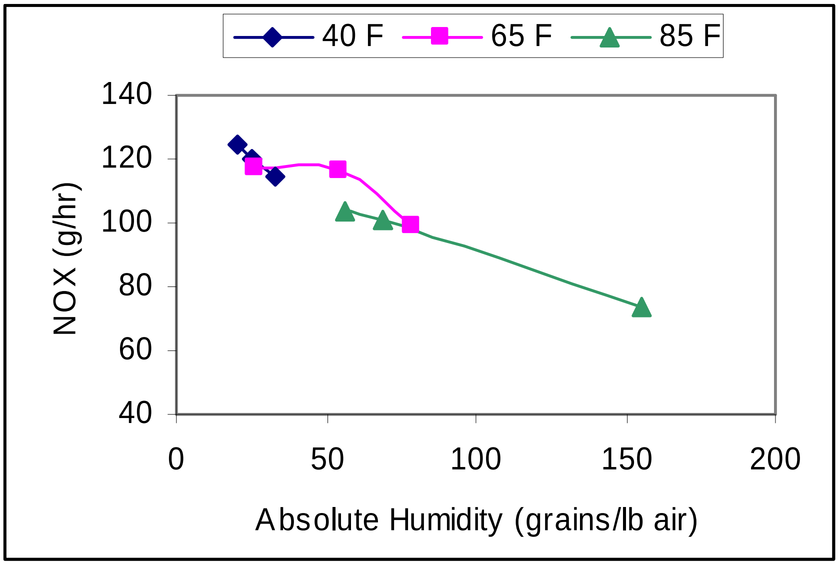

Figure 73: NO_X Emissions During Idling Conditions for School Bus with Cummins 5.9 L Engine.

5.6.5. Existing Correction Factors

SAE standard J1243[119] focuses on the measurement of NO_x. For comparing NO_x measurements taken under conditions of varying inlet humidity, the SAE J1243 standard includes a correlation that estimates what the NO_X measurement would have been if the experiment were conducted at a standard humidity of 75 g H_2O/kg dry air and a temperature of 85°F. The correlation was first developed in a 1973 SAE paper where a number of diesel engines were studied under varying humidity and temperatures. The data were taken for an absolute humidity range of 35-125 grains H_2O/lb dry air and a temperature range of 70-115 °F. The SAE NO_x correlation is as follows:

$$NOcorr = \frac{NOwet}{K_H} \tag{1}$$

$$NOwet = NOdry(ppm)[1 - \alpha(F/A)] \tag{2}$$

$$K_H = 1 + A(H - 75) + B(T - 85) \quad (3)$$

$$A = 0.044(F/A) - 0.0038 \quad (4)$$

$$B = -0.116(F/A) + 0.0053 \quad (5)$$

where NO_{dry} is the measured NO_x emissions in ppm, α the hydrogen to carbon ratio (= y/x in fuel with formula C_xH_y), F/A the fuel to air ratio (dry basis), H the humidity in grains of H_2O/kg dry air and T the intake air temperature in °C.

The SAE correlation was created in order to establish a NO_x correction for all diesel engines within a reasonable range of the ambient temperature and humidity constraints. The CFR40 86.1342-90, which is another correlation that only corrects for humidity variations, is as follows:

$$NO_{x\,corr} = NO_{x\,measured} * K' \quad (6)$$

$$K' = \frac{1}{(1 - 0.0026 * (H - 75))} \quad (7)$$

where H is the humidity in grains of H_2O in grains/lb of dry air.

The CFR40 correlation is only recommended for use in a temperature range from 68°F-85°F. Weather conditions in New Jersey fall out of both the SAE and CFR correlations. Moreover, since a wide variety of fuels, additives and exhaust gas after treatment devices will be tested in the mobile emissions study at ATC, it is likely that tests will be conducted under a wider range of inlet air and humidity conditions than that recommended for either the SAE or CFR40 standard. In Figure 74 below, the NO_x emissions for the DT466E are shown uncorrected. The figure shows that, although all tests were conducted during identical idle conditions, NO_x concentrations vary by as much as 100 ppm with respect to experiments conducted at the SAE standard condition of 39 % RH and 85 °F.

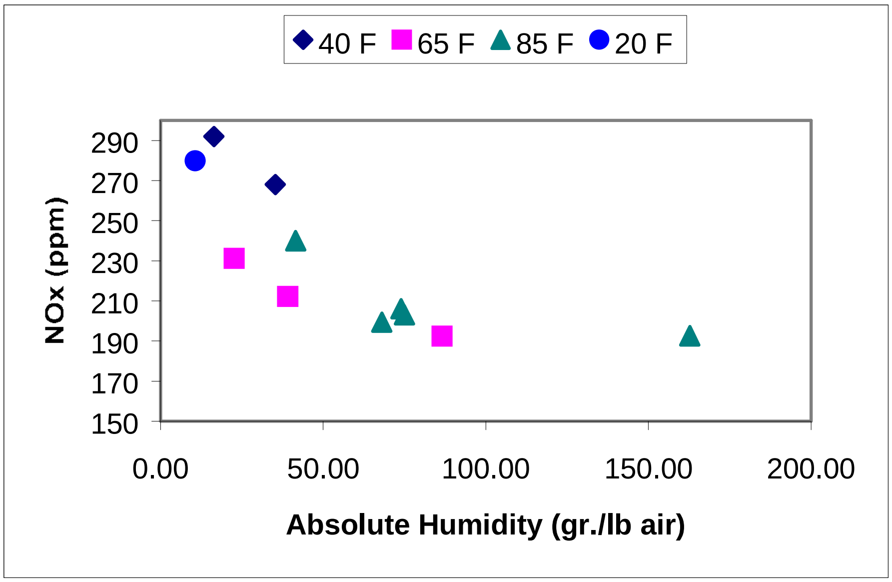

Figure 74: Uncorrected NO_x Emissions (ppm) for the School Bus with DT466E Engine.

Since the CFR40 and SAE standards were developed for limited temperature and humidity range, these correlations cannot correct well for a wider set of conditions. The following figures show that both the SAE and CFR40 standards perform poorly outside their recommended range. In Figure 75 and Figure 76, the SAE and CFR correlations are used to correct the NO_x emissions to the standard of 85°F and 39% RH. The open symbols represent the uncorrected measurements and the closed symbols represent the corrected measurements. An effective correction factor would result in the closed symbols following a roughly horizontal line at approximately 200 ppm. As show in Figure 10, the SAE 1243 correction factor actually *increases* the NO_x concentration at lower temperatures. This result underscores the danger in extending these correction factors outside the range for which they were originally developed.

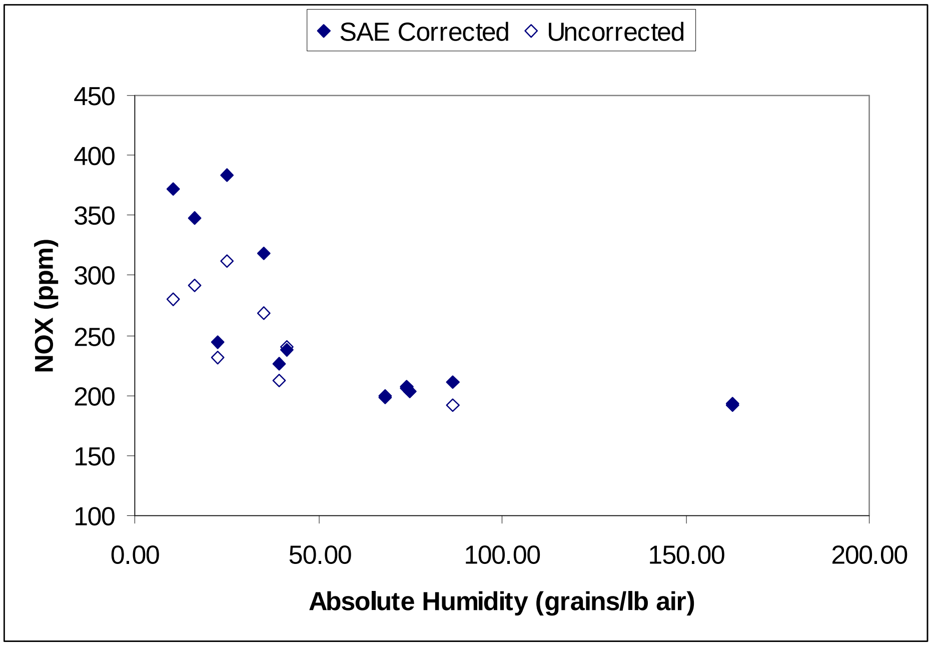

Figure 75: Corrected NO_x Emissions using the SAE J1243 Correction Factor.

As shown in Figure 76, the CFR40 standard performs better than the SAE J1243 standard shown in Figure 75 at lower temperatures, which is notable since the CFR40 correction factor does not include temperature. Both figures show that these standards are effective for the range of temperatures for which they were developed.

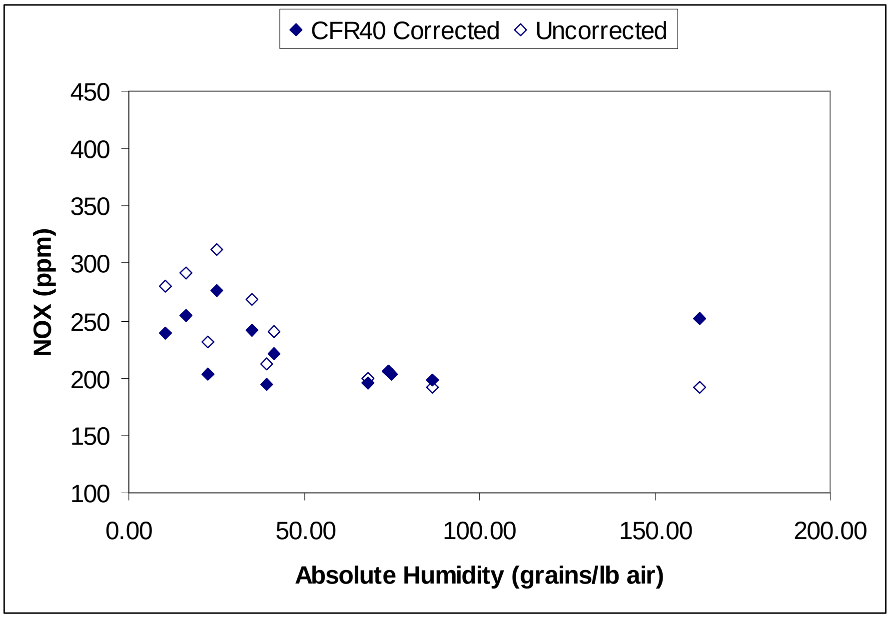

Figure 76: Corrected NO_x Emission Data using the CFR40 86.1342-90.

5.6.6. Development of Rowan University NO_X Correction Factor

The Rowan University NO_X correction factor was created using the steady state data points collected. The first step is to determine a standard condition. In order to compare the rNO_X with the other correlations, the condition of 85^{o}F and 40% RH was established as our standard condition. This is the similar standard condition for the SAE correction factor. Using this as the standard, the goal of the Rowan correction factor was to reduce the lower temperature points on each graph to values close to the emissions from the 85 ^{o}F and 40% RH test.

The next step was to determine what the correction factor should look like. The decision was made to model the Rowan correction factor after the SAE correlation. The equation for the rNO_X correction factor is shown below.

$$NOxcorr = \frac{NOxwet}{K_H} \tag{8}$$

$$K_H = 1 + A(H - 75) + B(T - 85) \quad (9)$$

where NO_{xwet} is the measured NO_X from SEMTECH-D, H is the absolute humidity in grains of H_2O per lb dry air, T is ambient temperature in Fahrenheit, and A and B are experimentally fit values specific to each engine.

To find the experimentally fit values, a non-linear regression was performed using POLYMATH for each engine. Figure 77 is a plot of uncorrected and corrected data for the new correction factor developed specifically for the DT466E engine. As shown in Figure 77, the new correlation factor performs well over the entire range of data, correcting NO_x concentration to within 30 ppm for a range of ambient temperatures of 20 to 85 °F and 37% to 90% RH.

