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**The Effect of Alternative Fuels and Aftertreatment  
Devices on Measured Mobile School Bus Emissions**

**By**

**Andrew Todd Toback**

A THESIS

PRESENTED TO THE FACULTY

OF ROWAN UNIVERSITY

IN CANDIDACY FOR THE DEGREE

OF MASTER OF SCIENCE

RECOMMENDED FOR ACCEPTANCE

BY THE DEPARTMENT OF CHEMICAL ENGINEERING

COLLEGE OF ENGINEERING

July 2007

# **The Effect of Alternative Fuels and Aftertreatment Devices on Measured Mobile School Bus Emissions**

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## **ABSTRACT**

Andrew Todd Toback

### **THE EFFECT OF ALTERNATIVE FUELS AND AFTERTREATMENT DEVICES ON MEASURED MOBILE SCHOOL BUS EMISSIONS**

2007

Dr. Robert Hesketh

Master of Science in Chemical Engineering

Since January 2002, the New Jersey Department of Transportation (NJDOT) has sponsored a research study at Rowan University to develop strategies for reducing diesel emissions from mobile sources such as school buses and class 8 trucks. This thesis presents research conducted on reducing emissions from school buses during mobile operating conditions. Four fuel blends and three aftertreatment devices were tested on three school bus engines.

For all of the tests, exhaust gas emission measurements were made using a Sensors Semtech-D to measure CO, CO<sub>2</sub>, NO<sub>2</sub>, NO, O<sub>2</sub>, and HC, along with a Sensors PM-300 to measure Particulate Matter (PM). In addition to the exhaust emissions measurements, instantaneous vehicle speed, engine speed, percent load and fuel flowrate were acquired from the engine electronic control module (ECM) during testing.

Prior work has suggested that alternative fuels reduce CO, HC, and PM emissions. In the work presented in this thesis, tests were conducted using a 20% biodiesel mixture with standard diesel fuel, ULSD, and a 20% biodiesel mixture with ULSD. Two diesel particulate filters and one diesel oxidation catalyst were also tested.

In order to evaluate the reductions, all tests were performed using a drive cycle developed by Rowan University. This drive cycle is a composite cycle developed from 11 actual school bus routes. The results reported herein were obtained by performing the drive cycle on a test track in Aberdeen, MD within the Aberdeen Test Center (ATC).

It has been well documented that NO<sub>x</sub> emissions are a strong function of

ambient temperature and humidity. In order to evaluate NO<sub>x</sub> emission reduction potentials, a NO<sub>x</sub> correction factor was developed to correct for temperatures and humidity observed during the course of the mobile testing. This thesis also presents the development of the new NO<sub>x</sub> correction factor from idle school bus data.

## ACKNOWLEDGEMENTS

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Special thanks go out to the undergraduate and graduates students that as a team were responsible in making this project groundbreaking in the field of mobile emissions research. In addition to the Rowan team, this project would not have been able to operate so smoothly without the dedication and support of the Aberdeen Test Center.

Finally, there is no real way to thank your parents, especially mine, for their continuing support and love, no matter what I do. Thank you to Mom and Dad for everything.

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## **1. Introduction**

### **1.1. Background**

Diesel engine exhaust is a significant source of atmospheric pollutants such as nitrous oxides (NO<sub>x</sub>), carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM). In fact, it has been estimated that heavy-duty diesel vehicle emissions are responsible for 80% of the PM and 33% of the NO<sub>x</sub> produced in the Northeast USA.<sup>1</sup>

The United States school bus fleet is a major contributor of diesel exhaust emissions. During each school year, school buses travel more than 4 billion miles every year and carry approximately 24 million children.<sup>2</sup> There are about 450,000 school buses in the United States,<sup>1</sup> 390,000 of which are powered by diesel fuel. School bus routes also produce the environmentally harmful pollutants listed previously, which may be reduced with the use of alternative fuels and the addition of engine retrofit emission reduction aftertreatment devices, each of which deserve ample consideration. Reduction of school bus emissions is particularly important because children are the most susceptible to the effects of diesel emissions.<sup>2</sup>

The 2007 model year of HDDVs are regulated to emit over 90% less pollutant than the previous emissions standards. In the state of New Jersey, regulations mandate that school buses be in service for no longer than 12 years. It is highly likely that pre-2007 buses will remain in service for years to come, perhaps as late as 2019. Accordingly, the New Jersey Department of Transportation (NJDOT) Bureau of Transportation Technology is currently sponsoring a research study at Rowan University to develop strategies for

reducing diesel emissions from school buses, with a particular emphasis on determining the most inexpensive and effective ways for the older vehicles to meet the new standards. Previous work has been performed on quantifying school bus idle emissions.<sup>3,4</sup> Retrofitting the older buses is a very promising way to have an entire fleet meet the 2007 standards without having to replace all of the older buses that are still within the 12-year usage period. Buses that have been retrofitted might use alternative fuels that burn cleaner and/or aftertreatment devices to reduce the pollutants.<sup>2</sup>

Particulate matter from diesel exhaust is of particular concern because of the potential health risks associated with its inhalation. The International Agency for Research on Cancer has classified these PM emissions as ‘probably carcinogenic to humans,’<sup>5</sup> while the California Air Resources Board (CARB) has identified diesel particulate matter as a toxic air contaminant leading to potential cancer risk and long-term conditions like asthma. Diesel PM is not only a cause of respiratory illnesses, but it is also harmful to the environment, as it is a precursor to urban ozone formation. Therefore, the standards regulating diesel exhaust emissions are becoming increasingly more stringent and work continues at a rapid pace to develop technologies to meet these standards.

Between the years of 1970 and 2000, diesel pollutant emission levels from on-road vehicles have been gradually lowering and PM, NO<sub>x</sub>, and HC emissions have decreased by an order of magnitude. These decreases are mainly a result of developments in engine designs. However, further improvements are still required to protect the environment and people’s health, so new regulations have been created that will begin implementing in 2007 and complete in 2010. The

ambitious 2007 standards include a decrease in NO<sub>x</sub> from 4.0 g/bhp-hr to 0.2 g/bhp-hr and PM from 0.1 g/bhp-hr to 0.01 g/bhp-hr.<sup>6</sup> The PM emission standard will take full effect in 2007. The NO<sub>x</sub> and NMHC standards will be phased in for diesel engines between 2007 and 2010. The phase-in would be on a percent-of-sales basis: 50% from 2007 to 2009 and 100% in 2010 (gasoline engines are subject to these standards based on a phase-in requiring 50% compliance in 2008 and 100% compliance in 2009). In order for these stringent criteria to be met, several areas of improvement must be explored, including fuel quality, aftertreatment technologies, and engine design.<sup>7</sup>

## **1.2. Project Goal**

### **1.2.1. NJDOT**

The NJDOT is continuously looking for new technologies or strategies to improve air quality in the state of New Jersey. The DOT attains its goals by providing funding to other agencies. Through research and results from other agencies, the NJDOT has developed an interest in reducing diesel exhaust emissions from HDDVs, specifically tractor trailer trucks and school buses. By reducing both idle and mobile emissions in these two groups of vehicles, air quality has the potential to improve.

### **1.2.2. 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<sub>3</sub>) and its precursors, lead, volatile organic compounds (VOC) and oxides of nitrogen (NO<sub>x</sub>), particulate matter (PM), sulfur dioxide (SO<sub>2</sub>), and carbon monoxide (CO).

Each state produces a State Implementation Plan (SIP) to the EPA. In New Jersey, the SIP is produced by the New Jersey Department of Environmental Protection (NJDEP). The SIP contains strategies to lower emissions from stationary sources such as factories and power plants as well as mobile sources. NJDOT's contribution to the SIP comes in the form of mobile sources.

### **1.2.3. Rowan University**

Rowan University's goal for this project is to contribute to NJDOT's portion of the SIP. The goals for the Rowan University school bus study is as follows:

- Evaluate potential idle and mobile emission reduction strategies and technologies for school buses and HDDV trucks.<sup>8</sup>
- Develop a mobile testing cycle representing NJ school bus routes.<sup>9</sup>
- Characterize school bus emissions and fuel consumption at idle.<sup>4</sup>
- Determine performance of alternative fuels and exhaust aftertreatment devices on school bus emissions.
- Determine the cost/benefit of developing programs to implement each strategy in the State of New Jersey.
- Investigate particulate exposure in school bus cabins.<sup>10</sup>

In addition to the work performed at Rowan University and reported elsewhere and that presented herein, work is ongoing on characterizing diesel emissions from a variety of on-road and off-road vehicles. For example, exhaust emissions



testing is currently being performed on recycling vehicles and a follow up transient PM study is being developed. The results from the NJDOT sponsored project have been published in six SAE journal publications to date.<sup>4, 8, 9, 10, 11, 12</sup>

### **1.3. Diesel Exhaust Emissions/Emissions Measurement**

The desired products of complete combustion are CO<sub>2</sub> and H<sub>2</sub>O. Along with the desired products, the byproducts are carbon monoxide (CO), unburned hydrocarbons (HC), oxides of nitrogen (NO<sub>x</sub>), and particulate matter (PM). Beginning in 1970, the EPA began limiting the quantity of byproducts an engine can emit into the atmosphere. The 2007/2010 emissions standards set by the EPA are the most stringent standards ever instituted. An engine meeting the new standards will be 95% cleaner than an engine produced only 5 years prior. The EPA regulates the following pollutants from mobile sources:

- Carbon monoxide (CO)
- Total Hydrocarbons (HC)
- Oxides of nitrogen (NO<sub>x</sub>)
- Particulate matter (PM)

Carbon monoxide is a tasteless, odorless gas formed from the incomplete combustion of hydrocarbons, in this case diesel fuel. CO emissions are dependent on ambient temperature and oxygen availability. For these reasons, CO emissions are higher in lower ambient temperature conditions as well as higher elevations. Transportation sources are responsible for 77% of the nationwide CO emissions.<sup>13</sup>

Unburned hydrocarbons are portions of the diesel fuel that are not combusted in the combustion chamber, and passed through to the exhaust. Some hydrocarbons formed can be hazardous to the environment or even cancerous.

HC can also react with NO<sub>x</sub> in the presence of sunlight to create ground level ozone. HC emissions are typically more of a concern in gasoline engines. HC emissions from diesel mobile sources only contribute to 17% of the HC emissions in the United States.

The EPA regulates oxides of nitrogen as the general term NO<sub>x</sub>. NO<sub>x</sub> emissions are the generic term for a group of highly reactive gases, all of which contain nitrogen and oxygen in varying amounts. NO<sub>x</sub> emissions are formed by nitrogen and oxygen in the air combining under conditions of high temperature and pressure. It has been found from previous research and research presented in this thesis that NO<sub>x</sub> emissions are dependent on ambient temperature and humidity. NO<sub>x</sub> emissions contribute to ground level ozone when reacted with HC emissions. Diesel engines account for more than half of the NO<sub>x</sub> formation in mobile sources.

Particulate matter emissions are described as tiny particles or liquid droplets suspended in the air. In the case of the diesel engine, these tiny particles and liquid droplets are from the incomplete combustion of the fuel and from crankcase oil leaking into the combustion chamber. The smaller size particulate matter (nanoparticles) is particularly dangerous because they can penetrate deep into the lungs. PM is currently classified as a probably carcinogen by the International Agency for Research on Cancer.<sup>14</sup> The diesel engine contributes to over half of the PM emissions from mobile sources in the United States.<sup>15</sup>

### **1.3.1. The importance of the diesel engine**

Diesel engines are often thought to be high polluters due to the visible smoke emissions that can be seen under high load. However, the diesel engine

has many advantages and relatively few disadvantages in comparison to the spark-ignition engine. Due to its robust design, the diesel engine has a better durability and reliability that translates to lower maintenance costs than the SI engine. The diesel engine can also produce higher torque with better fuel economy than the SI engine. Since CO<sub>2</sub> emissions are a direct result of combustion, diesel engines can perform the same amount of work as the SI engine while emitting less CO<sub>2</sub> emissions. While CO<sub>2</sub> is currently not regulated, HC, CO, NO<sub>x</sub> and PM emissions are regulated by the EPA. The diesel engine produces lower HC and CO emissions than the SI engine. However, PM and NO<sub>x</sub> emissions are higher in diesel engines than in SI engine. And, as discussed above, both PM and NO<sub>x</sub> pose serious air quality and health concerns.

### **1.3.2. Units of Emissions Measurement**

In order to quantify emissions, two forms of measure are used, distance specific emissions and brake specific emissions. Distance specific emissions are usually reported in grams per mile or grams per kilometer. Distance specific emissions are heavily dependent on how the engine is run for the specified distance. For example, if the vehicle is run at a continuous speed at low load for one mile the emissions in g/mi would be lower than if the mile was reached through a series of stops and harsh accelerations. For this reason, the emissions results presented in this thesis have all been obtained by from three specific school buses undergoing a highly repeatable mobile test cycle.

The second way to report emissions are brake specific emissions. This is the form of the EPA regulations and standards. Brake specific emissions are defined as the mass of emission being produced per the amount of power being

used by the engine at that moment. Brake specific emissions allow engines of various sizes and applications to be compared to each other. These emissions are reported as grams per brake horse power-hour (g/ bhp-hr) or equivalently in metric units of grams per kilowatt-hr (g/kW-hr).

In order to determine the potential hazard to the environment, a global warming potential (GWP) is calculated. By creating weighting factors for each pollutant and using CO<sub>2</sub> as the reference, the GWPs for the distance specific emissions can be compared. This value indicates the impact on the Earth's ozone layer.

### **1.3.3. EPA Regulations**

Federal Government Regulation of diesel engine exhaust emissions began in 1970 by controlling the opacity of the diesel smoke at high load conditions. In 1974, CO, HC, and NO<sub>x</sub> emission regulations were introduced. The CO standards for 1974 were 40 g/bhp hr while the combined HC + NO<sub>x</sub> standards were 16 g/bhp hr. PM regulations began in 1988 with a standard of 0.6 g/bhp hr. The beginning of the 1990's brought about even stricter emissions standards. By this time, electronic control modules (ECMs) were introduced to control the injection timing of the diesel engine. Controlling the injection time or inducing multiple injections can more evenly distribute the fuel in the combustion chamber. The result is lower PM, CO, and HC emissions.

By 2004, emissions for NO<sub>x</sub> and HC emissions had a combined standard of 2.5 g/bhp hr. PM emissions were regulated to 0.10 g/bhp hr. The 2004 standards set the precedent for the 2007/2010 standards. The new standards will make the new diesel engine over 90% cleaner than the 2004 engines. For the

2007/2010 standards, PM is regulated at 0.01 g/bhp hr and HC is reduced to 0.14 g/bhp hr. NO<sub>x</sub> emissions will be phased in to a final value of 0.20 g/bhp hr for 2010. In 2007, 50% of each diesel company's fleet will have to meet the 0.20 g/bhp while the other 50% is regulated to 1.2 g/bhp hr. By 2010, the all diesel engines will be phased into the 0.20 g/bhp NO<sub>x</sub> standard. Table 1 below shows the history of diesel emissions standards.