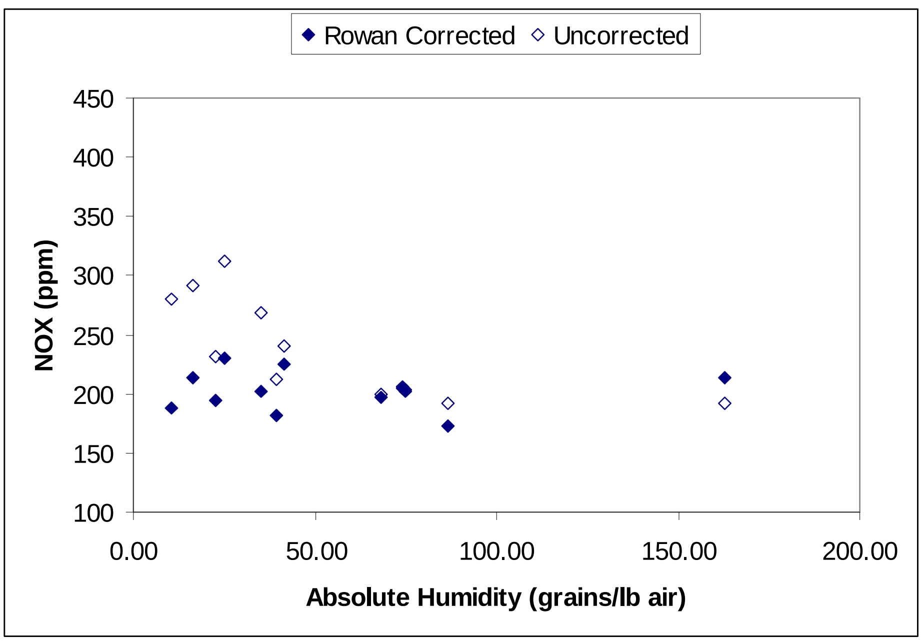

Figure 77: Engine Specific Corrected NO_X Emissions for the DT466E.

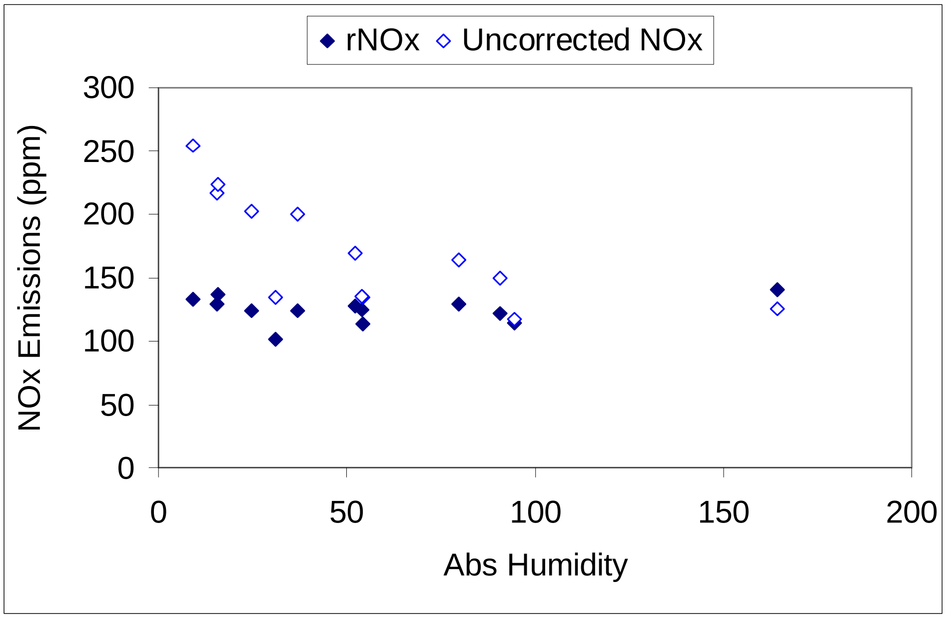

Figure 78: Engine Specific Corrected NO_X Emissions for the T444E.

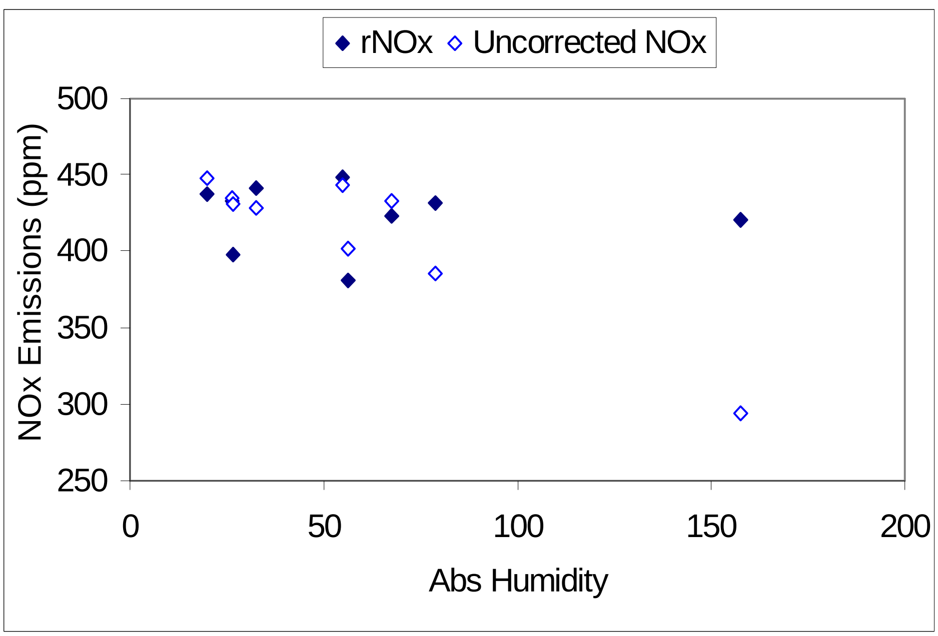

Figure 79: Engine Specific Corrected NO_X Emissions for the Cummins ISB Engine.

5.6.7. Conversion of Measured NO_X Emissions to Reportable Emissions.

After the NO_X emissions have been corrected in parts per million, the next step is to convert the emissions into grams so they can be compared to previous studies. The SEMTECH-D has a multitude of methods to convert concentrations to grams. The method employed by Rowan University uses the fuel flow rate to calculate the emissions in grams.

The first calculation in this series is to convert from ppm to g/kg fuel. For NO_X the equation takes for form of (10):

$$rNO_{xfs}\left(\frac{g\_NOx}{g\_fuel}\right) = \left(\frac{[NO_x]}{[CO]+[HC_1]+[CO_2]-[CO_2]_{ambient}}\right) \times \left(\frac{MW_{NOx}}{MW_{fuel}}\right) \qquad (10)$$

By multiplying by the fuel flow rate in kilograms per second, the next calculation will yield instantaneous grams of NO_X per second.

At this point there are two routes of reportable emissions, distance-specific and brake-specific emissions. Distance-specific emissions are emissions reported in terms of grams emitted per mile of travel. When using a cycle like the RUCSBC, distance specific emissions are useful to show the change between the rural, urban, and suburban portions of the cycle. Brake-specific emissions are currently the EPA standard reportable units and are measured by grams/bhp-hr. Reporting emissions in this format allows for a general comparison of all engines because the power produced is being used as a tool to lower the emission.

5.6.8. Comparison of correction factors in grams per mile

In the figures shown above, the Rowan University NO_X Correction Factor was shown to correct more efficiently than existing correction factors over the range temperatures used for the school bus idle study. The next test of the new correction factor is to see how it compares to the existing correction factors when applied to mobile tests.

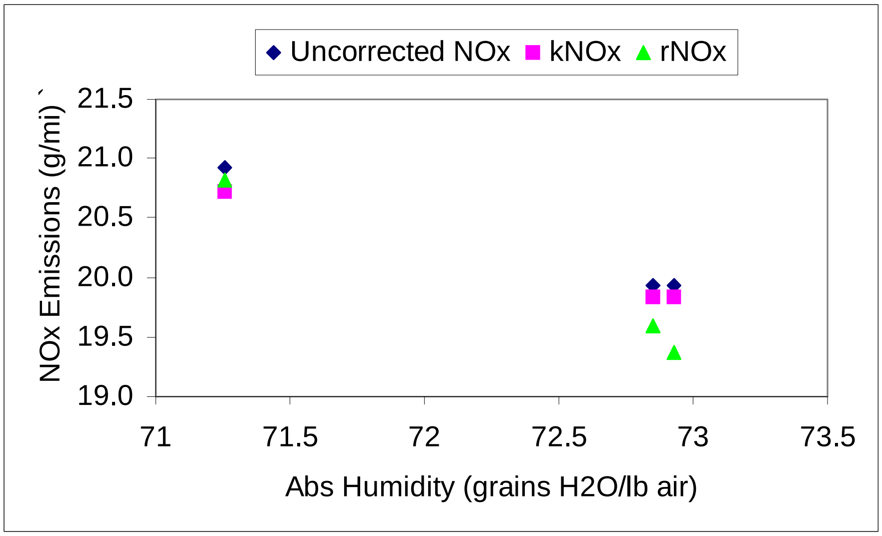

Figure 80: Comparison of correction factors applied to the DT466E for the Amoco ECD Baseline tests.

From the figure above, you can see that as the humidity increases, the Rowan University Correction factor is able to lower NO_X emissions more than the CFR 40 correction factor. The values used for the Rowan Correction Factor are shown below in Table 35.

Table 35: Engine Specific Values for the Rowan University NO_X Correction Factor.

Engine	**A**	**B**
’97 International T-444E	-0.00130	-0.01323
’97 International DT466	-0.00122	-0.00664
’96 Cummins 5.9L ISB	-0.00366	0.00414

5.7. The Effect of Alternative Fuels on Mobile Emissions

5.7.1. Introduction

Previous studies have shown that through the use of alternative fuels, reductions of up to 20% can be seen. This section provides results of mobile testing using ultra low sulfur diesel (ULSD), 20% biodiesel (B20) and a blend of the two (B20/ULSD) compared to standard low sulfur diesel (#2). These experiments were performed using the Rowan University Composite School Bus Cycle (RUCSBC) at the Aberdeen Test Center in Aberdeen, Maryland. Using the Rowan NO_X engine specific correction factor and particulate matter (PM) estimating technique, the results were compared to existing studies and the approaching 2007 USEPA HDDV emissions standards.

5.7.2. Experimental Procedure

The three school buses were performed within the 1 mile test track at the Aberdeen Test Center (ATC) in Aberdeen, Maryland. The 1 mile loop has 2 quarter mile straight sections with 1 quarter mile slightly banked turns. The mile loop offers uninterrupted space to use a drive cycle in order to capture the school bus emissions. All tests were performed using the Rowan University Composite School Bus Cycle (RUCSBC) with the same driver for each test in order to eliminate the driver as a source of error. The SEMTECH-D and PM-300 were used to collect HC, NO, NO_2, CO, CO_2, and PM emissions. Similarly, vehicular parameters from the ECM were recorded. Before each test, a series of calibration gases with known concentration were passed through the sensors in order to validate their accuracy. This auditing procedure was also performed after each test. This entire process takes approximately 20 minutes to complete. Four fuel types were examined in this series of tests. These compositions can be seen below in Table 36.

Table 36: Alternative Fuel test matrix for each school bus

Test	**Fuel Type**	**Fuel Makeup**
1	#2 Petroleum Diesel	Low Sulfur (~360 ppm) diesel)
2	B20	20% by Volume Biodiesel, 80% by Volume #2 Low Sulfur (~360 ppm) diesel)
3	ULSD	Ultra Low Sulfur Diesel (~15 ppm)
4	B20/ULSD	20% by Volume Biodiesel, 80% by Volume Ultra Low Sulfur Diesel (~15 ppm)

Each of these four fuel types were tested three times using the procedure described above. The published results are averages of the three runs. After the experiments were conducted for the fuel type, the fuel was drained from the fuel tank. After the new fuel type was added, the bus was idled for 30 min, and then driven around the Aberdeen Proving Grounds for an additional 30-45 minutes to completely deplete the fuel line of the previous fuel type.

5.7.3. Results

In total, 46 total tests were performed in the fuel study. Additional tests were conducted due to PM-300 equipment malfunctions or if a post test audit would fail. In the event of a post audit fail, the sensors were calibrated again, audited and the failed test was rerun.

The figure below shows the results for a 400 second interval of the RUCSBC. This plot shows the raw emissions results for the DT466E engine in terms of measured concentrations in parts per million (ppm).

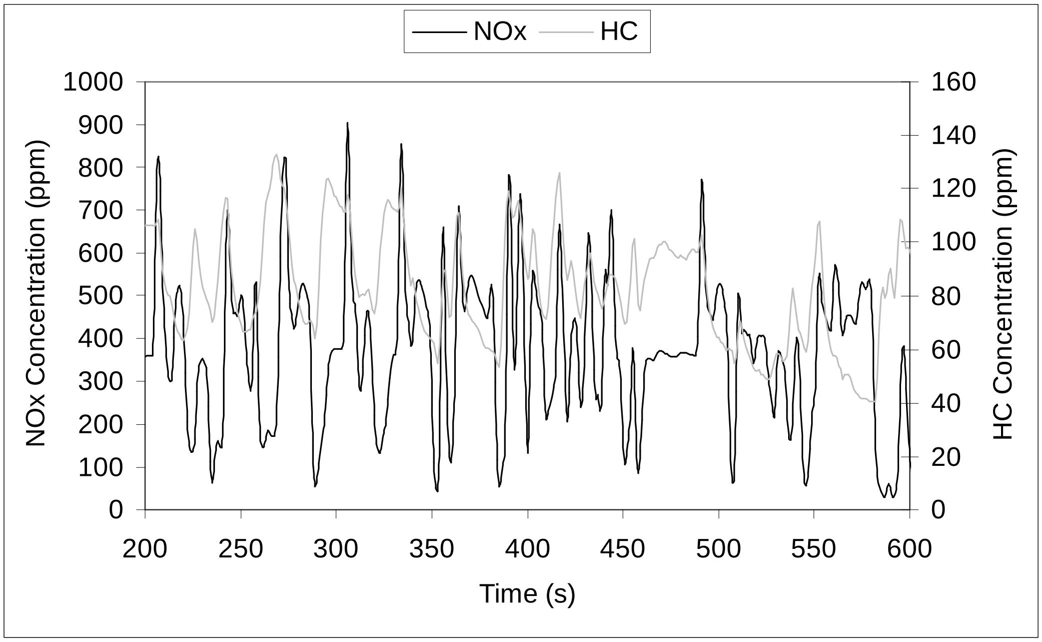

Figure 81: Raw Emissions results for a 400 second interval of the RUCSBC

5.7.3.1. Experimental Results – DT466E

The NO_X emissions reported in this section are the emissions corrected for ambient temperature and humidity as shown in previously. Results for the DT466E engine are shown below in Figure 82. The results show that for the four fuels tested, the CO_2 results vary by approximately 8%. This variation is also seen in the fuel consumption for the fuel types. Since CO_2 is the principle product of combustion, the variation of CO_2 is justified from the fuel consumption. CO results for the DT446E show slightly elevated levels using the 20% biodiesel fuel. The 3% increase in CO emissions does not agree with results from previous alternative fuel studies that suggest CO emissions decreasing by approximately 20%. Corrected NO_X emissions for both the B20 and ULSD are increased, however the blend of the two yielded decreased emissions by 3%. HC emissions showed favorable reductions for each alternative fuel type. For B20, the average reduction was 7%. ULSD showed reductions of 14% while the blend of the two produced a 43% reduction.

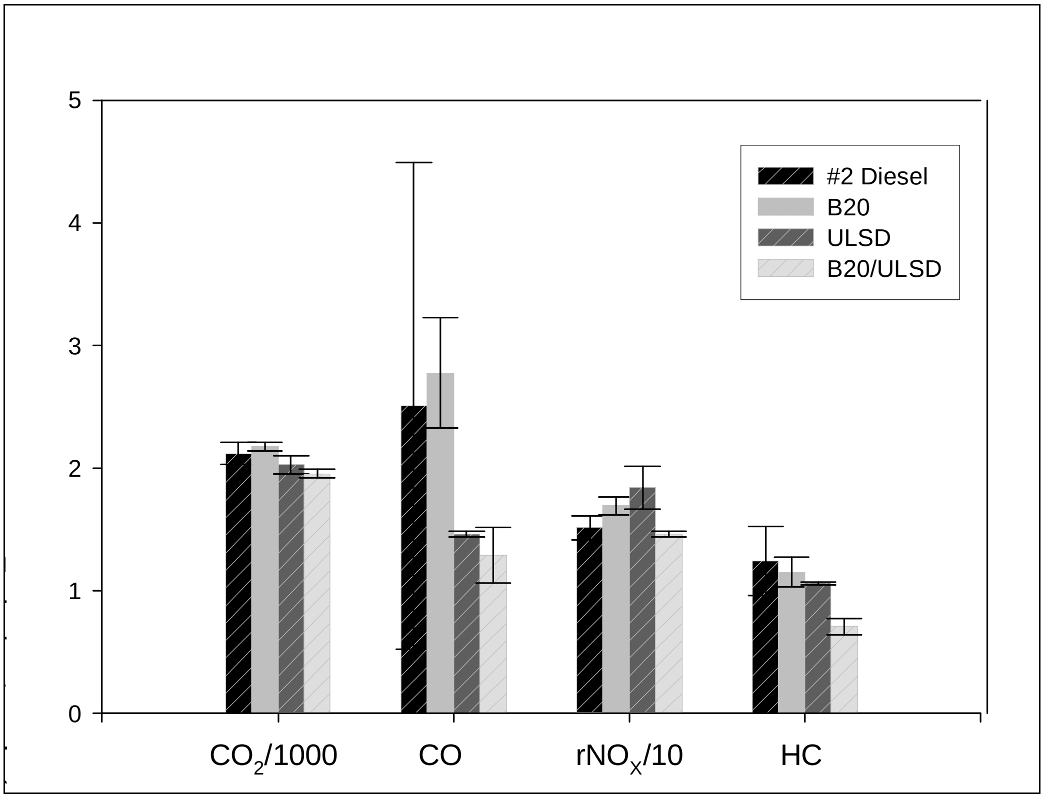

Figure 82: Gaseous Emissions summary for the DT466E

The plot also includes the error for the experiments. In the case of the CO emissions using #2 Diesel, two sets of experiments were performed. For one set of experiments, the ambient temperature was 88°F and the other the temperature was 55°F. CO emissions have been shown to be dependent on temperature.[120] Both sets of experiments passed sensor audits at the conclusion of the tests. Table 37 gives the #2 diesel emission level in g/mile and the percent increase (negative value in table) or decrease (positive value in table) for the respective alternative fuel.

Table 37: Alternative fuel reductions in emission levels for the DT466E when compared to #2 diesel.

DT466E	CO	rNO_x	HC
% Reduction			
# 2 (g/mile)	**2.5**	**17**	**1.2**
B20	**-10**	**-12**	**7**
ULSD	**42**	**-22**	**14**
ULSD/20% Bio	**49**	**3**	**43**

A summary of the PM as a function of bin size is shown below in Figure 83. In order to show each of the bin sizes on one plot, a log scale is used on the x-axis. These results show that for the B20, ULSD, and the blend of the two that slightly more particulates are found in the larger bin sizes.

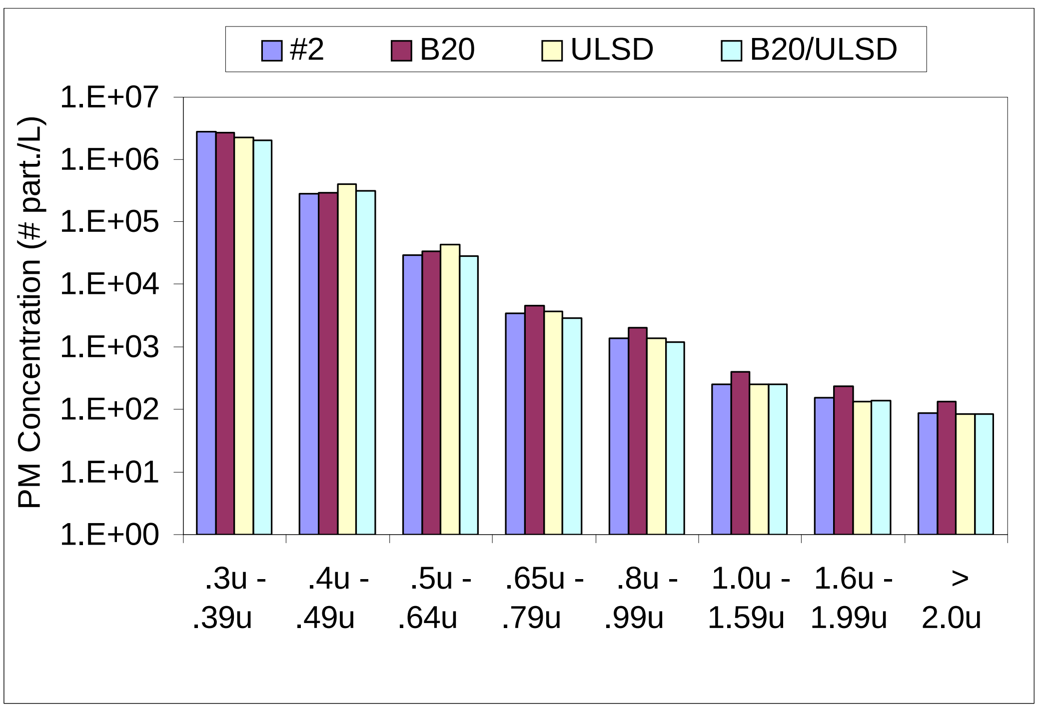

Figure 83: Average PM Concentrations for the DT466E

Using the PM estimation technique discussed in previously, you can see that although there may be more particulates in the higher size bin ranges, they do not contribute to the estimated mass as much as the PM in the lower bin size ranges. The estimated PM results are shown in Figure 84. The reductions for B20, ULSD, and B20/ULSD for the T444E engine were 4%, 18%, and 26% respectively. Intuitively, these results are logical. The combination of B20 and the ULSD fuel should yield the lowest particulate matter.

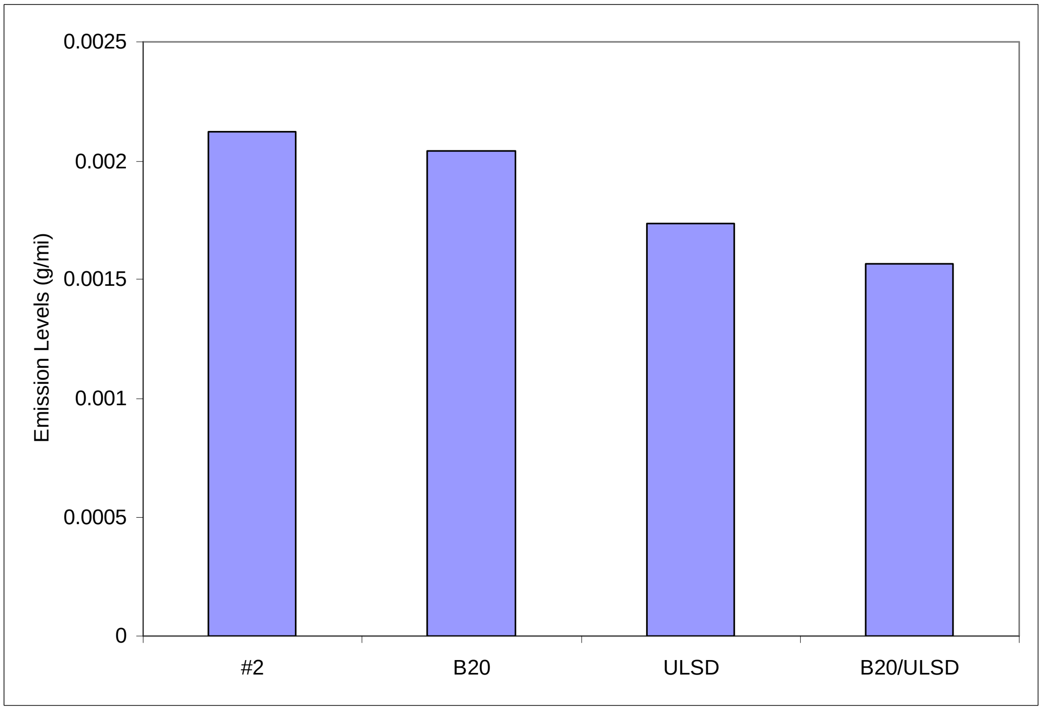

Figure 84: PM Mass Estimations for the DT466E

5.7.3.2. Experimental Results – T444E

Figure 85 represents the emissions results from the T444E engine using alternative fuels. The greatest reductions seen in this set of experiments were found in the CO emissions. Through the use of alternative fuels, CO was reduced by almost 50% or more. For the B20 fuel, HC emissions were reduced by 23% which is consistent with previous studies performed using biodiesel. In the case of the biodiesel blended with ultra-low sulfur diesel (ULSD) the reduction is 26%. Corrected NO_X emissions show reductions for each alternative fuel, the B20 showing the highest reduction of 14%.