Table 1: EPA Emission Standard History for HDDV's

<b>Year</b>	<b>CO (g/bhp-hr)</b>	<b>NO<sub>x</sub> (g/bhp-hr)</b>	<b>HC (g/bhp-hr)</b>	<b>PM (g/bhp-hr)</b>
<b>1974</b>	40	16		-
<b>1979</b>	25	5		-
<b>1984</b>	15.5	10.7	1.3	-
<b>1988</b>	15.5	6.0	1.3	0.60
<b>1990</b>	15.5	6.0	1.3	0.60
<b>1991</b>	15.5	5.0	1.3	0.25
<b>1993</b>	15.5	5.0	1.3	0.10
<b>1998</b>	15.5	4.0	1.3	0.10
<b>2004</b>	15.5	2.5		0.10
<b>2007/2010</b>	15.5	0.20	0.14	0.01

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 are ordered to pay fines totaling \$83.4 million, which is the largest

civil penalty ever for violation of environmental law.<sup>16</sup>

This penalty was also the third in a series actions brought against engine companies that allow their ECM's 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 \$26.7 million and the Ford Motor Co. for \$7.8 million.

In addition to the civil penalties, over 1 billion dollars will be spent in development of mobile emission testing. The first phase involves certification of a mobile emission monitoring system. The seven companies have been working with West Virginia University (WVU) authenticating WVU's Mobile Emissions Measurement System (MEMS). This procedure involved testing the MEMS against existing stationary emission testing equipment. During phase I, MEMS was compared to the EPA's ROVER (Remote On-board Vehicle Emissions Recorder).<sup>17</sup> WVU determined that their MEMS system was a more capable mobile analyzer than the ROVER.

The second phase completed with WVU involved developing test procedures that can be used with MEMS. Four tests cycles were created that encompassed acceleration, constant speed and constant time in NTE zones. The created zones represented urban, rural and highway driving. These cycles were performed mobile and with the use of a dynamometer. The dynamometer results verified the results from the mobile testing.<sup>18</sup>

The third phase involves implementing the MEMS and test cycles to vehicles manufactured prior to 2000. The results from the tests will give the EPA the actual emissions from the trucks to document instead of the estimated results

with the ill-programmed ECM.

The final phase of testing implements the first two phases for on road compliance checks. The trucks selected for compliance checks will be tested with the cycles suggested by WVU and will be tested with the MEMS.<sup>19</sup>

#### **1.3.4. Measurement of Emissions**

Diesel emissions are measured by putting a load on the engine and sampling the exhaust. There are various ways to place this load on the engine. Dynamometers as well as mobile testing are the two forms of engine loading procedures.

There are two types of dynamometers. The first is an engine dynamometer. An engine dynamometer is a test platform that tests only the engine without the rest of the vehicle. Loads are placed on the engine via the tail shaft. The advantage of an engine dynamometer is that it is more convenient to work with and has greater accuracy than if the engine were installed in a vehicle. The disadvantage is that the engine is only being tested under simulated conditions. Factors such as tire friction, wind velocities, and actual accelerations are difficult to simulate using an engine dynamometer. Currently, the engine dynamometer is the platform to certify HDDVs. Figure 1 below shows an engine dynamometer test platform. As seen in the figure, it is possible to install aftertreatment devices to the engine on the engine dynamometer test platform.

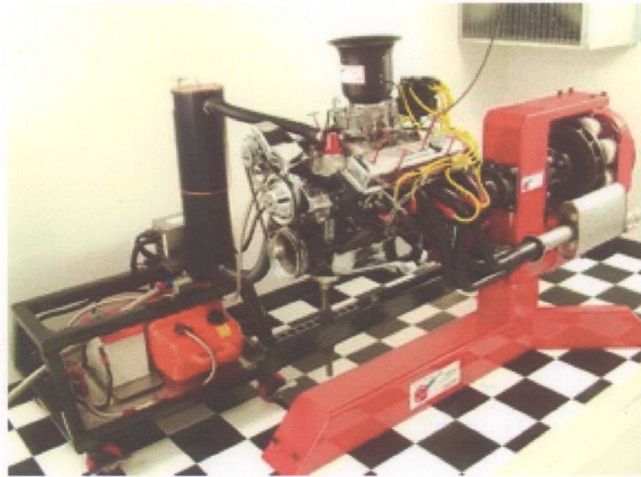


Figure 1: Engine dynamometer in-use<sup>20</sup>

Engine dynamometers follow load cycles for emissions testing. The most current load cycle used for engine certification is the Federal Test Protocol (FTP) heavy duty transient cycle. An illustration of the heavy duty cycle is shown in Figure 2. This is a plot of Percent Load on the engine as a function of time. The cycle is comprised of composite section in order to simulate on road heavy duty diesel emissions. The four sections are New York Freeway, New York Non-Freeway, Los Angeles Non Freeway, and Los Angeles Freeway. These four conditions characterize HDDV driving conditions of low load highway use and high load urban use.



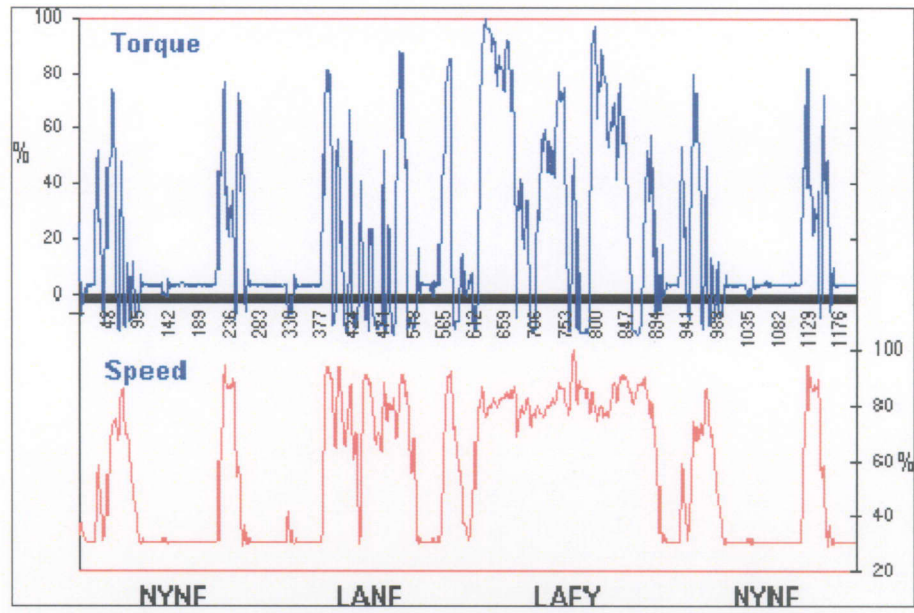


Figure 2: Federal Test Procedure heavy-duty transient cycle

Chassis dynamometers are the second form of emissions testing dynamometers. A chassis dynamometer functions by applying the load on the engine through the drive line. This function is typically accomplished by way of the drive wheels. In an HDDV application, the rear wheels are placed on rollers. As the vehicle undergoes testing, load is applied to the rollers which in turn is applied to the tires. Through the rear differential and transmission, the engine is introduced to the load. Depending on the cost and complexity of the mechanism used to apply a load to the rollers, chassis dynamometers can simulate either steady state or transient driving conditions. Figure 3 below shows a chassis dynamometer built into the floor.



Figure 3: Chassis dynamometer installed in ground

AC chassis dynamometers can simulate realistic, transient drive cycles. Drive cycles are repeatable speed vs. time plots that are used for chassis dynamometer emissions testing. For example, the central business district (CBD) cycle is shown below. This cycle was created to simulate urban driving conditions.

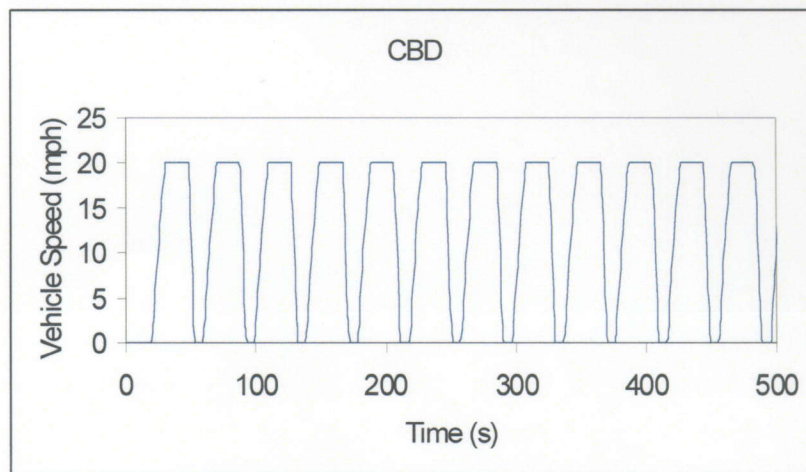


Figure 4: Central Business District drive cycle

The CBD is not an accurate representation of actual driving conditions. An additional cycle was created by West Virginia University using actual driving information from a delivery vehicle. Figure 5 illustrates that the CSHVC

demonstrates actual driving conditions. This drive cycle has been utilized in various research projects involving alternative fuels and aftertreatment devices.

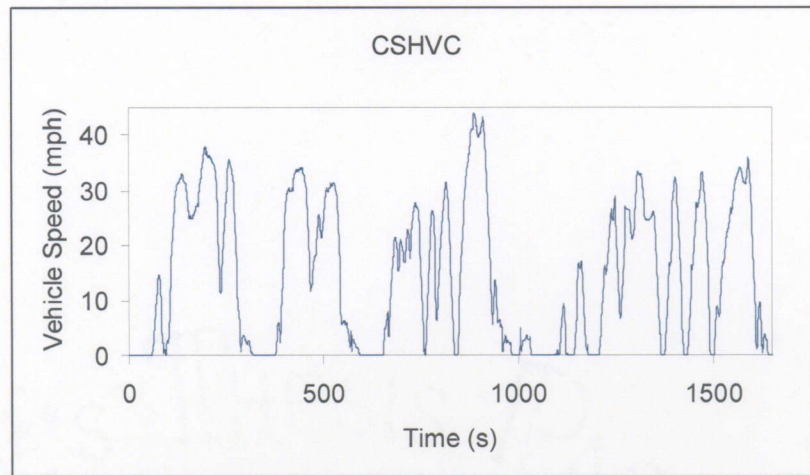


Figure 5: City Suburban Heavy Vehicle Cycle

Mobile in use testing is the most accurate way to capture real driving emissions. By installing portable emissions measurement equipment on a diesel vehicle and allowing it to perform its normal tasks, the emissions measured are not simulated emissions as with the dynamometer testing. The drawback to on-road mobile testing is repeatability. Performing tests to evaluate reduction techniques is more difficult than through the use of a dynamometer. Weather conditions such as precipitation, ambient temperature and humidity all pose additional uncertainties for mobile testing. Since CO emissions are sensitive to ambient temperature and NO<sub>x</sub> emissions are affected by ambient temperature and humidity, special correction factors must be used to correct for temperature and humidity. Another source of error is the human error associated with driving the vehicle on the same duty cycle each time. As will be described in detail in Chapter 2 of this thesis, the tests were performed on a 1 mile test track where the cycle could be used uninterrupted. Previous experiments performed by Rowan

University in the Medford school district show that repeatability is very important for distance specific emissions.<sup>3</sup>

Since the diesel engine Consent Decree of 1998, the EPA has been shifting their emphasis toward mobile testing. The goal of the EPA is to establish mobile testing as the certification standard for 2010.<sup>21</sup> Portable emissions measuring systems are being sought after to attain this goal.

Prior to the Rowan University school bus study, no test cycle was available that had been developed specifically to simulate school bus operating conditions. Therefore, a new cycle was developed, which is referred to as the Rowan University Composite School Bus Cycle (RUCSBC). The RUCSBC was developed using actual global positioning system (GPS) data from a variety of prototypical New Jersey school bus routes, including rural, urban and suburban routes. The school district routes were defined 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 was developed for the mobile testing procedure described by Hearne<sup>3</sup> and herein, but it can also be performed on a chassis dynamometer capable of applying realistic variable loads. The RUCSBC is shown in Figure 6.

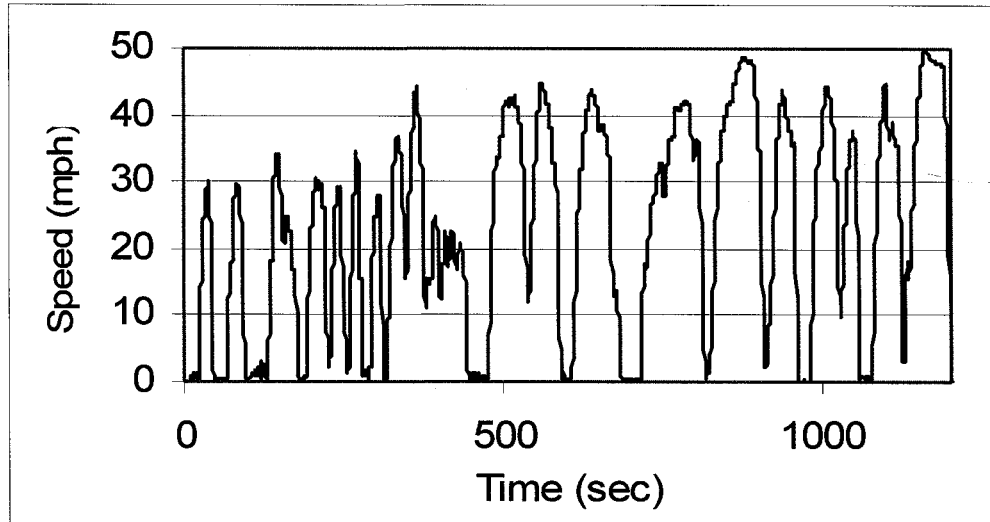


Figure 6: Speed vs. time for the Rowan University Composite School Bus Cycle (RUCSBC)

Compared to Figure 5, the RUCSBC is a more aggressive drive cycle. The accelerations and decelerations are shown by the sharpness of the lines above. It is important to again note the RUCSBC was created from actual school bus route data. Using a specific cycle for the driving application is an indication of the actual conditions experienced by and engine.

#### **1.4. Diesel Emissions Reduction Strategies**

A variety of technologies are currently available or under development specifically for reducing emissions from diesel vehicles. These technologies include alternative fuels, fuel additives, exhaust aftertreatment devices, crankcase filters and others. The present study focuses on the effectiveness of alternative fuels and aftertreatment devices on mobile school bus emissions.

##### **1.4.1. Alternative Fuels**

Alternative fuels are defined here as any diesel fuels other than standard

#2 low sulfur pump diesel that is currently commercially available. This list includes synthetic diesel fuels, ethanol diesel blends, biodiesel blends, water emulsions, compressed natural gas (CNG) and ultra-low sulfur diesel fuel. Synthetic diesel fuels are fuels that are created from a source other than crude oil. These fuels can be created from coal or natural gas and offer a higher cetane number as well as virtually no sulfur. The Fischer-Tropsch process is commonly used to create synthetic diesel fuel. Synthetic diesel fuel can be blended with #2 diesel.