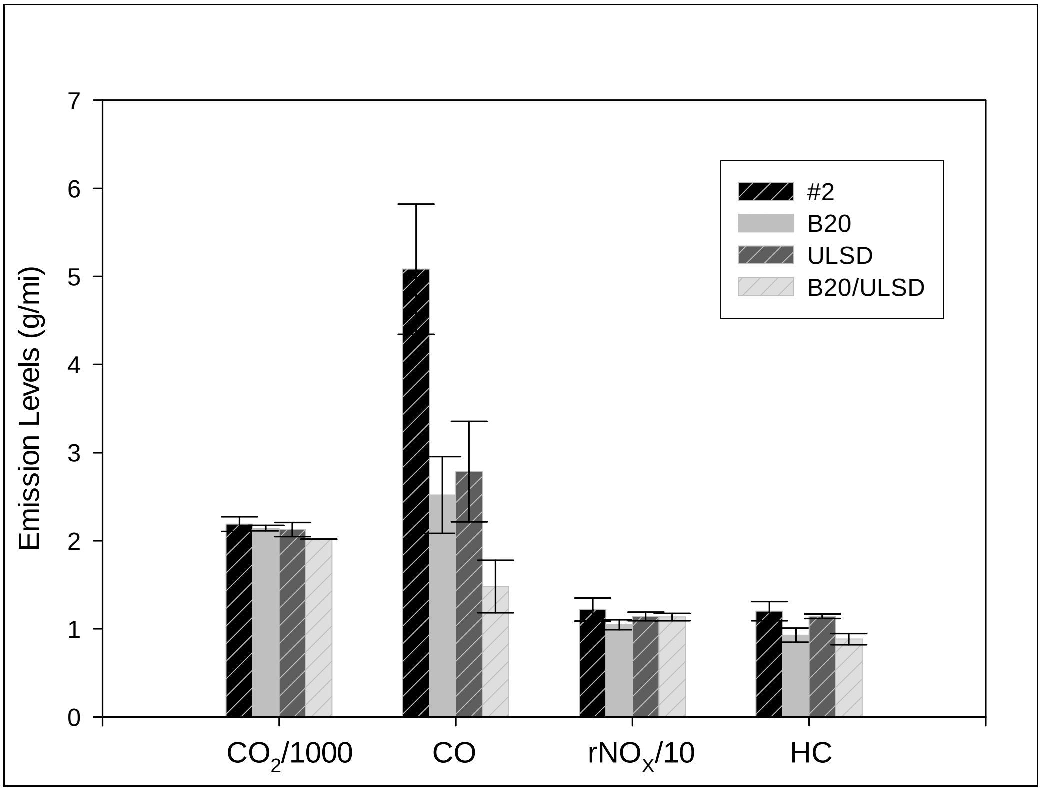

Figure 85: Gaseous Emission Summary for the T444E

Table 38 gives the #2 diesel emission level in g/mile and the percent increase (negative value in table) or decrease (positive value in table) for the respective alternative fuel.

Table 38: Alternative fuel reductions in emission levels for the T444E when compared to #2 diesel.

T444E	**CO**	**rNO_x**	**HC**
% Reduction			
# 2 (g/mile)	**5.1**	**12.2**	**1.2**
B20	**50**	**14**	**23**
ULSD	**45**	**6**	**5**
ULSD/20% Bio	**71**	**7**	**26**

PM emissions for the T444E on a particle count basis show that particulates are not significantly impacted by the use of alternative fuels. Figure 86 shows the results of the PM for the T444E. The results are plotted using a logarithmic scale and show that the

ULSD fuel for this engine produced the lowest amount of particulates for each of the bin sizes shown.

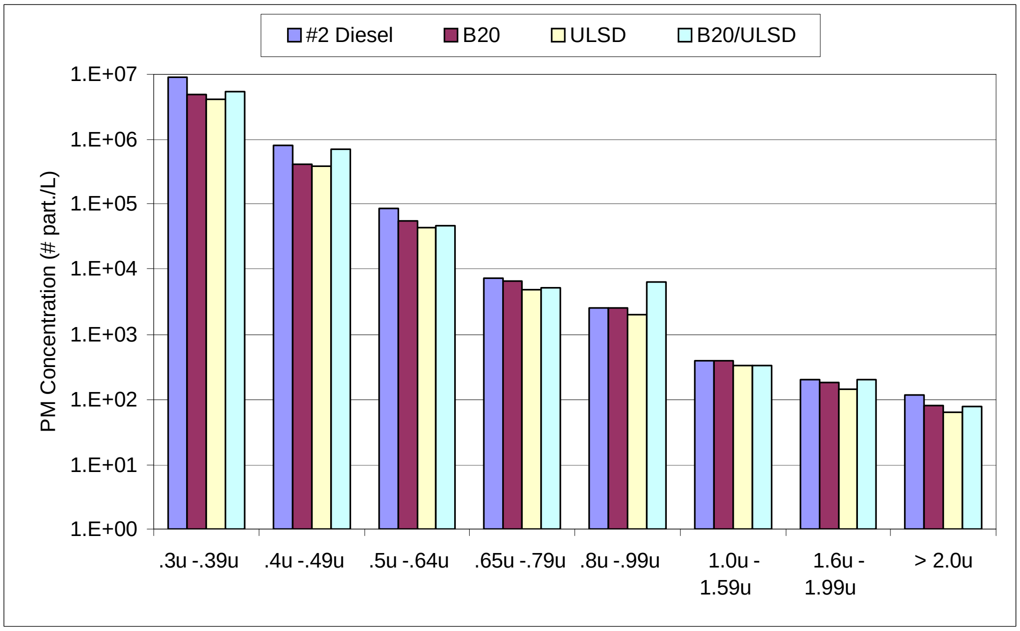

Figure 86: Average PM Concentrations for the T444E

Using the PM mass estimation it shows that the #2 diesel fuel produced the highest mass of particulate matter. The decrease ranges from 45% for the B20 to 52% for the ULSD and B20/ULSD. The T444E engine shows no sign of biodiesel influence on the B20/ULSD blend PM reductions. These results are shown in Figure 87.

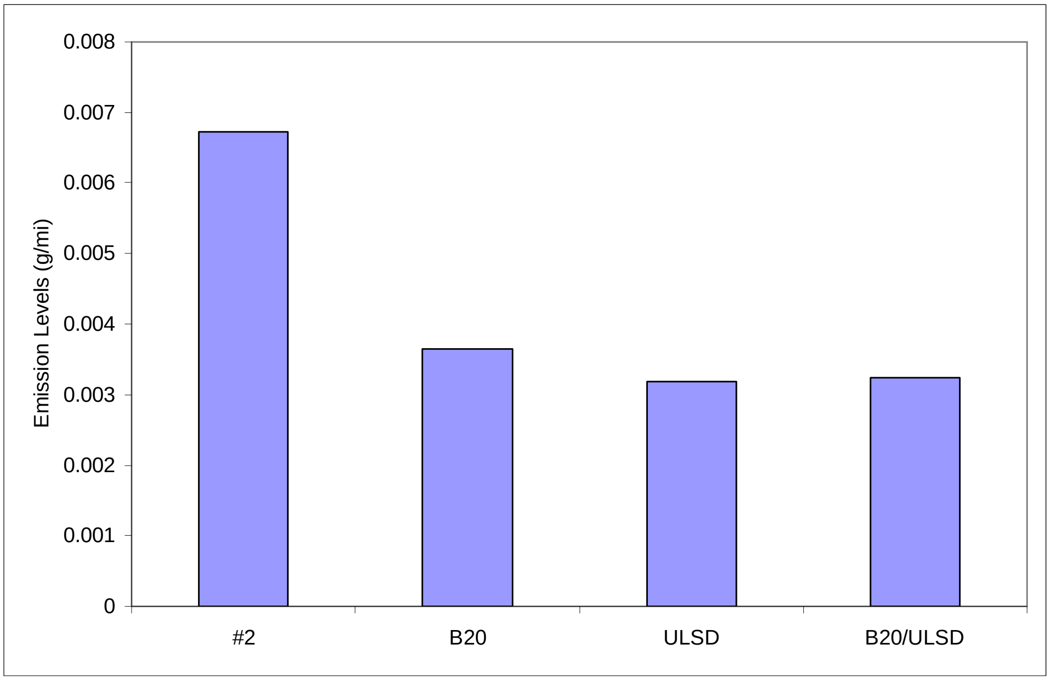

Figure 87: PM mass Estimations for the T444E

5.7.3.3. Experimental Results – Cummins ISB

The gaseous emissions results of the use of alternative fuels are found in Figure 88. For the Cummins ISB engine, CO and corrected NO_X emissions increased when using the B20 fuel. CO emissions varied significantly for the tests performed using the B20/ULSD fuel. The emissions ranged from 0.6 grams per mile to 2.7 grams per mile for the three experiments performed. The B20/ULSD fuel had the highest reduction in HC emissions with an average of 35%. Corrected NO_X emissions for all of the alternative fuels were within 20% of the #2 diesel baseline.

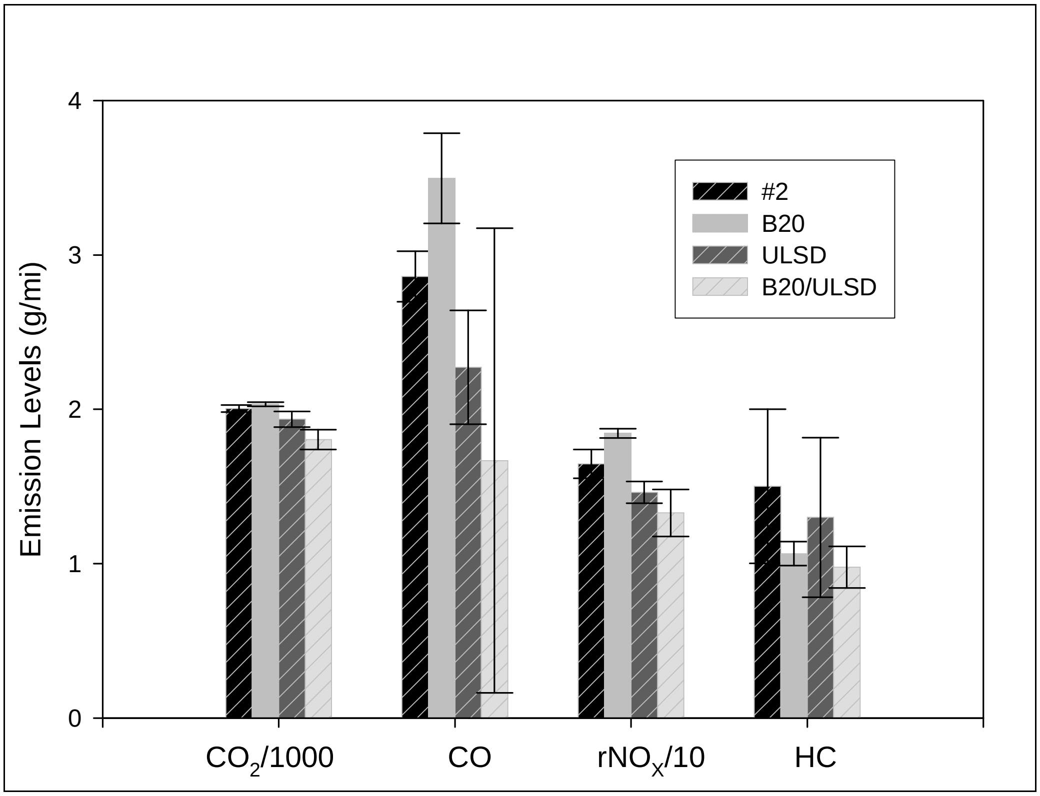

Figure 88: Gaseous Emission Summary for the Cummins ISB

Table 39 gives the #2 diesel emission level in g/mile and the percent increase (negative value in table) or decrease (positive value in table) for the respective alternative fuel.

Table 39: Alternative fuel reductions in emission levels for the T444E when compared to #2 diesel.

Cummins ISB	**CO**	**rNO$_x$**	**HC**
% Reduction			
# 2 (g/mile)	**2.9**	**17**	**1.5**
B20	**-22**	**-12**	**29**
ULSD	**21**	**11**	**13**
ULSD/20% Bio	**42**	**19**	**35**

Particulate count emissions for PM show that for #2 diesel fuel, the PM concentrations are higher for each of the bin sizes. This can be illustrated in Figure 89. This figure is plotted on a logarithmic scale in order to show the results of each bin size.

As a function of bin size, PM emissions for the B20/ULSD fuel decrease compared to the other alternative fuels.

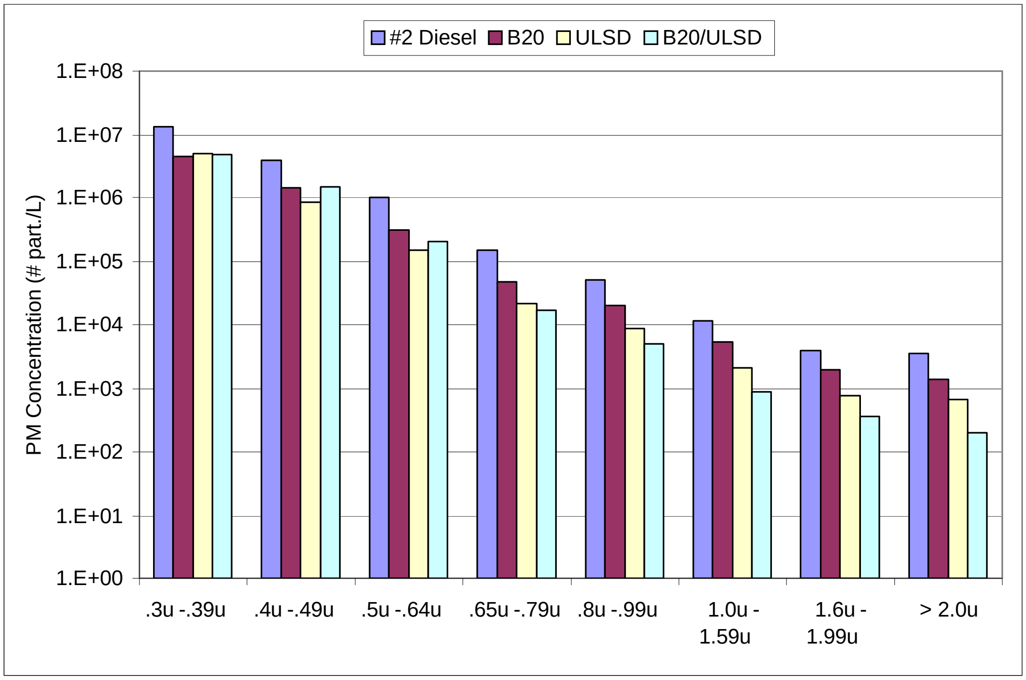

Figure 89: Average PM Concentrations for the Cummins ISB

The estimated mass of particulate matter shows similar results to Figure 89. For the Cummins ISB engine, the use of alternative fuels has shown to decrease the mass of PM emitted from the tailpipe. Figure 90 shows the PM mass reductions. The decrease ranges from 62% for the ULSD and B20/ULSD to 66% for the B20.

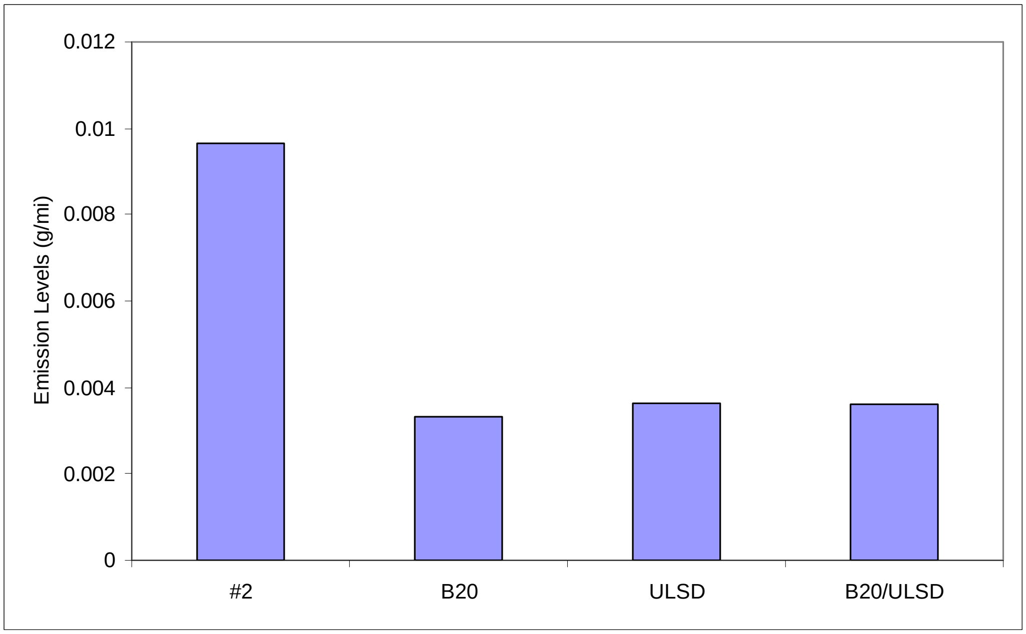

Figure 90: PM mass Estimations for the Cummins ISB

5.7.3.4. Comparison to 2007 EPA Standards

A comparison of the alternative fuels test results to the 2007 US EPA standards are shown below in Table 40. Currently, the EPA regulates brake specific emissions. Brake specific emissions measure mass of pollutant per unit of engine work. In order to obtain the amount of work performed by the school bus for this study, engine torque information was provided by the electronic control module. The Cummins ISB engine is omitted from this table due to its lack of an ECM.

CO emissions for #2 diesel already currently meet the 2007 standard. Since diesel engines emit low CO levels compared to spark-ignited engines, this standard is easy to reach. The emissions results from Table 40 suggest that the use of alternative fuels do not have the potential alone to meet the 2007 EPA standards for NO_X or HC emissions. The 1.2 g/bhp hr standard for NO_X emissions is going to be phased down to 0.2 g/bhp hr by 2010. However alternative fuels such as ULSD allow for NO_x emission reduction technologies (such as NO_x absorbers) to be used. #2 diesel contains too much sulfur in the fuel to be used with most NO_x reduction technologies. Also, ULSD fuel can be used with a diesel particulate filter (DPF) that can eliminate virtually all HC and PM emissions. Results from the use of DPFs are shown in the next section.

Table 40: Comparison of test results with 2007 standards

444	**CO g/bhphr**	**rNOx g/bhphr**	**HC g/bhphr**
2007 Standard	*15.5*	*1.20*	*0.14*
#2	1.43	3.42	0.34
B20	0.73	3.02	0.27
ULSD	0.78	3.19	0.32
ULSD/ 20%Bio	0.44	3.36	0.26
466	**CO g/bhphr**	**rNOx g/bhphr**	**HC g/bhphr**
2007 Standard	*15.5*	*0.20*	*0.14*
#2	0.74	4.49	0.32
B20	0.99	4.92	0.38
ULSD	0.44	5.48	0.32
ULSD/ 20%Bio	0.40	4.57	0.22

5.8. The Effect of Aftertreatment Devices on Mobile Emissions

5.8.1. Introduction

Results from previous aftertreatment device studies conclude that diesel oxidation catalysts (DOCs) and diesel particulate filters (DPFs) are effective ways of reducing CO, HC, and PM emissions. The use of a DPF has shown to reduce PM by over 90%. This section presents the results of testing the Nett Technologies Catalytic Muffler, the Johnson Matthey Continuous Regenerating Technology (JMI CRT) and the Lubrizol Purifilter. These experiments were performed using the Rowan University Composite School Bus Cycle (RUCSBC) at the Aberdeen Test Center in Aberdeen, Maryland. Using the Rowan NO_X engine specific correction factor and particulate matter (PM) estimating technique, the results were compared to existing studies and the approaching 2007 USEPA HDDV emissions standards.

5.8.2. Experimental Procedure

The three school buses were performed within the 1 mile test track at the Aberdeen Test Center (ATC) in Aberdeen, Maryland. The 1 mile loop has 2 quarter mile straight sections with 1 quarter mile slightly banked turns. The mile loop offers uninterrupted space to use a drive cycle in order to capture the school bus emissions. All tests were performed using the Rowan University Composite School Bus Cycle (RUCSBC) with the same driver for each test in order to eliminate the driver as a source of error. The SEMTECH-D and PM-300 were used to collect HC, NO, NO_2, CO, CO_2, and PM emissions. Similarly, vehicular parameters from the ECM were recorded. Before each test, a series of calibration gases with known concentration were passed through the sensors in order to validate their accuracy. This auditing procedure was also performed after each test. This entire process takes approximately 20 minutes to complete. Table 41 shows the test matrix for the aftertreatment testing.

Table 41: Aftertreatment test matrix for each school bus

Test	**Strategy**	**Fuel Makeup**
1	ULSD Baseline	Ultra-Low Sulfur Diesel (~15 ppm)
2	Nett DOC	Diesel Oxidation Catalyst
3	JMI CRT	Diesel Particulate Filter with high catalyst loading
4	Lubrizol Purifilter	Diesel Particulate Filter with low catalyst loading

Each of these aftertreatment devices were tested three times using the procedure described above. The published results are averages of the three runs. After the tests were performed, the next aftertreatment device was installed and tested.

5.8.3. Results

In total, 44 total tests were performed in the fuel study. Additional tests were conducted due to PM-300 equipment malfunctions or if a post test audit would fail. In the event of a post audit fail, the sensors were calibrated again, audited and the failed test was rerun. Also, the inactivity of the school buses between the alternative fuels study and the aftertreatment study led to front brake caliper freezing issues with the T444E.

The figure below shows the results for a 400 second interval of the RUCSBC. This plot shows the raw emissions results for the DT466E engine in terms of measured concentrations in parts per million (ppm).

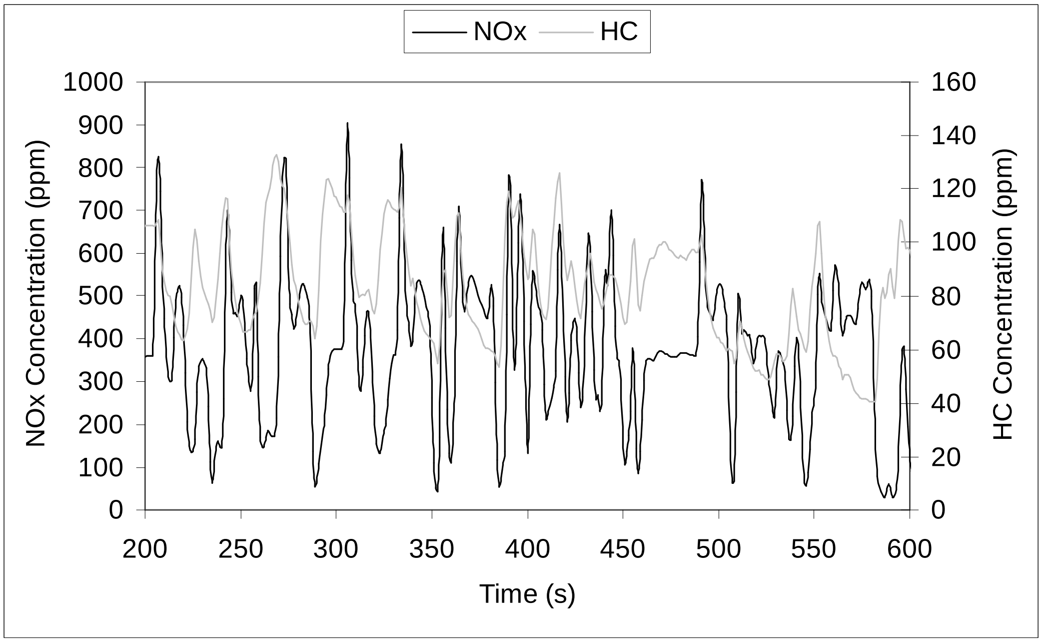

Figure 91: Raw Emissions results for a 400 second interval of the RUCSBC

5.8.3.1. Experimental Results – DT466E

The average results for the aftertreatment testing for the DT466E school bus are shown below in Figure 92. These emissions are reported in grams of gaseous pollutant per mile traveled on the RUCSBC. Like in the alternative fuels study, CO emissions for each test seem to have the most variation. Five ULSD baseline experiments were performed on the DT466E due to a failure with the PM-300 unit. These tests were split up between two days which varied in ambient temperature by 10°F. The higher values of CO were found on the cooler day of testing. CO emissions were significantly reduced through the use of aftertreatment devices. The DOC from Nett Technologies effectively reduced CO emissions by 62% while the two DPFs reduced CO emissions by 75% or more. Corrected NO_X emissions using the engine specific correction factor show the best NO_X reductions in the DOC of 14%.

HC emissions were also significantly reduced through the use of aftertreatments. The variation in HC emissions between tests is very small and there are clear reductions seen. The Lubrizol Purifilter and JMI CRT reduce HC emissions by 88% and 95% respectively while the Nett DOC reduces HC emissions by 74%.

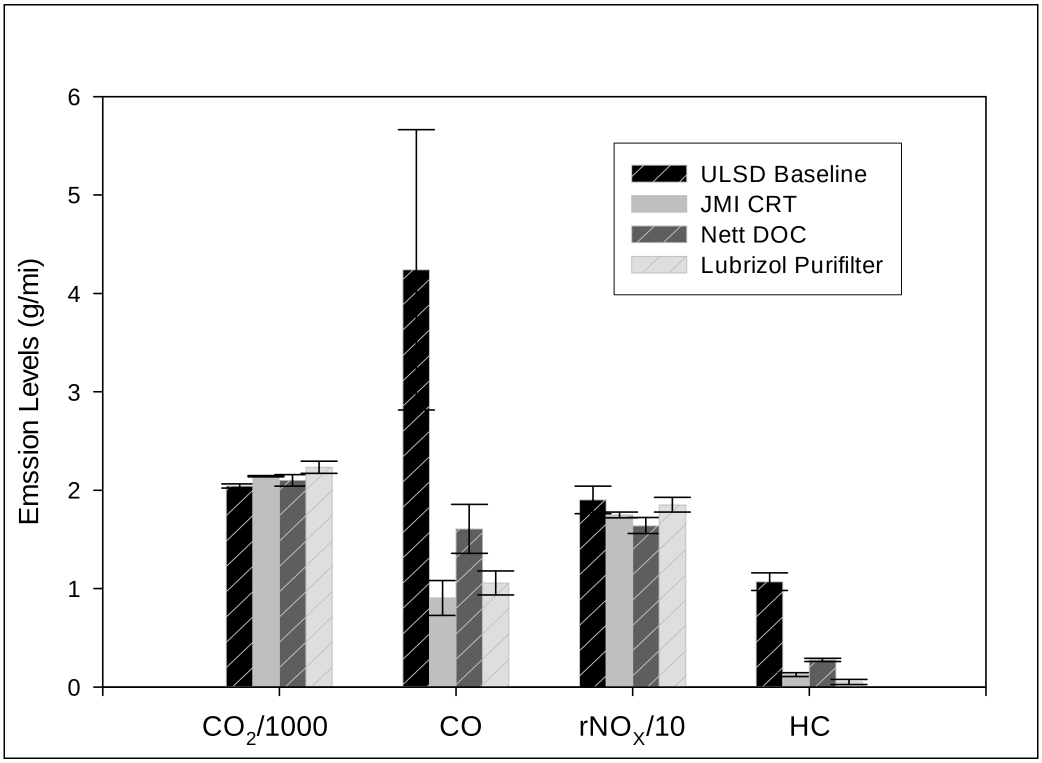

Figure 92: Aftertreatment Testing Results – DT466E

Table 42 below gives the ULSD baseline emission levels in g/mile and the percent increase (negative value in table) or decrease (positive value in table) for the respective alternative fuel.