Alcohol diesel fuels are fuel blends with methanol and ethanol added to them. Alcohol diesel blends typically need ignition improvers added to make them useful for diesel applications. Alcohol fuels are more suited for spark ignited engines. However, alcohol diesel fuels have been shown to reduce CO and HC emissions.<sup>22</sup>

Biodiesel is diesel fuel created from renewable resources. Renewable resources include plant oils and fatty acids from animals. Common oil sources for biodiesel are soybean, rape, sunflower, coconut, palm, and used frying oil. Biodiesel fuels have lower sulfur content, higher lubricity, and higher oxygen content. Lower sulfur content is beneficial for the use of aftertreatment devices. Higher lubricity will help sustain engine life, while higher oxygen concentrations aide in combustion.<sup>33</sup>

The addition of water into diesel fuel is called a water emulsion. Water emulsions are controversial. Adding water to the combustion chamber in the form of a liquid could damage cylinder walls and impede combustion. However, the research presented in chapter 3 shows that as ambient humidity increases,

NO<sub>x</sub> emissions decrease. This trend is the motivation behind water emulsions. Water emulsions are formed by adding liquid droplets into the diesel fuel. When the fuel is sprayed into the cylinder, it vaporizes due to the high temperature and pressure. Water in the vapor phase has been shown in previous studies to not damage cylinder walls.<sup>23</sup> Water emulsions are unstable. Over time the liquid droplets of water bind together to form larger molecules of water the lower to the bottom. In addition to lowering NO<sub>x</sub> emissions, in some applications water vapor in the fuel leads to better mixing of the fuel and air in the combustion chamber. Increased fuel and air mixing lead to lower PM formation.<sup>22</sup>

Compressed natural gas (CNG) can be used to power diesel engines. CNG fuel will lower PM and CO emissions; however HC emissions increase. Diesel engines also must be fitted with different parts to run using CNG. High pressure fuel lines as well as the injection system upgrades are needed.<sup>22</sup>

Ultra-low sulfur diesel (ULSD) is an alternative fuel made to have less than 15-ppm sulfur. By September 2006, all diesel fuel in the United States will be in the form of ULSD. 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 aftertreatment technology. The extremely low sulfur content of ULSD allows for the use of an aftertreatment where #2 diesel cannot be used. The higher sulfur in #2 diesel poisons the surface of the catalytic converter or catalyzed section of a diesel particulate filter. Previous studies show that ULSD by itself reduces HC emissions by 13 %, PM emissions by 13 %, CO emissions by 6 %, and NO<sub>x</sub> 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<sub>x</sub> emissions by 15 % to 20 %.<sup>24</sup>

#### **1.4.2. Aftertreatment Devices**

Aftertreatment devices are strategies to reduce emissions after the pollutants leave the engine. The goal of an aftertreatment device is to clean up the exhaust gas before it leaves the tailpipe. The three main types of aftertreatment devices used to reduce mobile diesel engine exhaust emissions are NO<sub>x</sub> adsorbers, diesel oxidation catalysts (DOCs), and diesel particulate filters (DPFs).

The main goal of a NO<sub>x</sub> adsorber is to reduce NO<sub>x</sub> emissions. Of the three types of aftertreatment devices that exist, the NO<sub>x</sub> adsorber was not tested for this study. NO<sub>x</sub> adsorbers use acid-base chemistry to convert NO<sub>x</sub> into N<sub>2</sub> and O<sub>2</sub>. This can be performed using the unburned hydrocarbons also found in the exhaust stream. This is called passive NO<sub>x</sub> regeneration. In diesel engines, the ratio of NO<sub>x</sub> to HC is very high. Therefore, there is not enough HC present to catalyze the NO<sub>x</sub>. Strategies to aide in passive NO<sub>x</sub> regeneration include combusting diesel fuel in the exhaust stream. By combusting diesel fuel in the exhaust stream, the exhaust gas temperature will increase. Increasing the exhaust gas temperature will in turn increase the efficiency of the catalyst. The two obvious setbacks to adding diesel fuel into the exhaust stream are increased PM emissions as well as increased fuel consumption. The combination of a NO<sub>x</sub> adsorber with a DPF has shown to reduce the PM emissions as well as the overall NO<sub>x</sub> emissions.<sup>25</sup>

Diesel oxidation catalysts (DOCs) are muffler replacements that contain precious metal catalysts to reduce carbon based pollutants in the exhaust stream. Specifically, CO, HC, and the organic fraction of PM are converted into CO<sub>2</sub>, and



H<sub>2</sub>O. A DOC is typically a honeycomb catalyst with a metal frame. Platinum and palladium are highly loaded onto the flow-through catalyst.<sup>26</sup> For the school bus tests discussed in this thesis, a DOC from Nett Technologies was tested. According to the manufacturers, conversion efficiency is increased by the design of the device, in that it forces the exhaust gas to flow turbulently, therefore increasing contact between the gas and catalyst.<sup>27</sup> The Nett DOC installed on the school bus equipped with the Cummins ISB engine is shown in Figure 7.

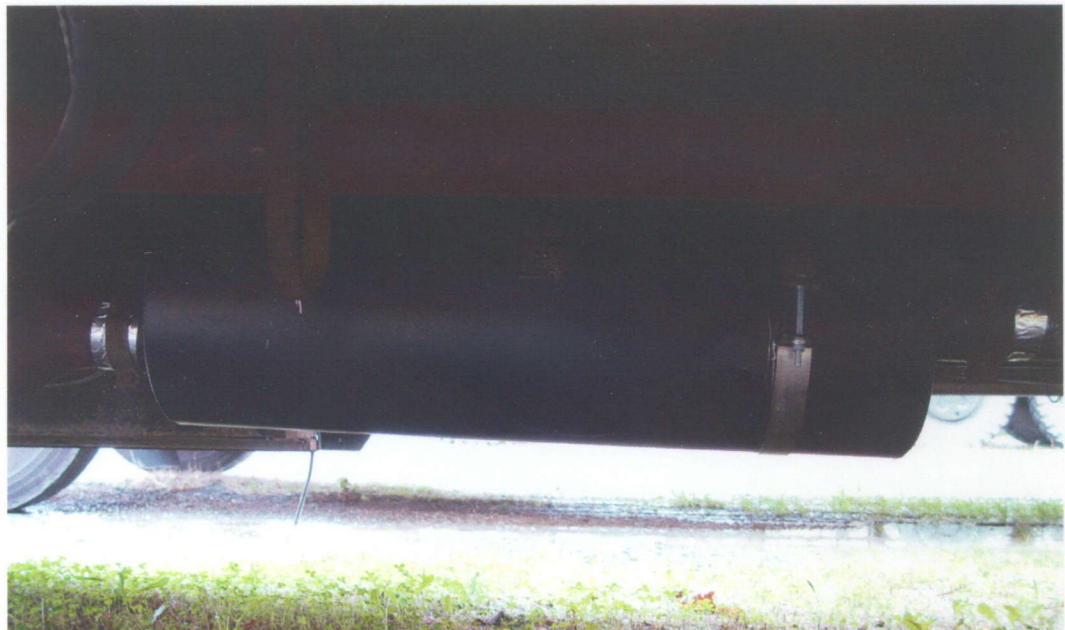


Figure 7: Nett Technologies DOC installed on the Cummins ISB engine school bus.

A diesel particulate filter removes PM from the exhaust stream as well as reducing HC and CO emissions like a DOC. DPFs work by using a wall flow design, in which the gaseous emissions diffuse through the walls of the catalyst while the liquid and solid portions of the exhaust are trapped in the filter. Materials used to construct diesel particulate filter include ceramic monoliths, wire mesh, woven silica fiber coils, ceramic foam, etc. A precious metal catalyst

is used to promote combustion of the carbon inside the filter, producing carbon dioxide. Studies show that most diesel particulate filters can achieve from 90 to 99% reduction of particulate matter, hydrocarbons, and carbon monoxide.<sup>28</sup>

Johnson Matthey's Continuously Regenerating Technology (CRT) is currently verified by the California Air Resource Board and the EPA.<sup>29</sup> The CRT is made up of two chambers. The first chamber is a ceramic monolith, coated with the platinum catalyst. In the first chamber, carbon monoxide and hydrocarbons are combusted to form carbon dioxide and water. The first chamber also converts some of the NO to NO<sub>2</sub>. In the second chamber, the exhaust passes through another monolith which forces the exhaust through the pores and the remaining soot is trapped and burned off by the NO<sub>2</sub>.

Certain application limits exist for this technology, such as the exhaust gas temperature, the NO<sub>x</sub> to PM ratio, and fuel sulfur content. The exhaust gas temperature for the CRT must be at least 275°C, the sulfur content must not exceed 50 ppm weight, and the exhaust NO<sub>x</sub> to PM ratio must be between 8:1 and 25:1 by weight. Figure 8 and Figure 9 show the CRT, where Figure 9 shows the CRT installed on the DT466E.

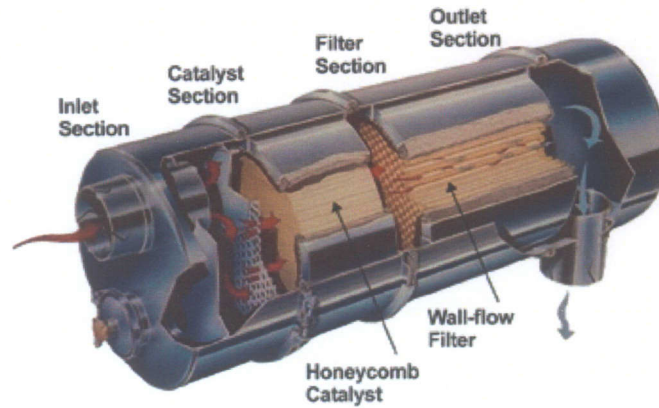


Figure 8: JMI CRT cutaway view



Figure 9: JMI CRT installed into the exhaust system of a DT466E school bus engine prior to mobile testing.

The Purifilter from Lubrizol Engine Control Systems, also verified by the EPA for the Voluntary Retrofit Program,<sup>29</sup> is a DPF that employs a platinum catalyst and silicon carbide (SiC) substrate. This system requires a minimum exhaust temperature of 280°C for 25% of the duty cycle in order for regeneration to occur.<sup>30</sup> This device has been verified to reduce PM by 90%, HC by 85%, and CO by 75% in the following vehicle models and applications: model year 1994 to

2003, highway heavy heavy-duty and medium heavy-duty, urban bus, 4 cycle, turbocharged or naturally aspirated, non-EGR engines.<sup>29</sup> Figure 10 shows the Lubrizol Purifilter installed on the T444E engine equipped school bus.



Figure 10: Lubrizol Purifilter installed into the exhaust system of a T444E engine prior to mobile emissions testing.

The EPA and the California Air Resources Board (CARB) has certified both the Lubrizol Purifilter and Johnson Matthey CRT particulate filters. The CARB verification for both of these DPFs falls under the Level 3 verification, which states that both technologies effectively eliminate more than 85% of the PM.<sup>31</sup> In order to guarantee that the DPF's would function properly with the school buses tested in this study, exhaust temperature profiles were obtained for each bus while undergoing the RUCSBC cycle. The temperature data were provided to both JMI and Lubrizol to ensure that the systems provided for testing would be effective for school buses operating under these conditions

## 1.5. Previous Work

In response to the increasingly stringent diesel emission standards and local/state efforts to improve air quality, many recent studies have been conducted to determine the most effective means for reducing diesel emissions for a variety of different engines and duty cycles. Such studies have considered alternative fuels and various aftertreatment devices.

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 %.<sup>32</sup> Previous research has shown that PM, HC, and CO reductions are better from higher percent biodiesel blends. One tradeoff to increasing the biodiesel blend is that it can significantly increase NO<sub>x</sub> depending on the duty cycle.<sup>33</sup> The tests for this study were conducted on engine and chasis dynamometers. Real world NO<sub>x</sub> emissions were not presenting in this work.

In a European study performed by Eminox, the JMI CRT was tested for a period of 8 years on 16,000 HDDV applications. In this paper, the problems with retrofitting an HDDV with a DPF are discussed. If the duty cycle temperature is too low, passive regeneration becomes difficult and soot loading can occur. Soot loading creates increased back pressure on the engine, which can lead to decreased fuel economy, or even engine malfunction. An additional cause of DPF failure is a runaway active regeneration. Active regeneration takes place at high temperatures where O<sub>2</sub> governs the PM combustion kinetics. The outcome of this study is the installation of a back pressure monitoring device that alerts the driver if the backpressure approaches dangerous limits.<sup>34</sup> This study took place over 8

years. For the Rowan aftertreatment study, the DPFs will not be installed long enough to accumulate soot and cause a backpressure engine inefficiency.

Emissions regulations are more stringent in the state of California than the rest of the United States. In a study performed by NREL in conjunction with JMI and Englehard, HDDVs in the state of California were tested using the WVU mobile test platform. The vehicles used were larger than the typical school bus engine. Average engine size for this study was 10L. The CSHVC was the cycle used for the tests. Results showed higher NO<sub>x</sub> emissions of approximately 30-40 grams per mile. The exhaust pipe from the turbocharger to the aftertreatment device was insulated in order to prevent the outside air or wind to lower the exhaust temperature. This ensures that the exhaust temperatures do not fall below 250°F where NO<sub>2</sub> is no longer effective for passive regeneration. HC and PM emissions through the use of aftertreatment were virtually eliminated. This study continued for 4 years to test the durability of the units. At the conclusion of the test, the CRT and DPX were concluded to be durable, and still effectively eliminate HC and PM emissions.<sup>35</sup> This study was conducted with the WVU chassis dynamometer. Factors such as wind resistance and road friction are not taken into account for these experiments.

A Japanese study on the effect of particulate matter concentrations through the use of a DOC and DPF showed that particle counts are only slightly reduced when using a DOC. PM sampling was performed using a dilution tunnel into a constant volume sampler (CVS). This study concluded that the wall-flow DPF is the most effectively at removing particulate matter from the tailpipe. At the 50 nm size range, the DPF was effective at reducing 97% of the PM.<sup>36</sup> This study

was performed on an engine dynamometer. Mobile emissions testing

In a year-long durability study by the National Renewable Energy Laboratory (NREL), five diesel vehicles were tested during a year long period of having an diesel particulate filter installed. The vehicles were tested for emissions using the WVU mobile emissions measurement system. A school bus, three tractor trailers, and a refuse hauler were tested using the CSHVC. The results show that the use of ultra low sulfur diesel and a diesel particulate can effectively eliminate 90% of the PM mass from the tailpipe. After the year long test was completed, it was also found that the DPFs showed no significant signs of degradation. The DPFs also significantly reduced CO and HC emissions; however, CO emissions after one year of use were slightly elevated. The CO emissions after the year long period were still far below the CO emissions from the test vehicle without the DPF installed.<sup>37</sup> Again using a chassis dynamometer does not provide real world driving conditions. Wind resistance and road friction were not taking into account.