Table 42: Aftertreatment reductions in emission levels for the DT466E when compared to the ULSD baseline.

DT466E	CO	rNO_x	HC
% Reduction			
ULSD Baseline	**4.2**	**19**	**1.1**
JMI CRT	**79**	**8**	**88**
Nett DOC	**62**	**14**	**74**
Lubrizol Purifilter	**75**	**3**	**95**

A summary of the PM as a function of bin size is shown below in Figure 93. In order to show each of the bin sizes on one plot, a log scale is used on the x-axis. These results show that the use of a DOC effectively reduces the number of particulates in the first three bin sizes while the two DPFs tested significantly reduce the number of particulates for all bin sizes.

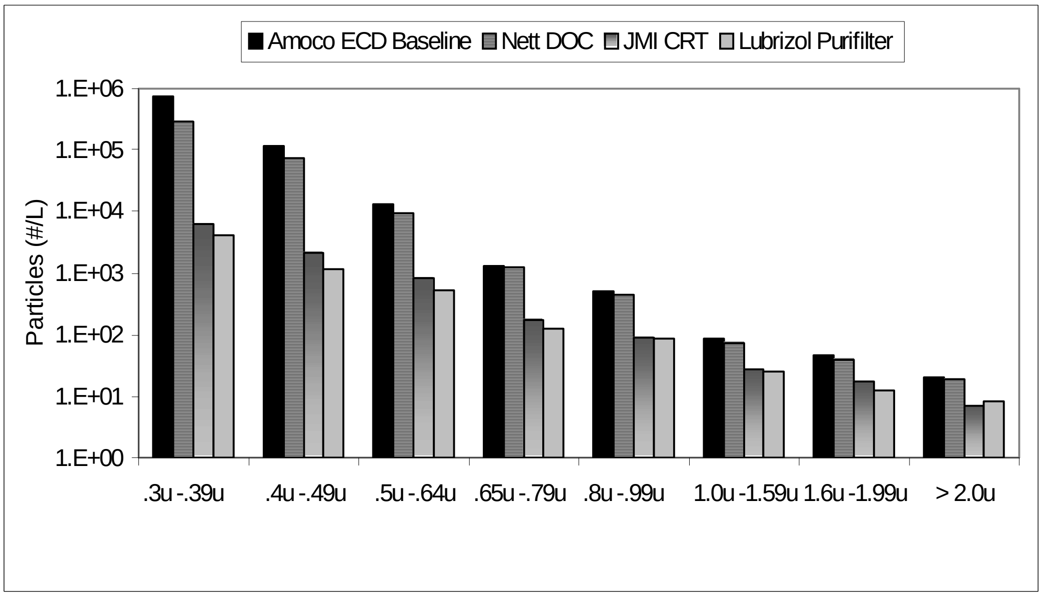

Figure 93: Average PM Concentrations for the DT466E

PM mass estimates show similar trends in Figure 94 of the aftertreatment test results for the DT466E engine. The DOC from the Nett reduced PM mass by 60%, however, the two DPF's, namely the Lubrizol Purifilter and the JMI CRT, both reduced PM by 99%.

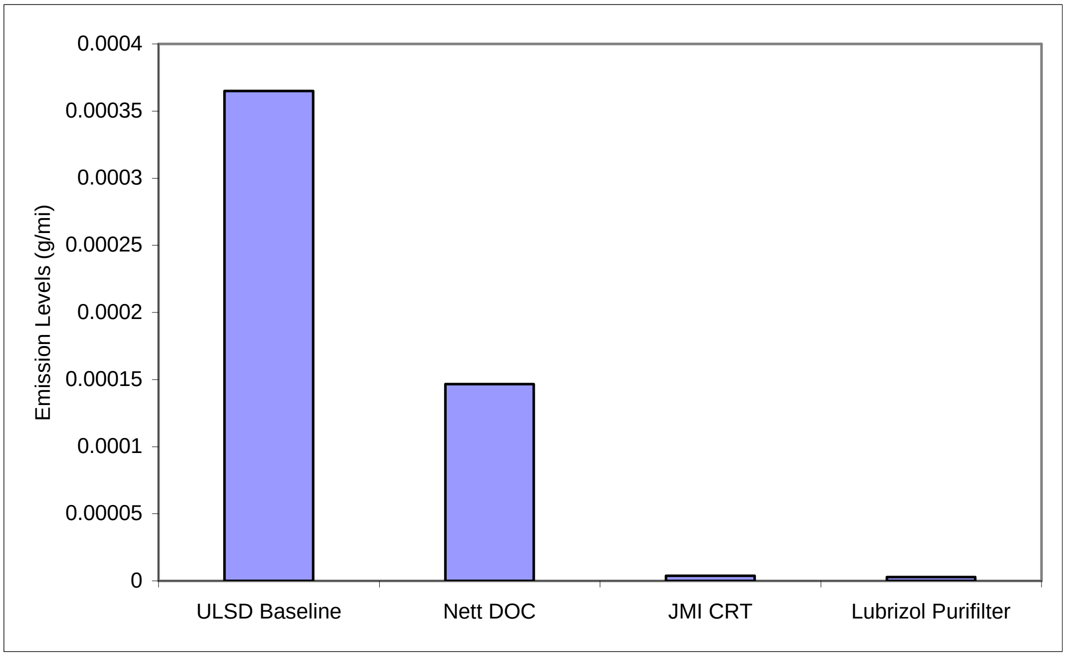

Figure 94: PM Mass Estimations for the DT466E

5.8.3.2. Experimental Results – T444E

Figure 95 shows the test results for the T444E engine. CO emissions from the T444E were reduced by 69% and HC emissions were reduced by 94% using the CRT. The DOC resulted in a 66% reduction in CO emissions and 81% reduction in HC emissions. The Purifilter reduced HC emissions by 55% while reducing CO emissions by 54%. The CRT resulted in 10% increase in corrected NO_X, while the DOC had a much higher increase (28%) in terms of corrected NO_X. The Purifilter showed a 12% reduction in NO_X. These results are summarized in Table 43.

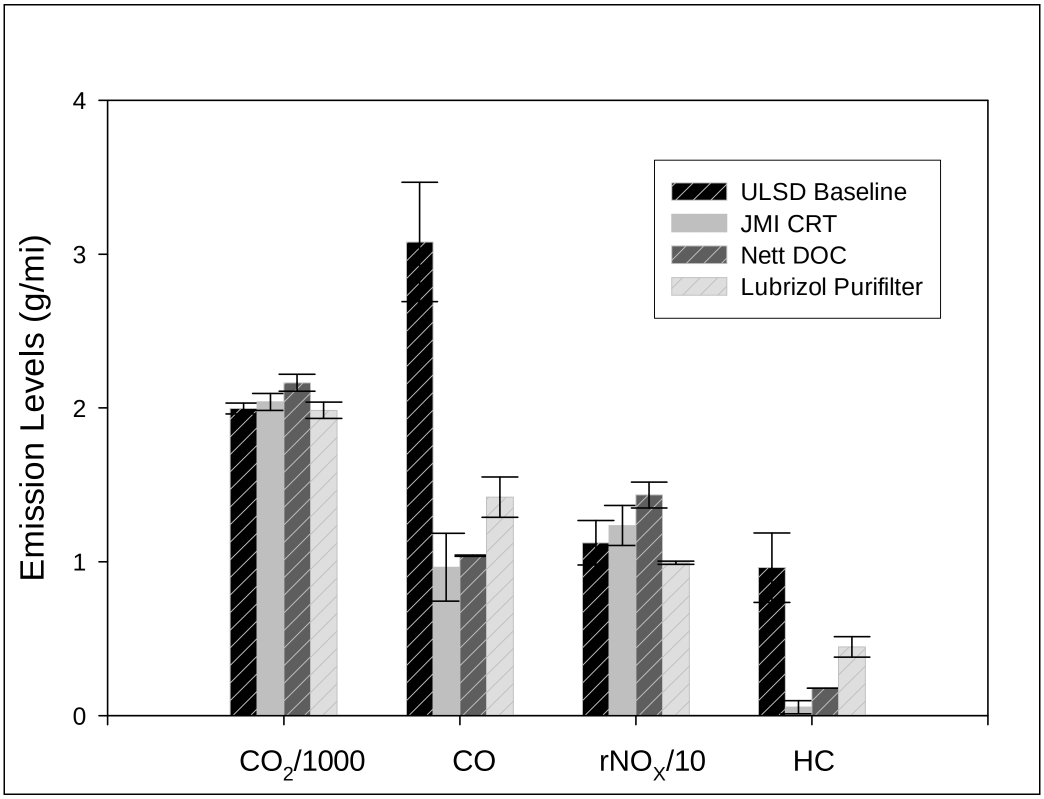

Figure 95: Gaseous emissions measurements for the T444E

Table 43: Aftertreatment reductions in emission levels for the T444E when compared to the ULSD baseline.

T444E	**CO**	**rNO_x**	**HC**
% Reduction			
ULSD Baseline	**3.1**	**11**	**1.0**
JMI CRT	**69**	**-10**	**94**
Nett DOC	**66**	**-28**	**81**
Lubrizol Purifilter	**54**	**12**	**55**

The PM results for the school bus equipped with the T444E engine showed significant PM reductions with the use of a DPF. Figure 96 shows the PM reductions as a function of bin size. For each of the bin sizes that the PM-300 can measure, PM was reduced by over 90%. The DOC also reduced PM significantly for this engine. The Lubrizol Purifilter effectively reduced all of the PM above 2 microns.

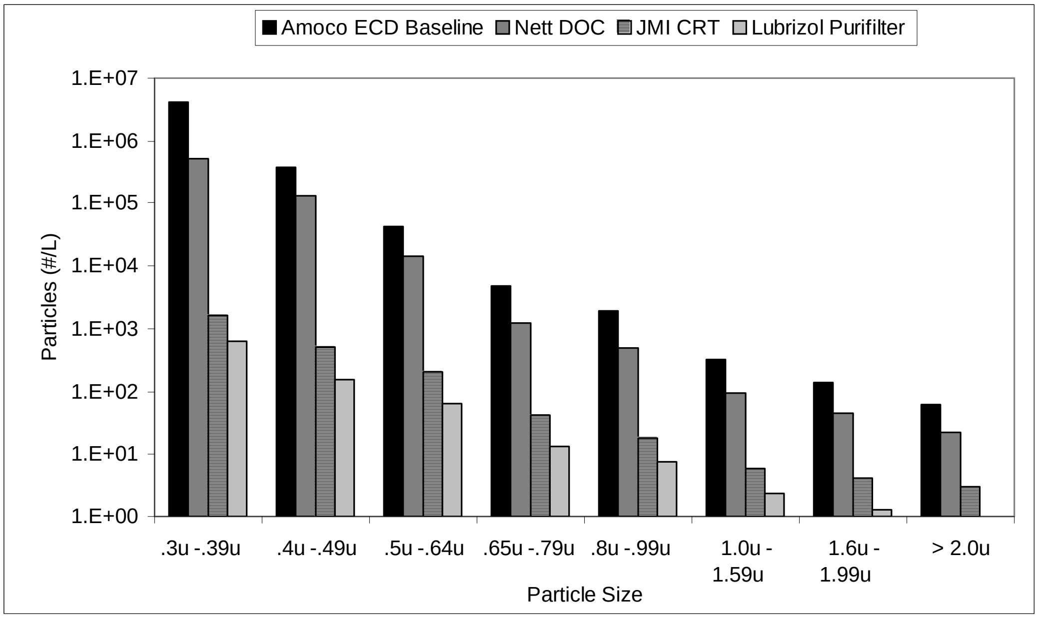

Figure 96: Average PM Concentrations for the T444E

The estimated PM emissions for the T444E engine showed significant reductions through the use of aftertreatment devices. The DOC showed an 88% reduction in the estimated mass of PM while the DPFs showed 99.9% reduction in PM mass. Figure 97 shows that for the CRT and Purfilter, virtually none of the PM from the school bus was emitted from the tailpipe.