Mayer and coworkers have performed a study to evaluate the long-term efficiencies of the Purifilter and CRT. This study is part of an effort to retrofit diesel vehicles in Switzerland. Before retrofitting, the filters were tested for filter efficiency. After 2000 hours, the filters were tested again. The results show that both the CRT and Purifilter were capable of remaining over 99% efficient for particles above 70nm in diameter. In addition, this study found that after 2000 hours, the percentage of failure for 12 different traps tested was 2% per year.<sup>38</sup> These engines were not testing using a consistent drive cycle.

## 1.6. Thesis Organization

The results presented in this thesis are aimed at quantifying emissions for both alternative fuels and aftertreatment devices in school buses undergoing mobile testing using a repeatable drive cycle developed specifically for school buses. Chapter 2 details the experimental procedure used to acquire and analyze emissions data from the school buses. The specifics of the emission measurement equipment, the testing location, the test vehicles, and the data management are also discussed in this chapter. Finally, chapter 2 discusses the estimation of PM mass from PM concentration provided by the equipment selected for this study. Chapter 3 discusses the development of a NO<sub>x</sub> correction factor for each individual engine tested for this study. The correction factor was developed by testing each school bus in an environmental chamber at various ambient temperature and humidity. This correction factor was used in subsequent chapters to compare the results of the mobile testing.

Chapter 4 presents a complete analysis of the effect of alternative fuels on mobile school bus emissions. 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 results showed that there was variation between the buses tested. The two international buses showed slight increases or decreases in NO<sub>x</sub> emissions while the Cummins ISB engine had a significant increase in NO<sub>x</sub> using the biodiesel fuel.



Chapter 5 contains the analysis of three aftertreatment devices: a diesel oxidation catalyst (DOC), a DPF with high catalyst loading (JMI CRT) and a DPF with low catalyst loading (Lubrizol Purfilter). Each of these tests were conducted using Amoco ECD fuel (~15 ppm sulfur). Each of the aftertreatments are effective in eliminating CO, and HC emissions. The PM reduced through the use of a DPF is significant. NO<sub>x</sub> emissions were neither increase or decreased significantly through the use of aftertreatment technologies.

Chapter 6 provides conclusions and suggestions for future work on both emission reduction technologies for school buses and recycling vehicles.

## 2. Experimental Procedure and Equipment

### 2.1. Introduction

The purpose of this chapter is to introduce the school buses, equipment and facilities and data acquisition systems used for this study. Also included in this chapter are the data analysis techniques used for comparing emissions from each school bus configuration.

### 2.2. School Bus Selection

Three school buses were selected for this study. The criteria for the selection were as follows:

- engine popularity with respect to the existing NJ school bus fleet,
- school bus age and mileage,
- instrumentation advantages using the vehicle interface (VI) and
- availability at the time of purchase.

#### 2.2.1. School Bus Types in NJ

To fully understand the types of school buses that operate in New Jersey, NJDOT provided a comprehensive study of the engines used in school buses across the entire state. As shown in Table 2, 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 selected are shown in bold.

Table 2: Engine types used in NJ School Districts<sup>39</sup>

Engine Manufacturer	Engine Model	Total Number of buses in New Jersey
Caterpillar	3116	581
Caterpillar	3126	1356
Caterpillar	3406	1
Caterpillar	3208	13
<b>International</b>	<b>T-444E</b>	<b>2232</b>
International	DTA 466	15

<b>Engine Manufacturer</b>	<b>Engine Model</b>	<b>Total Number of buses in New Jersey</b>
International	DTA 360	891
<b>International</b>	<b>DT 466</b>	<b>1113</b>
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
<b>Cummins</b>	<b>5.9L B series</b>	<b>1816</b>
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

After viewing the survey, it was decided to attempt to select the three most statistically popular buses. Unfortunately the Caterpillar engine was not available for sale at the time of purchase. The fourth most popular engine is the 7.3 International. This engine is found in older school bus models and is no longer produced. It was decided to choose the 5<sup>th</sup> most popular engine, the DT466E from International. An advantage to choosing the DT466E was the Vehicle Interface (VI), which is standard equipment for this newer technology.

Table 3 contains a list of the school buses purchased for use in this study. The buses used for testing make up 47% of the of the New Jersey fleet.

Table 3: Engine selection for school bus emissions testing

<b>Engine</b>	<b>Year</b>	<b>Chassis/Body</b>	<b>Engine Hp</b>	<b>Rated RPM</b>	<b>Mileage</b>
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

## **2.2.2. Engine Specifications**

### **2.2.2.1. 1997 International T-444E**

The International T-444E is an 8-cylinder (V-8) diesel engine and is commonly used in truck and bus Vehicle Classes 2 through 8 trucks and buses. This particulate engine is rated at 190 hp and has a 7.3 L displacement. The T-444E turbo is air-to-air intercooled with a wastegate and the engine has a 17.5:1 compression ratio. The DI system on this engine is a HEUI (hydraulically actuated, electronically controlled unit injectors) system. The T-444E used by Rowan University for emissions testing is shown in Figure 11.

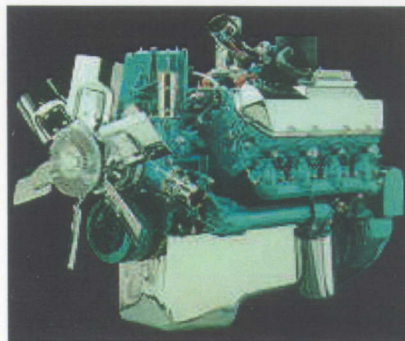


Figure 11: International T-444E diesel engine

### **2.2.2.2. 1997 International DT-466E**

The DT466 is an in-line 6-cylinder diesel engine. This engine is rated at 190 hp and has a 7.6 L displacement. This is also a HEUI DI system and is its

turbocharger is air-to-air intercooled with a wastegate. 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 12.

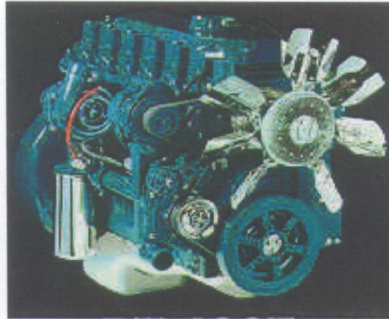


Figure 12: International DT-466E diesel engine

#### **2.2.2.3. 1996 Ford Cummins 5.9 L ISB Series**

The ISB engine is a 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). This engine is also a DI system and its turbocharger is air-to-air intercooled with a wastegate. The ISB engine has a 16.5:1 compression ratio. The 96' Cummins B Series is not equipped with an ECM. The lack of VI necessitated additional instrumentation that will be discussed further. The Cummins 5.9L B Series engine used by Rowan University for emissions testing is shown in Figure 13.

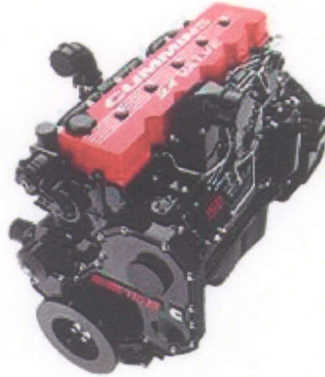


Figure 13: Cummins 5.9 L B Series diesel engine<sup>40</sup>

### **2.2.3. Electronic Control Module (ECM)**

The Electronic Control Module (ECM) is an on-board computer system that controls a variety of functions in newer diesel engines. The primary goal of the ECM is to open and close the intake and exhaust valves according to the correct crank angle. The ECM is normally mounted near the engine in the engine compartment and reads a variety of signals. 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, engine oil and coolant temperature, and fuel consumption.

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. The data link is normally found inside the cabin of the vehicle. 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.<sup>41</sup>

#### **2.2.4. 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 emissions analyzer that measures THC, NO, NO<sub>2</sub>, O<sub>2</sub>, CO, and CO<sub>2</sub> emissions. The SEMTECH-D is a collection of stand-alone scaled down lab equipment that is controlled using Microsoft Windows based Labview software. Installation of the SEMTECH-D on a school

bus takes approximately 20 minutes and requires few tools. The unit weighs approximately 78 lb. A front panel display of the SEMTECH-D mobile emissions analyzer can be seen in Figure 14. To keep the size and weight of a portable unit, changes were made to each individual sensor 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.<sup>41</sup>

Another important function of the SEMTECH-D is the vehicle interface (VI). This SAE J1708 protocol connection allows for the SEMTECH-D to obtain engine information from the engine's (ECM). This engine information gives SEMTECH-D the ability to convert emission concentrations into mass using the fuel flow rate. In addition, 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.<sup>41</sup>



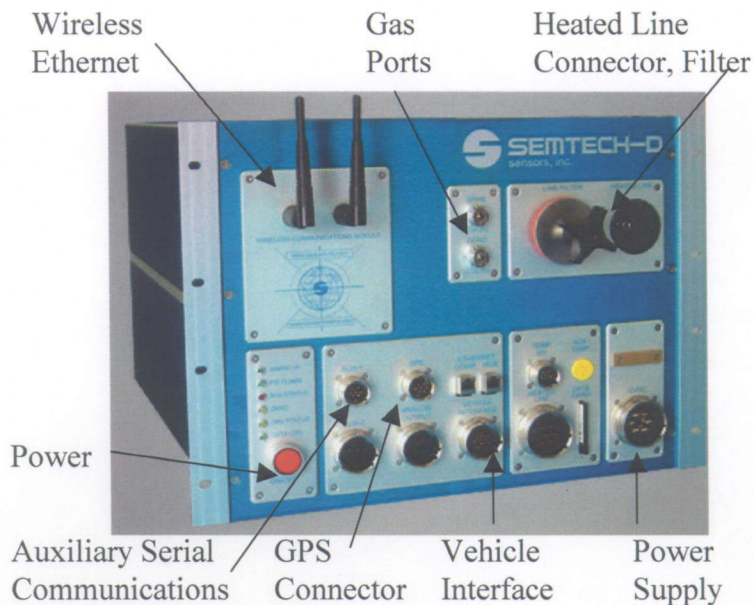


Figure 14: Sensors inc. Semtech-D mobile emissions analyzer

Sensors Inc.'s Non-Dispersive Ultraviolet (NDUV) system is currently the newest technology for  $\text{NO}_x$  detection. Sensor Inc. employs a dual NO and  $\text{NO}_2$  detection system based on a plasma powered ultraviolet light to detect NO and  $\text{NO}_2$  separately. Unlike other forms of detection, the NDUV does not deteriorate over time. For the NDUV to operate, the sample is chilled in order to remove the water content. Some heavier hydrocarbons and approximately 5% of the  $\text{NO}_x$  sample are also lost during the drying process.

The NDUV operates at a rate of 2 Hz to collect the continuous concentration measurements for NO and  $\text{NO}_2$  to the Semtech-D data collection software via an internal EIA-232 serial connection.<sup>41</sup> The accuracy for NO is 15 ppm, or 3 % of the reading for NO, whichever is greater, and 10 ppm, or 3 % of reading for  $\text{NO}_2$ , whichever is greater, over the range of 0 – 5000 ppm and 0 – 500 ppm, respectively.<sup>41</sup>

The Non-Dispersive Infrared (NDIR) analyzer is used by the Semtech-D to measure CO and CO<sub>2</sub> emissions. This sensor also needs the incoming sample to be dried to remove heavy hydrocarbons and water vapor that cause interference with the sensor. If the sample were not dried interference would occur in the infrared channels. The NDUV operates on a continuous 0.83 Hz data rate to collect concentration measurements of CO and CO<sub>2</sub> to the Semtech-D data collection software via an internal EIA-232 serial connection.<sup>41</sup> The NDUV for CO has an accuracy of 50 ppm, or 5 % of reading, whichever is greater, in the range of 0-1500ppm

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. By passing the sample over a hydrogen flame, the concentration of HC is measured by the amount of sample combusted. 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 FID has an accuracy of 5 ppm, or 1 % of reading, in the range of 0 – 100 ppm.<sup>41</sup>

Oxygen (O<sub>2</sub>) concentration is read using an electrochemical sensor by the Semtech-D gas analyzer. Electrochemical sensors also require the sample to be dry before passing over them. The sensor detects the partial pressure of O<sub>2</sub> 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. The other selected emissions can be measured using electrochemical cells but the technologies discussed above

are more accurate and reliable.

In order to convert the concentration measurements in ppm to mass emissions in g/hr, one of two techniques are used. The first method is the use of the exhaust mass flowmeter. The goal is to convert to a volumetric flow rate. A volumetric flow rate can then be multiplied by each constituent to determine the instantaneous mass (g/s) of each gas measured. Using the mass flow rate and the density of the exhaust stream, the volumetric flow rate is calculated. The density is found by taking an average molecular weight of the sample knowing the concentrations and molecular weights of each constituent in the exhaust sample. This constituents are water, CO<sub>2</sub>, CO, HC, NO, NO<sub>2</sub>, O<sub>2</sub>, and N<sub>2</sub>. Once the density is found, the volumetric flow rate of the exhaust is found using the ideal gas law. Using the volumetric flow rate of the exhaust, along with the density and the instantaneous wet concentration of each constituent, the instantaneous mass is calculated.

The second technique to obtain real time mass emissions is the use of the fuel flow rate. This technique is part of the code of federal regulations CFR40 part 86.345-79. By knowing the amount of CO<sub>2</sub>, CO, and HC and their molecular weights, mole fraction is set up between the two to determine the grams of particular constituent per gram of fuel consumed. An example of such a calculation is shown below in equation 1:

$$NO_{fs} \left( \frac{g_{NO}}{g_{fuel}} \right) = \left( \frac{[NO]}{[CO] + [HC_1] + [CO_2] - [CO_2]_{ambient}} \right) \times \left( \frac{MW_{NO}}{MW_{fuel}} \right) \quad (1)$$

where [NO] is the concentration of NO in ppm, etc.

In the case of the diesel engine, the HC and CO concentrations are negligible

with respect to CO<sub>2</sub> in the denominator of the equation above. For these gases to impact this equation, their concentrations would have to be above 1000ppm. For diesel engines this is unlikely in any normal driving condition.

Fuel flow rate can be found manually using a volumetric flow meter or this information can be provided by the ECM of the engine. The ECM determines the fuel flow rate by using the injector size and pulse width. The pulse width is the duration of time that the injector is open to allow fuel into the engine before the combustion stroke. Once the fuel flowrate is known, mass emissions can be obtained by multiplying the ratio in equation 6 by the measured fuel flow rate as shown below in equation 2:

$$NO(g / sec) = NO_{fs} \left( \frac{g_{NO}}{g_{fuel}} \right) \times Fuelflow(g / sec) \quad (2)$$

Both of the methods described above will provide mass emissions in g/s. Given the emissions in g/s, there are two possible means of reporting the data. SEMTECH-D uses a 1Hz sampling rate for the data. This means that for every second there is a data point. By adding the data points together for the total test, you are given the total grams of a particular constituent. By dividing that number by either the GPS or ECM distance traveled, the end result is an emission report in g/mi. This unit of measure allows an approximation of emissions from any school bus engine in the NJ fleet if the total miles of the route are known.

Converting the real time mass emissions to g/bhp-hr requires the torque being used by the engine for each second of the cycle. SEMTECH-D calculates torque by using a preset maximum lug curve provided by the engine manufacturer and the % load of the engine from the ECM. A lug curve shows the maximum amount of power the engine can produce at a given RPM. Lug curves are usually

using an engine dynamometer to place a load on the engine. At a given RPM, the maximum amount of power available is found by determining the maximum load that can be applied without stalling the vehicle. The ECM can calculate the % of the maximum available power that the vehicle needs at the RPM of the engine at any time. This percentage is then applied to the lug curve to determine the actual amount of torque being used at that instant in time during the test.

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 Labview based graphical user interface (GUI) for control, monitoring, and analysis of the data collected by the unit. The data collected is stored in the compact flashcard of the Semtech-D. At the end of the test, the data can be downloaded to the laptop using the SEMTECH-D software, or the card can be removed and read from the laptop after the SEMTECH-D is shut down.

The SEMTECH-D employs a two-point calibration for its CO, CO<sub>2</sub>, NO, NO<sub>2</sub>, and THC sensors; a zero and high point. The unit contains 4 inputs for calibration gas: the ambient port, span/audit port, the sample port, and zero port. The audit feature allows for a verification that the sensors are operating correctly. 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. Normally the SEMTECH-D does not require the use of the span gas. When the span gas is run, SEMTECH-D calculates factors that are saved within the unit. After the sensors are zeroed these factors from the span are accurate in the audit

more times than not. Below the steps are listed:

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. These audits are recorded for record keeping to verify if there is an anomaly that the sensors were operating normally.
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.

Another advantage of using the ECM via the VI is the ability to use the SEMTECH-D drive trace software. This software was developed specifically to suit the needs of Rowan University but has become part of the official software distributed to all SEMTECH-D users. The drive trace portion of the SEMTECH-D software writes a previously entered drive cycle on the drive cycle screen as a continuous line on a plot of speed vs. time. The position of the vehicle tested is

shown on the same plot as a dot. The goal of the driver is to accelerate and decelerate in order to make the dot follow the line. When the speed of the vehicle is within 3mph of the cycle, all lights on the screen will turn green. When the vehicle tested ventures outside of those limits, the lights on the screen turn yellow to alert the driver. 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.

### 2.2.5. 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.<sup>42</sup> The PM-300 can be seen in Figure 15.



Figure 15: Sensor's Inc. PM-300 particulate analyzer

The PM-300 operates using a system of dilutions to approximate the total concentration of particulates in the exhaust sample. A 4 LPM sample is taken

from the exhaust and is transported using a heated line to the unit where the first dilutor removes a small portion of the sample. The first dilutor is a set dilution from the user. For all tests performed the first dilution was set to 10:1. This means that 1 part of particulate rich exhaust is diluted by 10 parts of ambient air. The correct dilution is reached by means of a mass flow controller. The remaining sample leaves the unit via the drain port. The second dilution is a fixed dilution of 100:1. The final diluted sample is then pumped into the optical light scattering bench at a volumetric rate of 1.2LPM. The light scattering is performed using a semiconductor-laser as the light source. After the particulates are counted using the light scattering bench, the sample passes through a 47mm PTFE filter where the particles are collected for mass measurement.

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 °F. 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. The problem with counting particles within this range is that the majority of the particles in diesel exhaust (on a number basis) are 100 times smaller in diameter. On a mass basis, the particles collected in the range of the PM-300 make up approximately half of the effective total mass of PM collected. The figure below shows how the majority of particles themselves are in the nano range and that the PM-300 can only effectively measure half of the total mass of particulates.



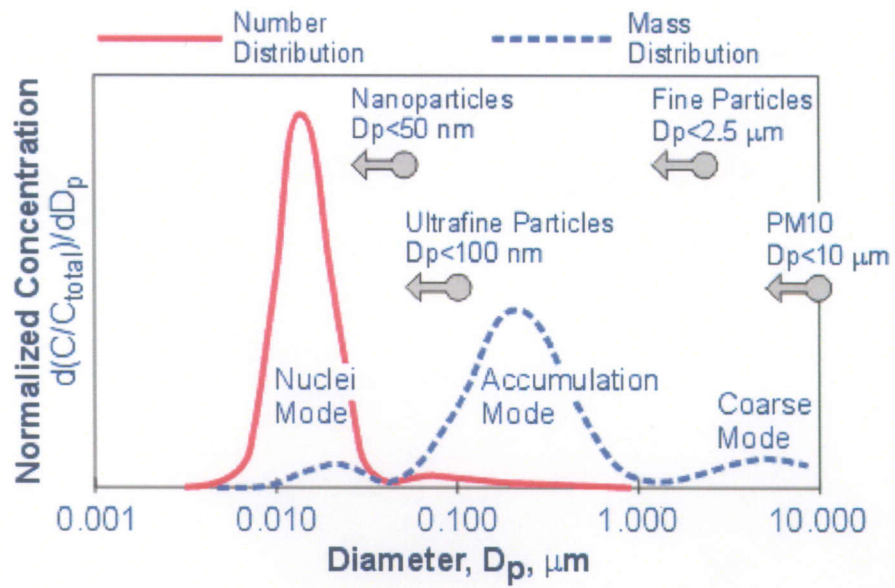


Figure 16: Particulate Breakdown in Number and Range of Mass.

The PM-300 uses a dilution ratio of 1000 L for all of the tests performed by Rowan University. An example of an Excel graph of PM data from the PM-300 is shown in Figure 17.



Figure 17: Excel graph of PM data separated by bins

Data analysis for the PM-300 involves estimating the total mass of particulates based on the concentrations of the bins that the PM-300 is able to measure. This estimate is performed on the assumption that the PM data resembles a normal distribution. Previous studies concur that diesel exhaust particulate that account for the most mass do in fact lie on a curve that could be considered a normal distribution.

The baseline data for each school bus is fitted with a curve that follows the equation:

$$c_{particulates} = c_{max} e^{\frac{(\log(p) - \log(\mu))}{\sigma}} \quad 3$$

Figure 18 is a plot of the #2 diesel baseline data for the DT466E engine. The squares in the figure represent actual data. The diamonds represent the

correction factor applied.

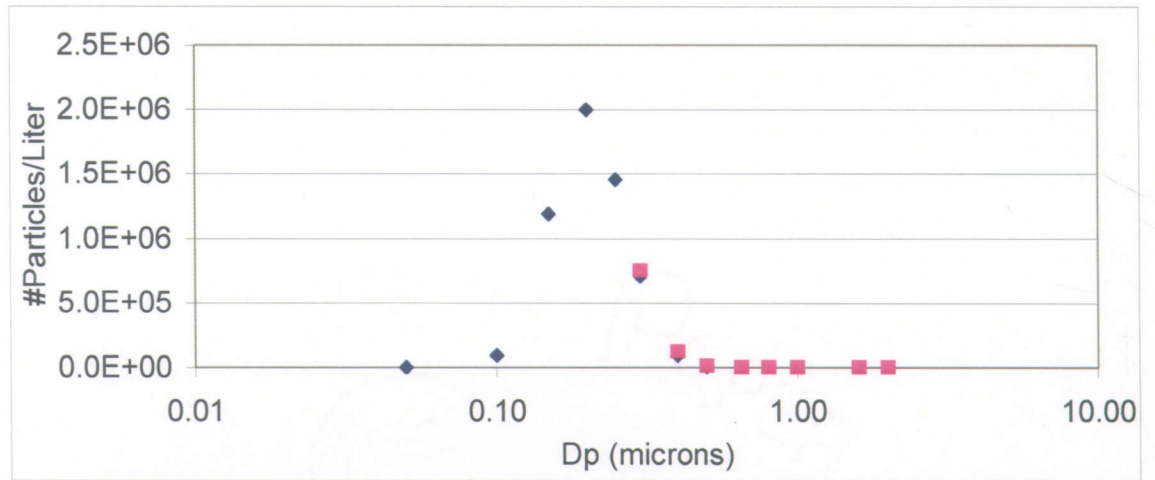


Figure 18: Curve Approximation of the DT466E Baseline Data

Using the approximation above, the mass result for the DT466E baseline data is 0.0011 grams per mile. This is the method used for all mass estimates in Chapter 4.

### 2.2.6. 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. The ruggedized frame uses a collection of VME bus circuit cards to collect the desired data. ADOCS was used to measure vehicle and engine parameters not provided by the ECM or the Semtech-D unit, specifically for the Cummins ISB Engine. 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. The complete ADOCS 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 19.

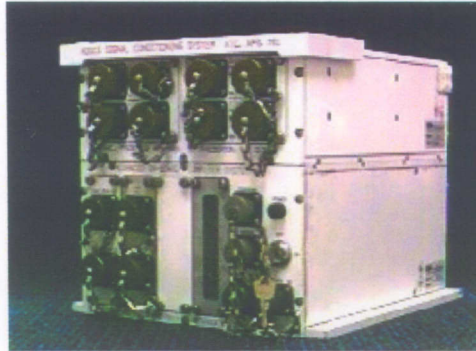


Figure 19: ADvanced Onboard Computer System (ADOCS)

For the purpose of school bus emissions testing, ADOCS was used for only a few parameters. The Cummins bus had a volumetric 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.

### **2.3. Aberdeen Test Center**

All the tests performed in this study were conducted at the Aberdeen Test Center (ATC) in Aberdeen, Maryland (50 miles North of Baltimore). 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 and environmental chamber.

#### **2.3.1. Test Track**

All of the mobile experiments performed in this study were 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 this test track was scheduled so there was no outside interference by other vehicles to ensure the composite school bus cycle was operated smoothly.

### **2.3.2. Environmental Testing Chamber**

As will be described below in Chapter 3, school bus idle tests were also conducted at ATC in order to develop a NO<sub>x</sub> correction factor. 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. Temperature can be varied from -70 to 170 °F, and relative humidity can be raised to 98 %. Data acquisition and control instrumentation are located in a separate room adjacent to the environmental chamber<sup>43</sup>.

### **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.<sup>43</sup> 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 (ASTM D86): 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.
- API gravity (ASTM D287): An arbitrary scale expressing the gravity or density of liquid petroleum products.
- Flash point (closed and open cup) (ASTM D93): 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.
- Cetane index % (ASTM D4737): A calculated value, derived from fuel density and volatility, giving a reasonably close approximation to cetane number.
- Particulate contamination
- Sulfur Content (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(ASTM D 445).
- Density or specific gravity (ASTM D 4052).

#### **2.4. Bus Instrumentation**

Table 4 is a summary school bus emission testing instrumentation used for these tests. If a measurement was taken following an SAE standard testing measurement method, the method is noted in Table 4. As mentioned above,

exhaust gas emissions measurements included O<sub>2</sub>, CO, CO<sub>2</sub>, NO<sub>2</sub>, NO, unburned hydrocarbons (HC), and particulate matter (PM). In addition to tail pipe emissions, the intake air temperature, ambient air temperature and humidity, and engine operating parameters were also monitored. The data was acquired using several systems as described below.

#### 2.4.1. Instrumentation Table

Table 4: School bus emissions testing instrumentation.

Sub-System	Measurements	Measurement System	SAE Standard	Sensor
	Humidity	ADOCS		Thermo-hygrometer
<b>Ambient Atmospheric Conditions</b>	Temperature	SEMTECH-D		
	Humidity	SEMTECH-D		
	Barometric pressure	ATC Post-Wide Meteorological System		
<b>School Bus Exterior</b>	Ambient Temperature Just Outside Bus	SEMTECH-D		Thermo Couple Type K
	Ambient Humidity Just Outside Bus	SEMTECH-D		Thermo-hygrometer
<b>Engine</b>	Crankcase temperature	ADOCS		Thermo-Couple on Dipstick Type K
	Vehicle Speed/ Distance	SEMTECH-D		GPS
	Engine Speed, RPM	SEMTECH-D	J1003	ECM
	Exhaust	ADOCS		Thermo

<b>Sub-System</b>	<b>Measurements</b>	<b>Measurement System</b>	<b>SAE Standard</b>	<b>Sensor</b>
	Temperature 1			Couple Type K
	Exhaust Temperature 2	ADOCS		Thermo Couple Type K
	Exhaust Temperature 3	ADOCS		Thermo Couple Type K
	Throttle Position	SEMTECH-D		ECM
<b>Exhaust Gas (Tail Pipe Emissions)</b>	Oxygen	SEMTECH-D		Electrochemical sensor
	CO	SEMTECH-D	J177	Non-Dispersive Infrared (NDIR)
	CO <sub>2</sub>	SEMTECH-D	J177	Non-Dispersive Infrared (NDIR)
	NO <sub>2</sub>	SEMTECH-D	J177	Non-Dispersive Ultraviolet (NDUV)
	NO	SEMTECH-D	J177	Non-Dispersive Ultraviolet (NDUV)
	THC	SEMTECH-D	J215	Heated Flame Ionization Detector (FID)
	PM	PM300		Photo Diode
<b>Fuel</b>	Mass flow rate Supply	ADOCS/ Cummins	J1003	Flowmeter
	Mass flow rate Return	ADOCS/ Cummins		Flowmeter/ECM
	Chemical analysis of liquid fuel	ATC Chemical Lab		--
	Boost Pressure	SEMTECH-D		ECM



### **2.4.2. 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. 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.).

### **3. Development of a New NO<sub>x</sub> Correction Factor**

#### **3.1. Background**

As discussed in Chapter 1, ambient temperature and humidity have an effect on NO<sub>x</sub> 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<sub>x</sub> 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<sub>x</sub> Correction Factor (rNO<sub>x</sub>).

#### **3.2. 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.<sup>44</sup> 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 5.

Table 5: Engine Data for the School Buses Tested

<b>Chassis</b>	<b>Engine</b>	<b>Rated Power</b>
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 6 were chosen based on typical weather conditions experienced by a New Jersey school bus during the course of a school year.<sup>45</sup> Each of the 3 buses were tested at each condition listed in Table 6. 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<sub>x</sub> and all other data points collected will be corrected to that value.<sup>46</sup>

Table 6: Environmental Test Matrix for Each Bus

<b>Test</b>	<b>Temperature °F</b>	<b>Relative Humidity %</b>	<b>Absolute Humidity (grains H<sub>2</sub>O/ lb. dry air)</b>
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 20 is an example of the NO<sub>x</sub> emissions and oil temperature from a typical test conducted on the DT466E bus at 40°F and 40% relative humidity. Figure 20 shows that the measured NO<sub>x</sub> emissions vary as the engine warms up. The higher NO<sub>x</sub> 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.