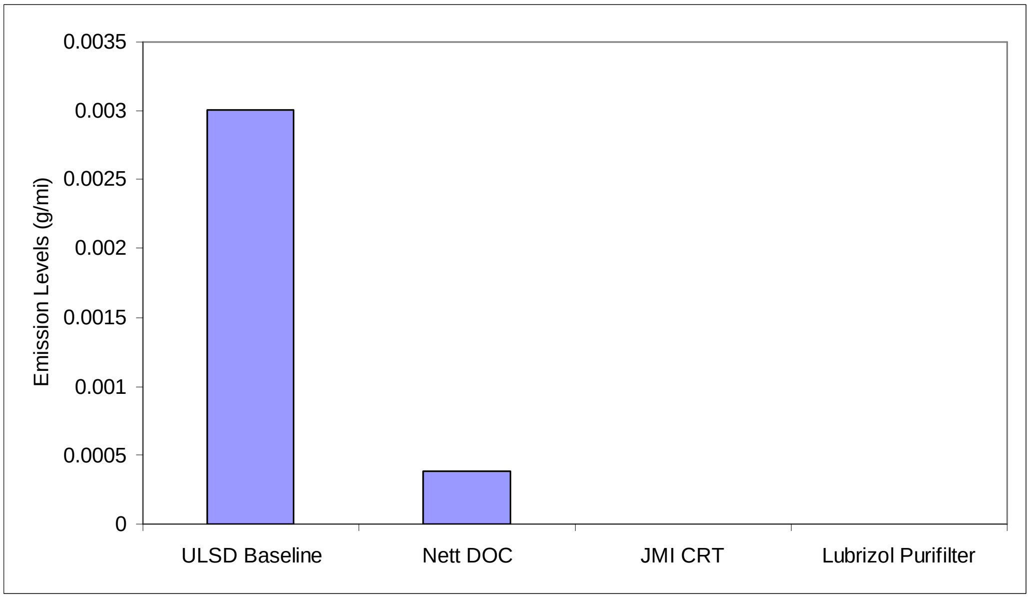

Figure 97: PM Mass Estimations for the T444E

5.8.3.3. Experimental Results – Cummins ISB

Testing for the Cummins ISB engine produced similar trends to the T444E; however CO reductions were not as significant. Figure 98 shows the gaseous emissions results for the Cummins ISB engine. The DOC reduced CO emissions by 39% and HC emissions by 81%. The Lubrizol Purifilter was slightly oversized for the Cummins application. Due to its larger design, gaseous emissions were able to flow through the particulate trap without contacting the walls containing the reduction catalyst. CO emissions were only reduced by 18% while HC emissions were reduced by 22%. The CRT was the most effective aftertreatment device at reducing CO emissions for this particular school bus. CO emissions using the CRT were reduced by 48%. HC emissions using the CRT were significantly reduced by 92% however. These reductions are included in Table 44.

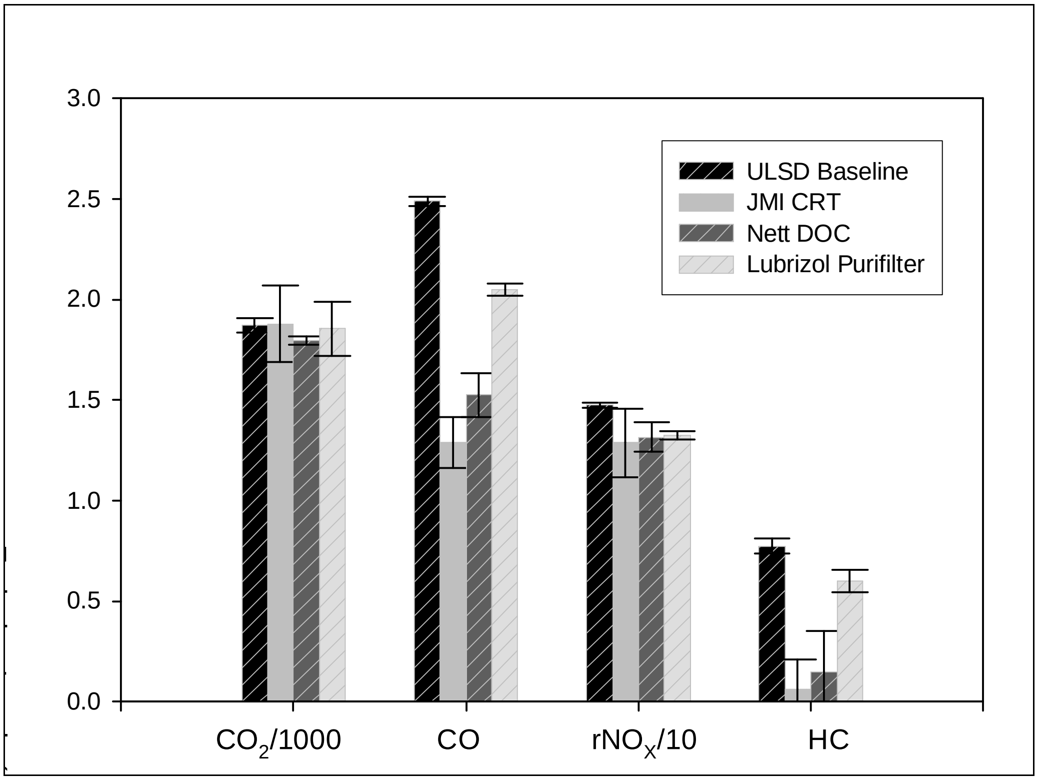

Figure 98: Gaseous emissions measurements for the Cummins ISB

Table 44: Aftertreatment reductions in emission levels for the Cummins ISB when compared to the ULSD baseline.

Cummins ISB	CO	rNO_x	HC
% Reduction			
ULSD Baseline	**3.1**	**11**	**1.0**
JMI CRT	**48**	**13**	**92**
Nett DOC	**39**	**11**	**81**
Lubrizol Purifilter	**18**	**10**	**22**

PM particle counts for the Cummins ISB engine show that the use of a DPF significantly reduces the number of particles for each of the bin sizes measured. The largest reductions occur in the first three bin sizes, where the largest contribution to the overall mass of particulate matter is. The results also show that the use of a DOC can also reduce particles, however is not as effective as a particulate trap. Figure 99 below shows the PM concentrations as a function of bin size.

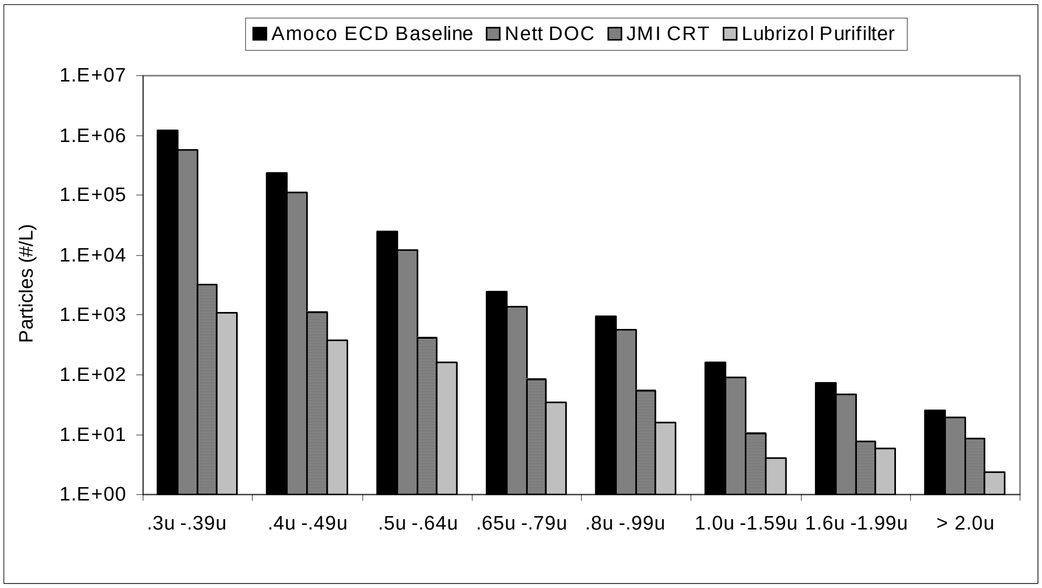

Figure 99: Average PM Concentrations for the Cummins ISB

Estimated PM mass emissions when using a DPF showed similar results, as demonstrated in Figure 100, to the T444E. The Nett DOC exhibited a 53% reduction in mass, which was not as significant as the T444E. The use of a DPF eliminated 99.7% of the PM using the CRT and 99.9% of the mass using the Lubrizol Purifilter.

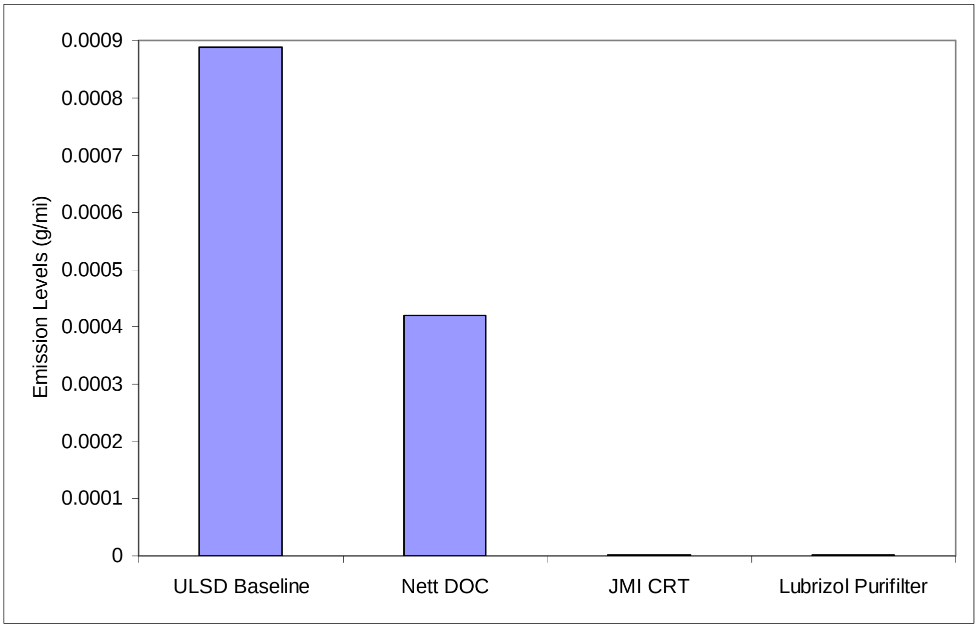

Figure 100: PM Mass Estimations for the Cummins ISB

5.8.3.4. Investigation of NO and NO_2 Emissions

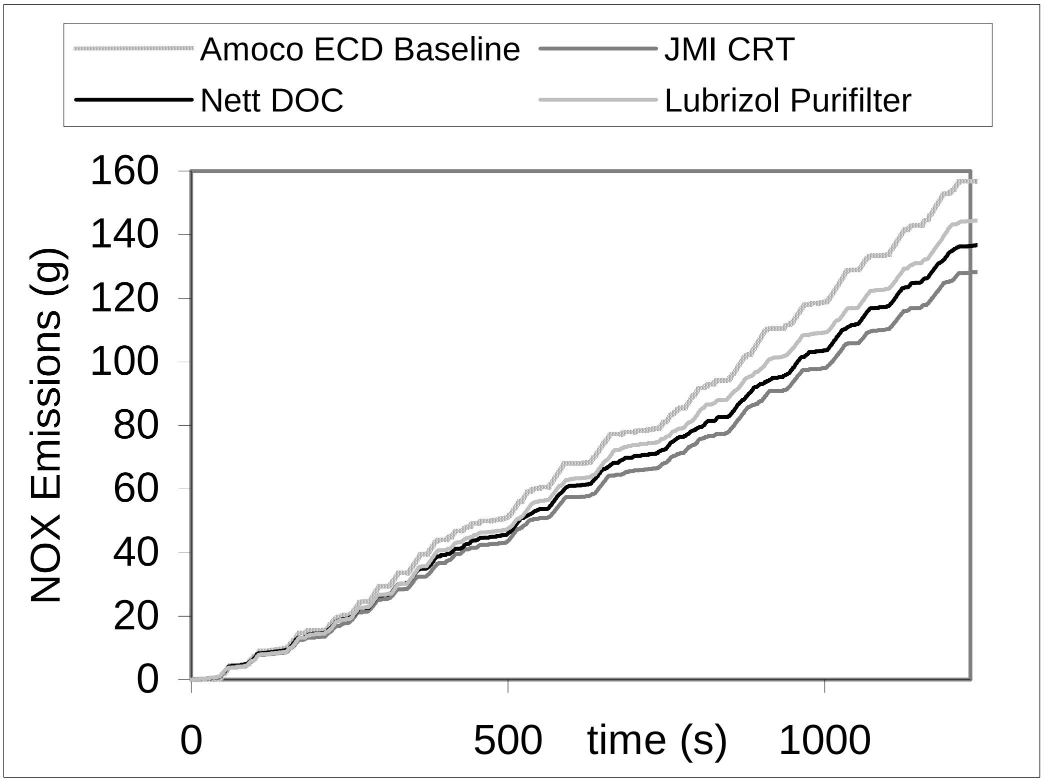

Figure 101: Total cumulative NO_X emissions for the DT466E during a single RUCSBC test.

In order to examine the chemistry of the catalyst for the three aftertreatment technologies, the NO_X emissions were further analyzed. Figure 101 is a cumulative plot of total NO_X emissions for the DT466E engine with the baseline fuel, DOC, CRT, and Purifilter, respectively. The figure represents the total accumulation of NO_X emissions in grams as a function of time during the single cycle of the RUCSBC. NO_X emissions are primarily a mixture of NO and NO_2. Of these two gases, NO emissions are typically much higher than NO_2 emissions. Figure 102 and Figure 103 below show the breakdown of each constituent for the DT466E.

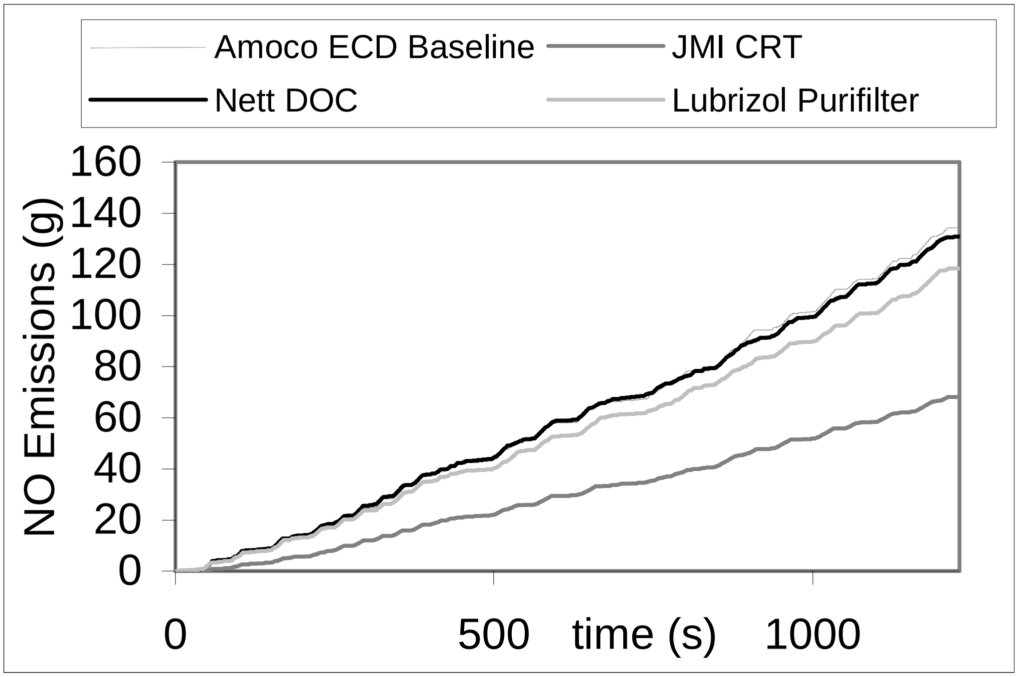

Figure 102: Total cumulative NO emissions for the DT466E bus during a single RUCSCB test.

As shown in Figure 102, NO emissions were the lowest for the experiments performed using the CRT. Conversely, the Nett DOC shows little reduction in NO.

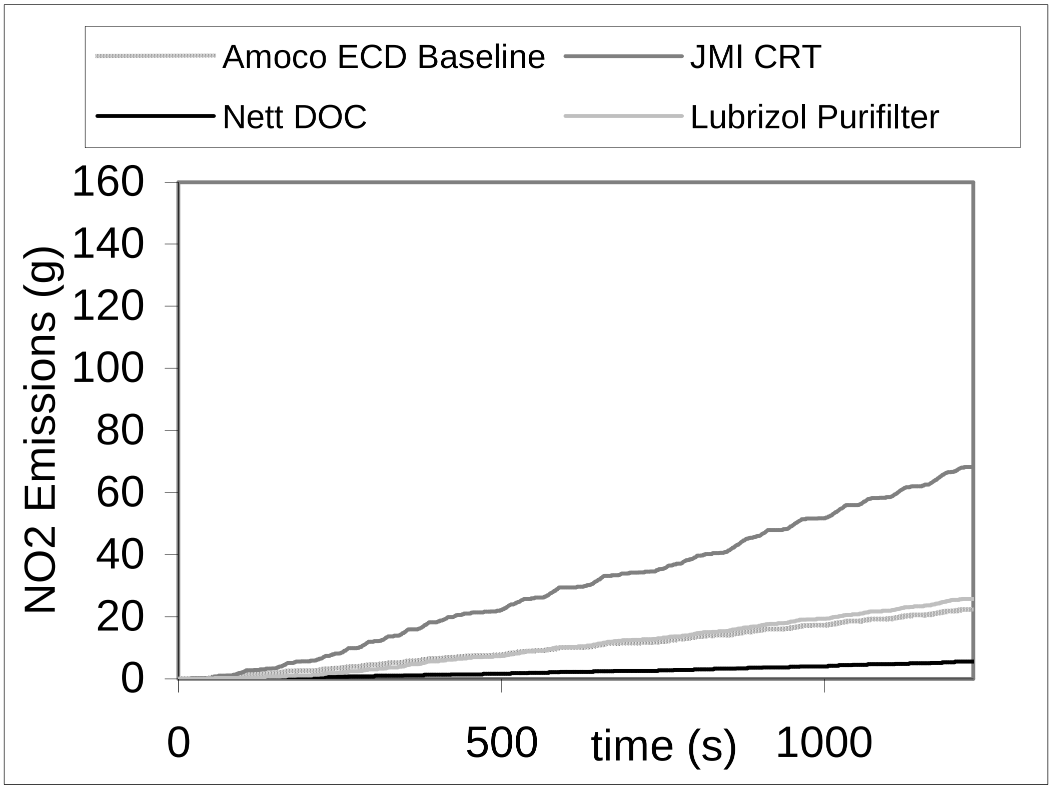

Figure 103: Total cumulative NO_2 emissions for the DT466E bus during a single RUCSCB test

The Johnson Matthey CRT and Lubrizol Purifilter processes require the conversion of NO to NO_2 to aid in the oxidation of CO and HC. However, the CRT used for this experiment had a high catalyst loading while the Purifilter used for this study had a low catalyst loading. This explains why the NO_2 emissions are higher for the tests using the CRT compared to the Purifilter. The two figures above also show that the catalyst used by the Nett DOC selectively reduces NO_2 emissions but not NO emissions.

5.8.3.5. Comparison to 2007 EPA Standards

A comparison of the alternative fuels test results to the 2007 US EPA standards are shown below in Table 40. Currently, the EPA regulates brake specific emissions. Brake specific emissions measure mass of pollutant per unit of engine work. In order to obtain the amount of work performed by the school bus for this study, engine torque information was provided by the electronic control module. The Cummins ISB engine is omitted from this table due to its lack of an ECM.

CO emissions for #2 diesel already currently meets the 2007 standard. Since diesel engines emit low CO levels compared to spark-ignited engines, this standard is easy to reach. The emissions results from Table 45 suggest that the use of aftertreatment devices can reduce HC emissions to below the EPA standard. However, DOCs and DPFs are not effective in reducing NO_X emissions to below the standard. The 1.2 g/bhp hr standard for NO_X emissions is going to be phased down to 0.2 g/bhp hr by 2010. In conjunction with ULSD fuel and a DPF, the addition of a NO_X absorber can potentially reduce both HC, PM, and NO_X emissions simultaneously.

Table 45: Comparison of test results with 2007 standards

444	**CO g/bhphr**	**rNOx g/bhphr**	**HC g/bhphr**
2007 Standard	*15.5*	*1.20*	*0.14*
ULSD Baseline	0.91	4.21	0.28
JMI CRT	0.28	3.56	0.01
Nett DOC	0.29	3.85	0.05
Lubrizol Purifilter	0.55	4.45	0.18
466	**CO g/bhphr**	**rNOx g/bhphr**	**HC g/bhphr**
2007 Standard	*15.5*	*0.20*	*0.14*
ULSD Baseline	1.22	5.47	0.31
JMI CRT	0.26	4.91	0.04
Nett DOC	0.46	4.68	0.08
Lubrizol Purifilter	0.28	4.98	0.01

5.9. Conclusions

With increasing pressure to meet the National Ambient Air Quality Standards (NAAQS) set by USEPA, New Jersey continues to actively research and develop strategies to help meet the standards, which may include alternative fuels and aftertreatment devices. However, prior to the present study, very little data was available to quantify emission levels for school buses under realistic mobile testing conditions. Using a mobile test cycle created to simulate actual school bus conditions, three alternative fuels and three aftertreatment technologies were tested at the Aberdeen Test Center in Aberdeen, MD. Mobile NO_X emissions were corrected for temperature and humidity using an engine specific correction factor developed from a school bus idle study.

5.9.1. Alternative Fuels Testing

For the research conducted in this study, # 2 conventional petroleum diesel (low sulfur ~360 ppm), B20 (20% by volume biodiesel, 80% by volume #2 conventional petroleum (~360 ppm) diesel), ultra low sulfur diesel (~15 ppm), and a biodiesel-ultra low sulfur diesel (20% by volume biodiesel, 80% by volume ultra low sulfur diesel (~15 ppm)) mixture were examined. The conclusions are:

- Corrected NO_X emissions were slightly affected by the alternative fuels tested. However, ULSD and B20/ULSD allow for use of NO_X reduction technologies.
- The two International engines showed an increase or slight decrease in corrected NO_X emissions, whereas the Cummins ISB engine had significant reductions when using the ULSD and B20/ULSD.

- HC emissions were reduced for all buses by all alternative fuels between 20 to 43%.
- ULSD reduced CO by roughly 40% for the T444E and Cummins.
- B20/ULSD provided reductions in CO of 46% for the T444E.
- B20/ULSD reduced PM emissions (for PM > PM0.3) by 26% for the DT466E.
- B20 and ULSD decreased PM emissions (for PM > PM0.3) by 4% and 18%, respectively, for the DT466E.
- No effect of alternative fuels on CO emissions was observed for the DT466E.

5.9.2. Aftertreatment Testing

Two diesel particulate filters and a diesel oxidation catalyst were also tested using the composite school bus cycle. Results for this testing suggest that the use of an aftertreatment device will meet the 2007 standards for HC and PM emissions. As a result of this study, the following conclusions can be made:

- As expected, each technology effectively reduced CO and HC emissions. The JMI CRT provided the best overall reductions in CO and HC.
- Corrected NO_X emissions are not significantly lowered using any of the three technologies.
- NO emissions are lowered using the JMI CRT. However, NO_2 emissions rise as part of the catalytic chemistry used to lower HC, CO and PM. The SC17L from Lubrizol showed only slightly elevated NO_2 emissions.
- NO_X emissions using the Nett Catalytic Muffler are reduced by an average of 6%. Only the NO_2 constituent of the NO_X emissions was reduced by the catalyst.

- For the particle sizes collected, PM reductions using the Nett DOC exceed the 20% suggested by Nett Technologies for the engines tested in this study.
- PM reductions using the JMI CRT for the size range that contributes the majority of PM mass are greater than 95% and the Lubrizol Purifilter produced PM reductions of greater than 99% for the same size range.

5.9.3. Rowan University's Partnership for Clean NJ School Buses Website

In order to make the results of these studies available and useful to the public, a website has been created. This website informs those interested of the work that has been performed with school buses and the reasons behind doing the work. It is written in a non-technical manner and introduces readers with little or no background in this topic to some of the health effects of diesel exhaust as well as some of the emission reduction strategies. In this website, the user can input some rather simple and easy-to-obtain information about their school district and the data that has been collected from the fuels and aftertreatment testing has been compiled into a program that uses this information to estimate the amount of pollutants emitted from the school buses in their area each year. It also estimates the savings in emissions that could be achieved if the school district implemented the emission reduction strategies that were explored in this testing. The program outputs this information to the user and shows the estimated costs of implementing each of the strategies. Therefore, the user can compare the emissions savings and costs associated with implementing the school buses, for instance, with aftertreatment devices to alternative fuels. The website also offers a list of some resources that school bus districts can explore for more information on the topic and to fund implementation of these strategies. The website address is www.jeffgladnick.com/dev/yucis/schoolbus/index.cfm

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