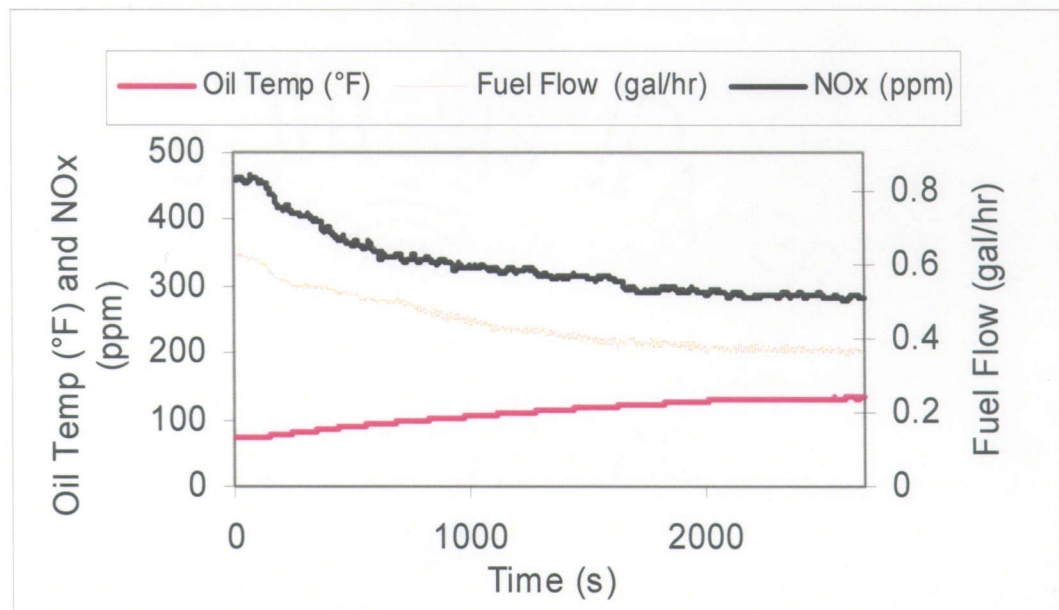


Figure 20: Transient NO<sub>x</sub> Concentration, Oil Temperature and Fuel Flow Rate for DT466E at Ambient Temperature of 40 °F and 40% Relative Humidity.

### 3.3. Experimental Results – NO<sub>x</sub> emissions

Figure 21, Figure 22 and Figure 23 show the NO<sub>x</sub> 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<sub>x</sub> 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.

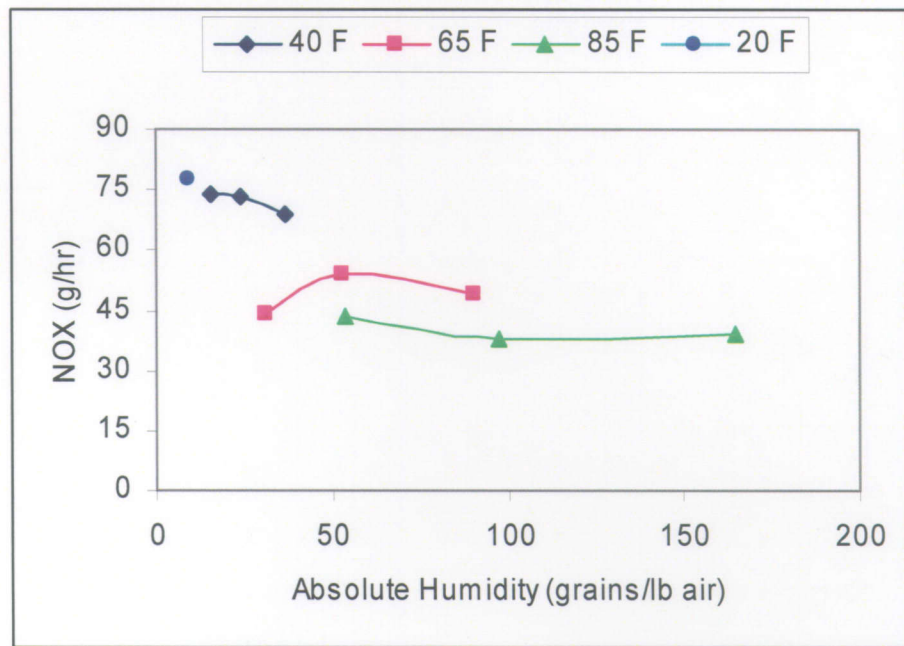


Figure 21: NO<sub>x</sub> Emissions During Idling Conditions for School Bus with T444E Engine.

The NO<sub>x</sub> emissions shown above in Figure 21 demonstrate the effect of humidity on NO<sub>x</sub> emissions. As expected, the results showed that for each of the

buses tested, as humidity increases, NO<sub>x</sub> emissions decrease. Since a higher inlet temperature should result in a higher cylinder temperature, it might be expected that NO<sub>x</sub> would increase with increasing inlet temperature due to the well-known thermal NO<sub>x</sub> mechanism. However, for each of the three buses tested in this study, NO<sub>x</sub> emissions was generally found to decrease with increasing ambient temperature.

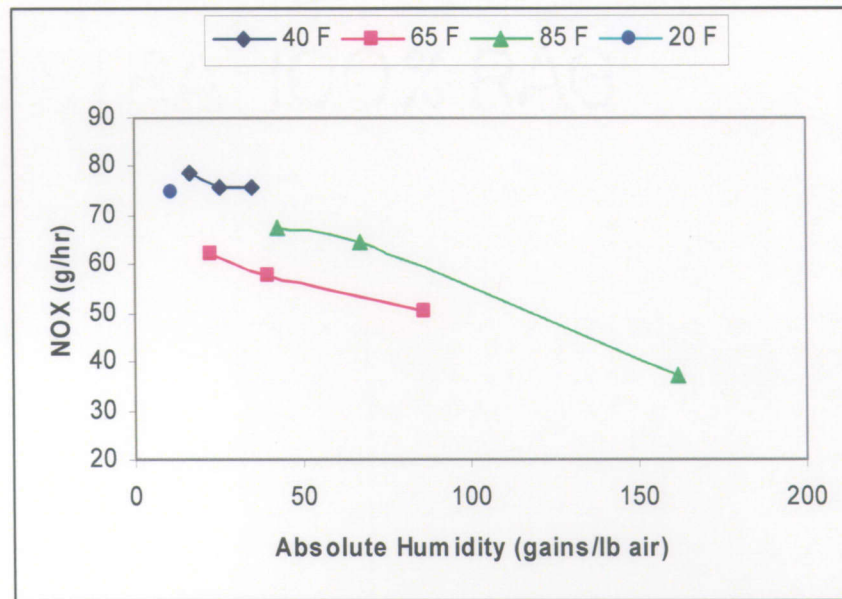


Figure 22: NO<sub>x</sub> Emissions During Idling Conditions for School Bus with DT466E Engine.

Figure 22 also shows a decrease in NO<sub>x</sub> emissions as humidity increases. For the DT466E, the measured NO<sub>x</sub> emissions were slightly lower than those measured for the T444E engine. The DT466E engine showed a slight increase in NO<sub>x</sub> when the ambient temperature was increased from 65 °F to 85 °F.

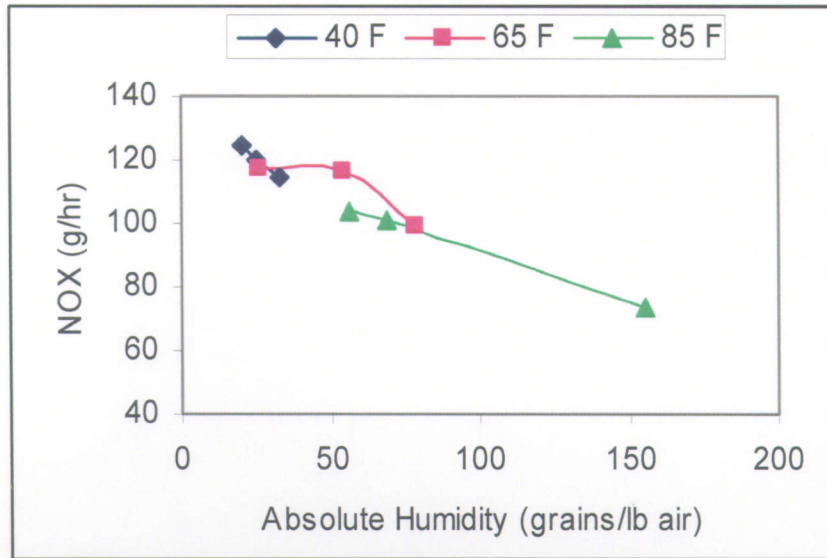


Figure 23: NO<sub>x</sub> Emissions During Idling Conditions for School Bus with Cummins 5.9 L Engine.

### 3.4. Existing Correction Factors

SAE standard J1243<sup>47</sup> focuses on the measurement of NO<sub>x</sub>. For comparing NO<sub>x</sub> measurements taken under conditions of varying inlet humidity, the SAE J1243 standard includes a correlation that estimates what the NO<sub>x</sub> measurement would have been if the experiment were conducted at a standard humidity of 75 g H<sub>2</sub>O/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<sub>2</sub>O/lb dry air and a temperature range of 70-115 °F.<sup>48</sup> The SAE NO<sub>x</sub> correlation is as follows:

$$NO_{corr} = \frac{NO_{wet}}{K_H} \quad (4)$$

$$NO_{wet} = NO_{dry}(ppm)[1 - \alpha(F/A)] \quad (5)$$

$$K_H = 1 + A(H - 75) + B(T - 85) \quad (6)$$

$$A = 0.044(F/A) - 0.0038 \quad (7)$$

$$B = -0.116(F/A) + 0.0053 \quad (8)$$

where  $NO_{dry}$  is the measured  $NO_x$  emissions in ppm,  $\alpha$  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:

$$NO_{x\,corr} = NO_{x\,measured} * K' \quad (9)$$

$$K' = \frac{1}{(1 - 0.0026 * (H - 75))} \quad (10)$$

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 24 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<sub>x</sub> concentrations vary by as much as 100 ppm with respect to experiments conducted at the SAE standard condition of 39 % RH and 85 °F.

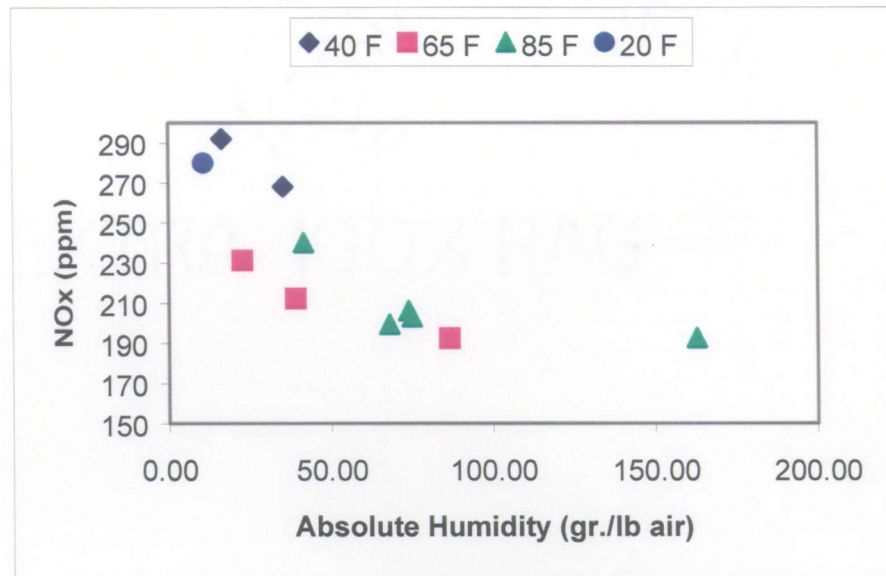


Figure 24: Uncorrected NO<sub>x</sub> Emissions (ppm) for the School Bus with DT466E Engine.

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 25 and Figure 26, the SAE and CFR correlations are used to correct the NO<sub>x</sub> 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 Figs. 10, the SAE 1243

correction factor actually *increases* the NO<sub>x</sub> concentration at lower temperatures. This result underscores the danger in extending these correction factors outside the range for which they were originally developed.

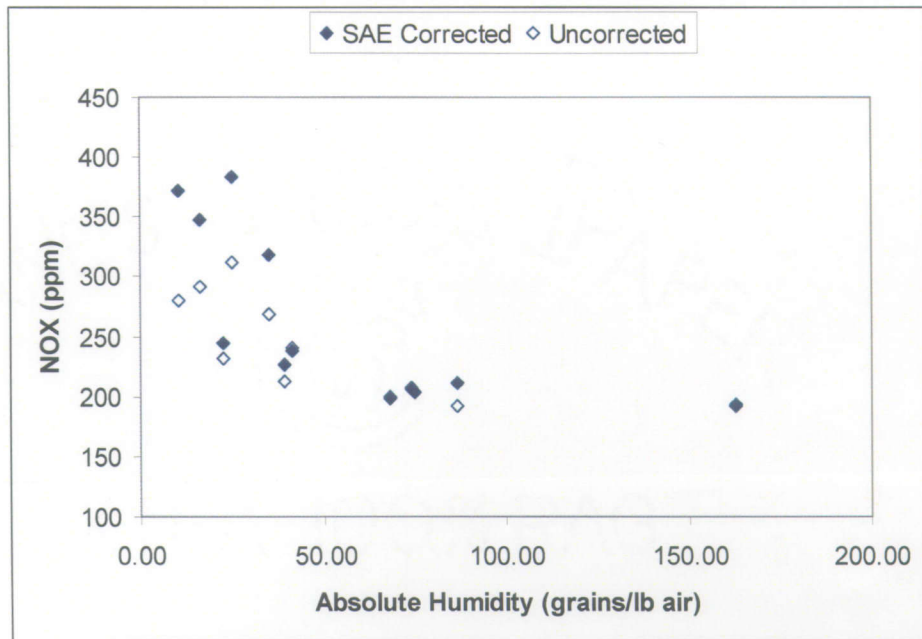


Figure 25: Corrected NO<sub>x</sub> Emissions using the SAE J1243 Correction Factor.

As shown in Figure 26, the CFR40 standard performs better than the SAE J1243 standard shown in Figure 25 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.

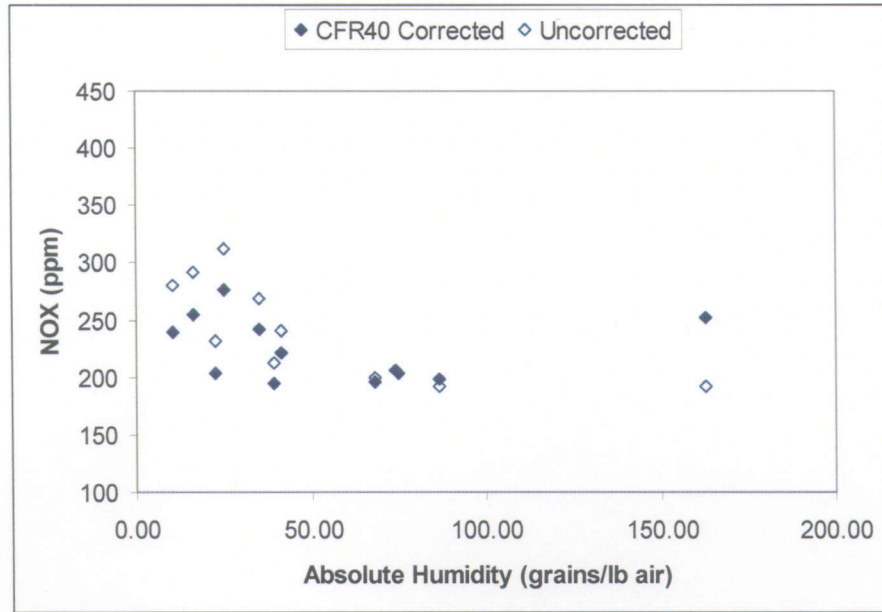


Figure 26: Corrected NO<sub>x</sub> Emission Data using the CFR40 86.1342-90.

### 3.5. Development of Rowan University NO<sub>x</sub> Correction Factor

The Rowan University NO<sub>x</sub> 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<sub>x</sub> with the other correlations, the condition of 85°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 °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<sub>x</sub> correction factor is shown below.

$$NO_{xcorr} = \frac{NO_{xwet}}{K_H} \quad (11)$$

$$K_H = 1 + A(H - 75) + B(T - 85) \quad (12)$$

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 12 is a plot of uncorrected and corrected data for the new correction factor developed specifically for the DT466E engine. As shown in Fig. 12, 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.

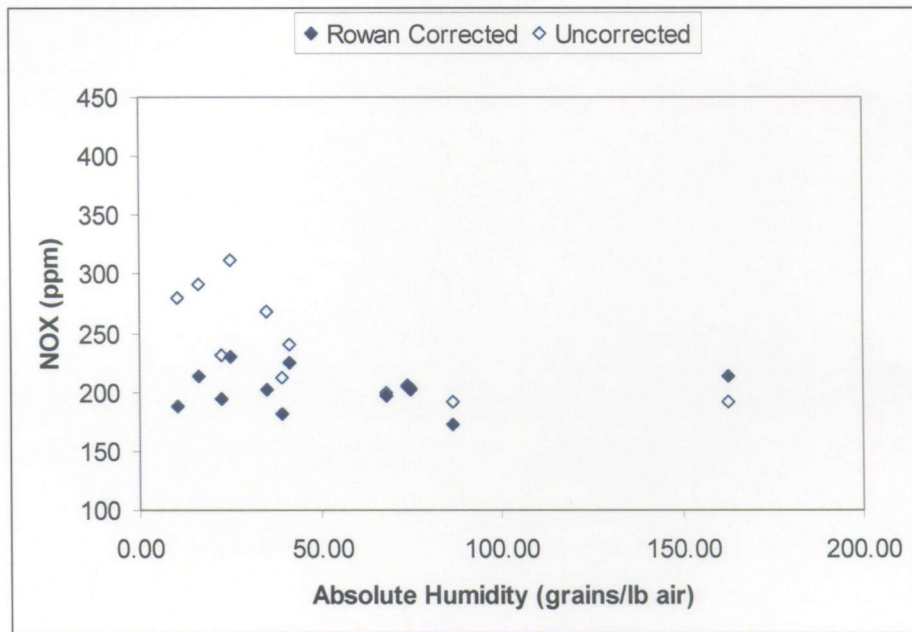


Figure 27: Engine Specific Corrected  $NO_x$  Emissions for the DT466E.

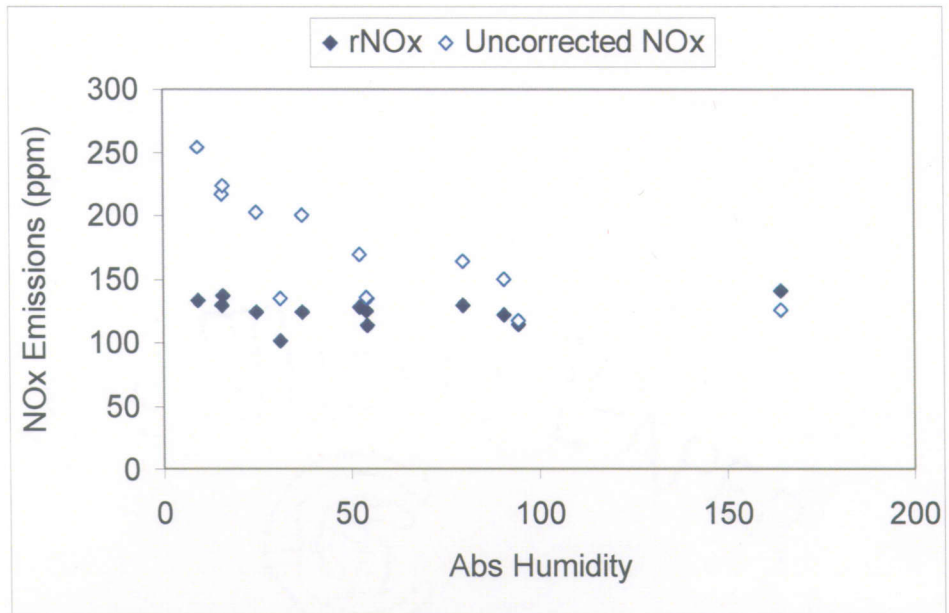


Figure 28: Engine Specific Corrected NO<sub>x</sub> Emissions for the T444E.

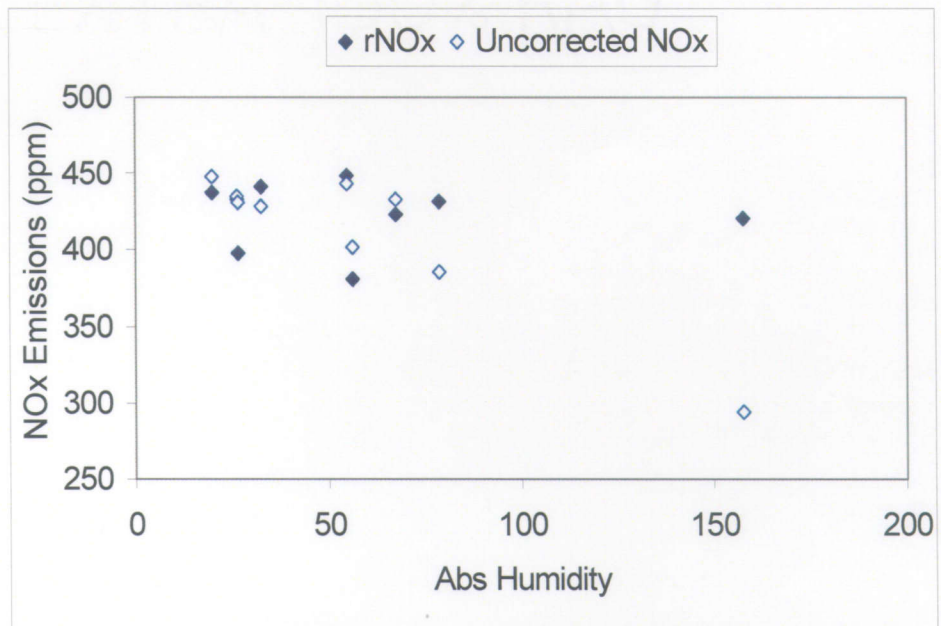


Figure 29: Engine Specific Corrected NO<sub>x</sub> Emissions for the Cummins ISB Engine.

### 3.6. Conversion of Measured NO<sub>x</sub> Emissions to Reportable Emissions.

After the NO<sub>x</sub> 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<sub>x</sub> the equation takes for form of (13):

$$rNO_{xfs} \left( \frac{g_{NOx}}{g_{fuel}} \right) = \left( \frac{[NO_x]}{[CO] + [HC_1] + [CO_2] - [CO_2]_{ambient}} \right) \times \left( \frac{MW_{NOx}}{MW_{fuel}} \right) \quad (13)$$

By multiplying by the fuel flow rate in kilograms per second, the next calculation will yield instantaneous grams of NO<sub>x</sub> 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 the 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.

### **3.7. Comparison of correction factors in grams per mile**

In the figures shown above, the Rowan University NO<sub>x</sub> 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.

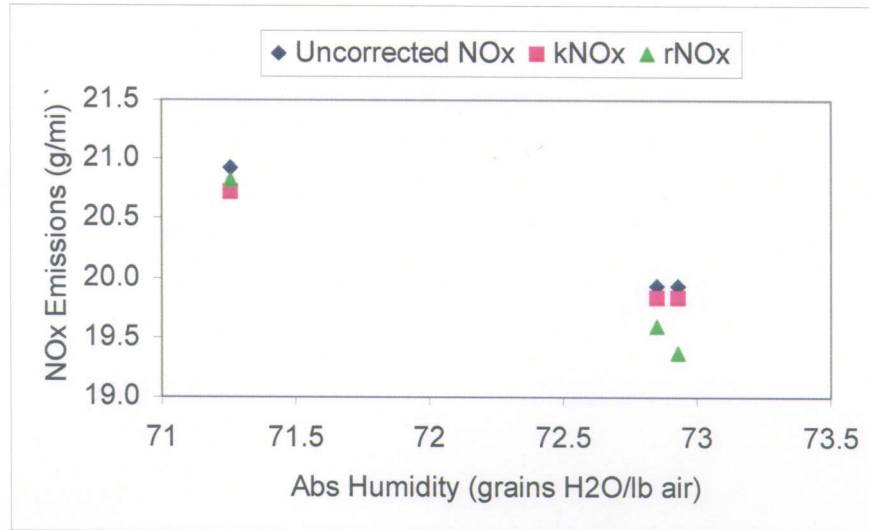


Figure 30: Comparison of correction factors applied to the DT466E for the Amoco ECD Baseline tests.

From the figure above, you can see that as the humidity increases, the Rowan University Correction factor is able to lower NO<sub>x</sub> emissions more than the CFR 40 correction factor. The values used for the Rowan Correction Factor are shown below in Table 7.

Table 7: Engine Specific Values for the Rowan University NO<sub>x</sub> 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

## **4. The Effect of Alternative Fuels on Mobile Emissions**

### **4.1. Introduction**

Previous studies have shown that through the use of alternative fuels, reductions of up to 20% can be seen. This chapter 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<sub>x</sub> 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.

### **4.2. 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<sub>2</sub>, CO, CO<sub>2</sub>, 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 8.

Table 8: Alternative Fuel test matrix for each school bus

<b>Test</b>	<b>Fuel Type</b>	<b>Fuel Makeup</b>
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.

### 4.3. 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).

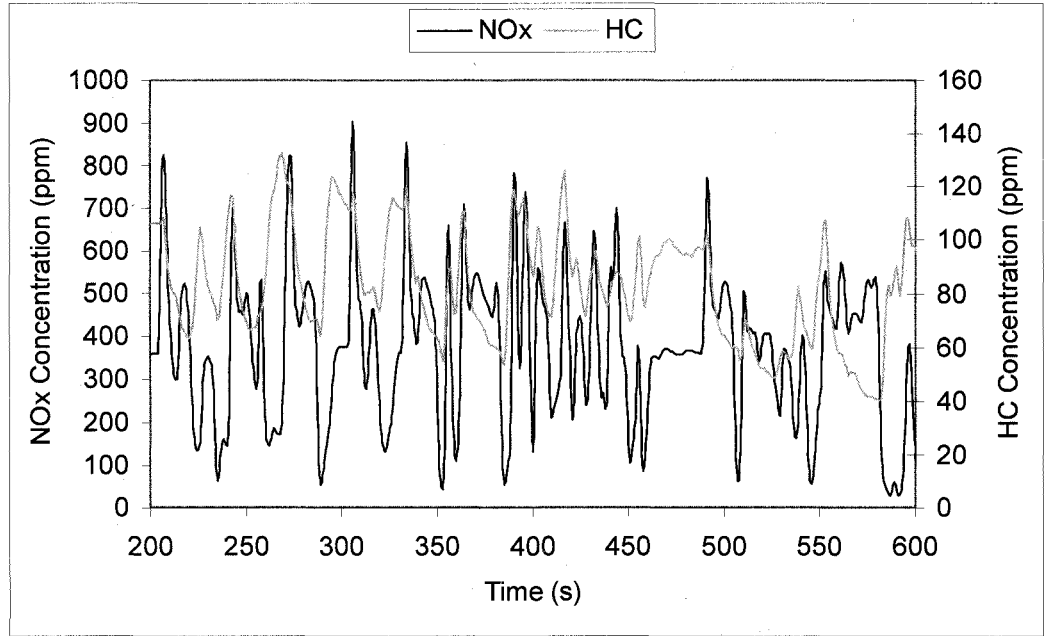


Figure 31: Raw Emissions results for a 400 second interval of the RUCSBC

Figure 31 shows raw PM data results taken during the same 400 second interval as the figure above. The data is reported on a logarithmic scale in order to include each of the bin sizes. As you can see, the 0.3 micron bin size accounts for the largest concentration of particulates.

#### 4.3.1. Experimental Results – DT466E

The NO<sub>x</sub> emissions reported in this section are the emissions corrected for ambient temperature and humidity as shown in Chapter 3. Results for the DT466E engine are shown below in Figure 32. The error bars shown in the figure represent the standard deviation of the tests from the averages presented. The results show that for the four fuels tested, the CO<sub>2</sub> results vary by approximately 8%. This variation is also seen in the fuel consumption for the fuel types. Since CO<sub>2</sub> is the principle product of combustion, the variation

of CO<sub>2</sub> 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<sub>x</sub> 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.

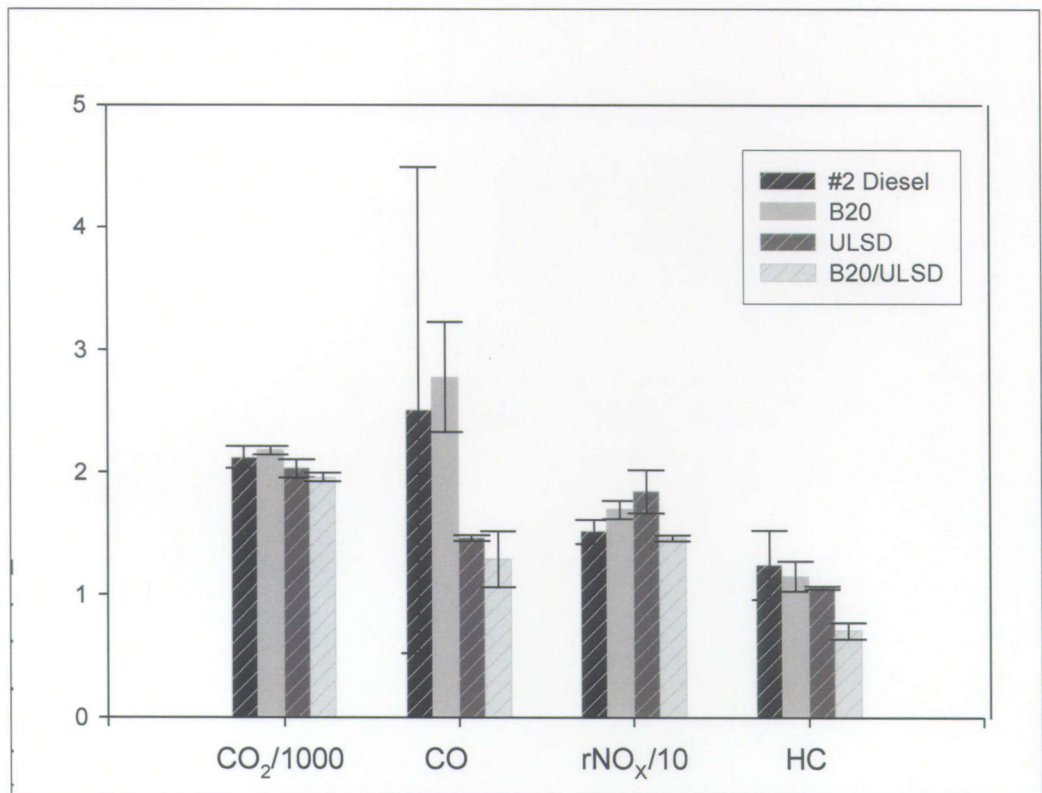


Figure 32: Gaseous Emissions summary for the DT466E

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.<sup>4</sup> Both sets of experiments passed sensor audits at the conclusion of the tests. Table 8 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 9: Alternative fuel reductions in emission levels for the DT466E when compared to #2 diesel.

<b>DT466E</b>	<b>CO</b>	<b>rNO<sub>x</sub></b>	<b>HC</b>
<b>% Reduction</b>			
<b># 2 (g/mile)</b>	<b>2.5</b>	<b>17</b>	<b>1.2</b>
<b>B20</b>	<b>-10</b>	<b>-12</b>	<b>7</b>
<b>ULSD</b>	<b>42</b>	<b>-22</b>	<b>14</b>
<b>ULSD/20% Bio</b>	<b>49</b>	<b>3</b>	<b>43</b>

A summary of the PM as a function of bin size is shown below in Figure 33. 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.

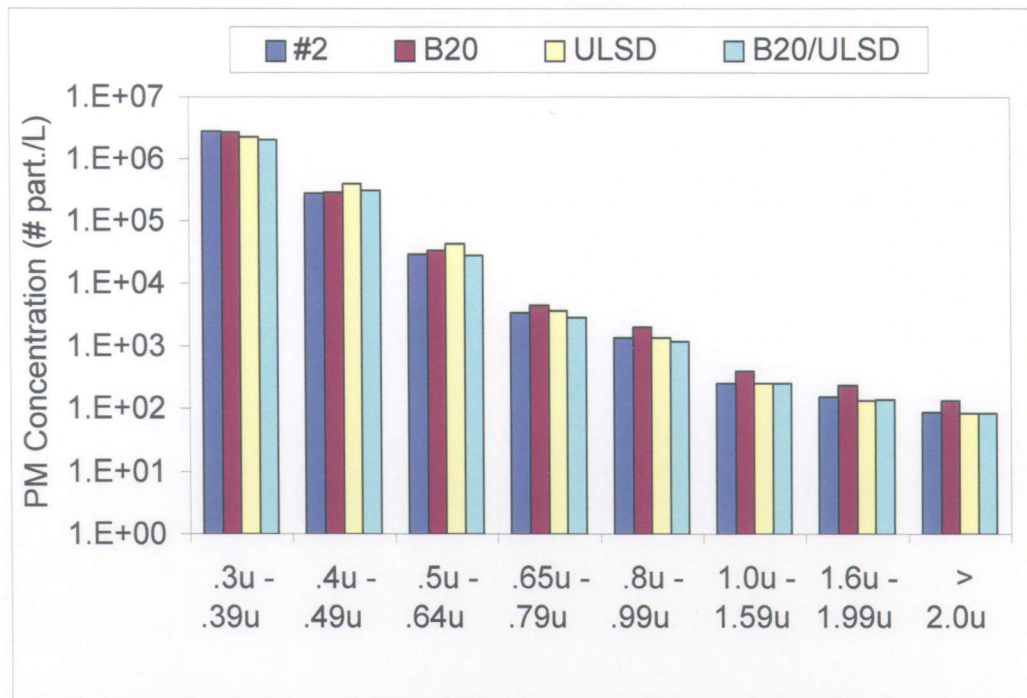


Figure 33: Average PM Concentrations for the DT466E

Using the PM estimation technique discussed in Chapter 3, 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 34. 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.

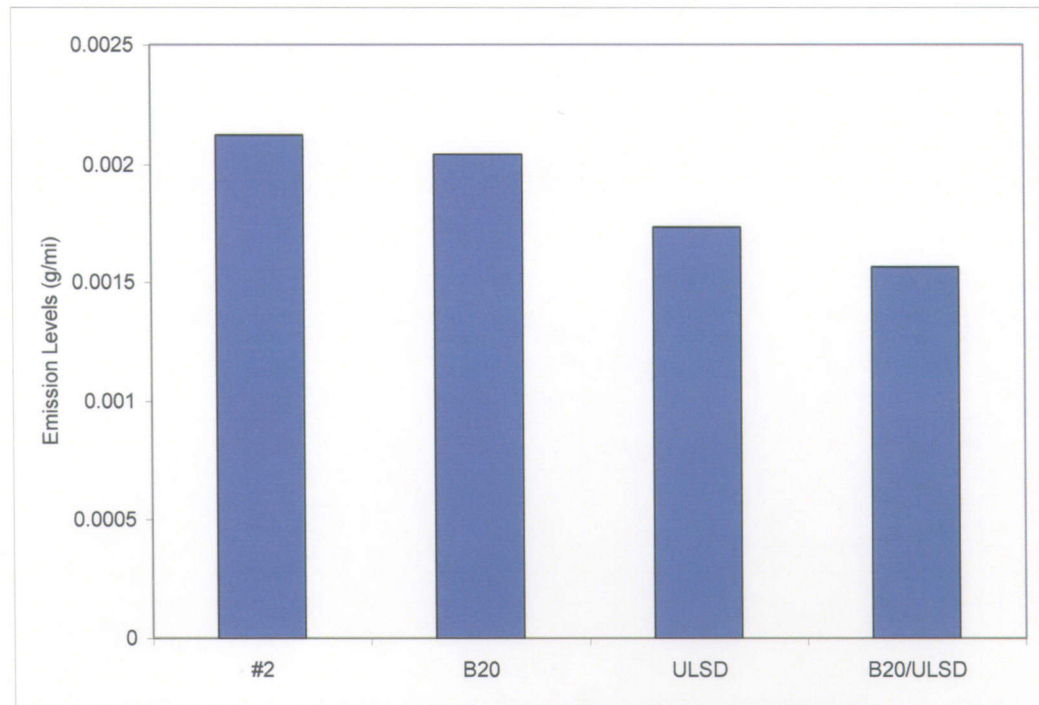


Figure 34: PM Mass Estimations for the DT466E

#### 4.3.2. Experimental Results – T444E

Figure 35 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<sub>x</sub> emissions show reductions for each alternative fuel, the B20 showing the highest reduction of 14%.

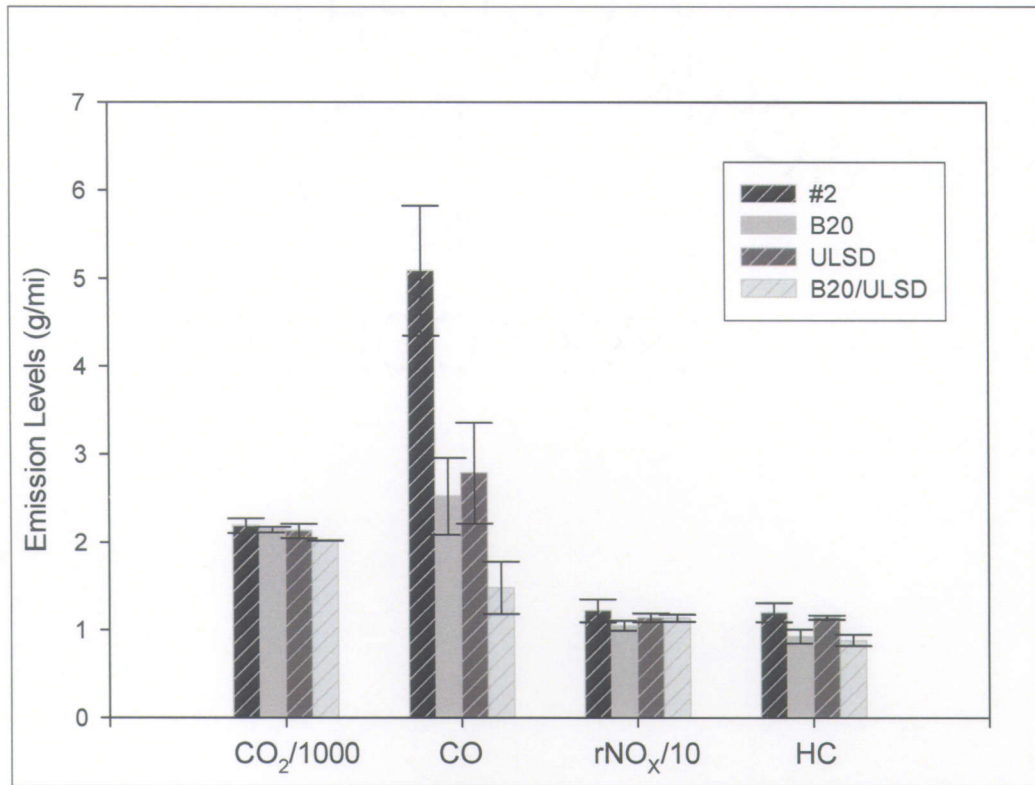


Figure 35: Gaseous Emission Summary for the T444E

Table 10 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 10: Alternative fuel reductions in emission levels for the T444E when compared to #2 diesel.

T444E	CO	rNO <sub>x</sub>	HC
<b>% Reduction</b>			
<b># 2 (g/mile)</b>	<b>5.1</b>	<b>12.2</b>	<b>1.2</b>
<b>B20</b>	<b>50</b>	<b>14</b>	<b>23</b>
<b>ULSD</b>	<b>45</b>	<b>6</b>	<b>5</b>
<b>ULSD/20% Bio</b>	<b>71</b>	<b>7</b>	<b>26</b>

PM emissions for the T444E on a particle count basis show that particulates are not significantly impacted by the use of alternative fuels. Figure

36 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.

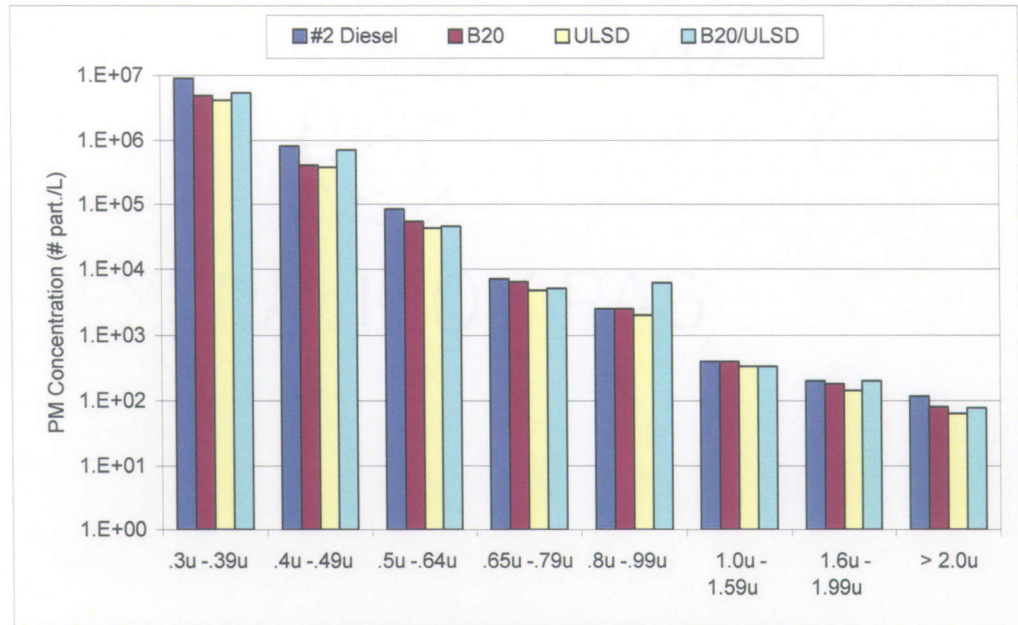


Figure 36: Average PM Concentrations for the T444E

Using the PM mass estimation is 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 37.



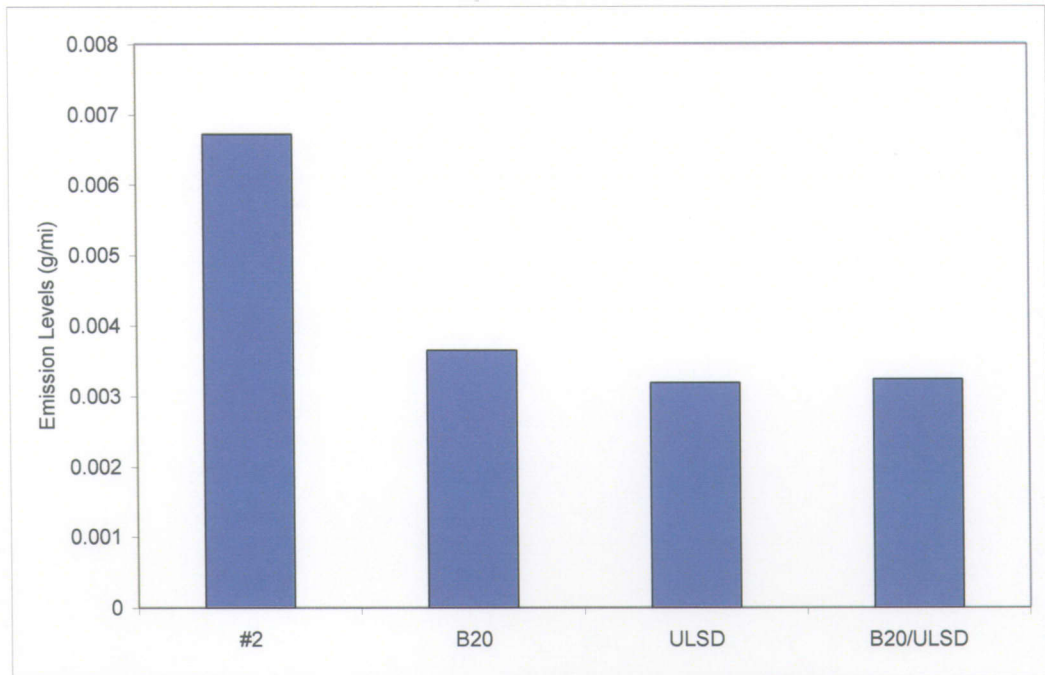


Figure 37: PM mass Estimations for the T444E

#### 4.3.3. Experimental Results – Cummins ISB

The gaseous emissions results of the use of alternative fuels are found in Figure 38. For the Cummins ISB engine, CO and corrected NO<sub>x</sub> 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<sub>x</sub> emissions for all of the alternative fuels were within 20% of the #2 diesel baseline.

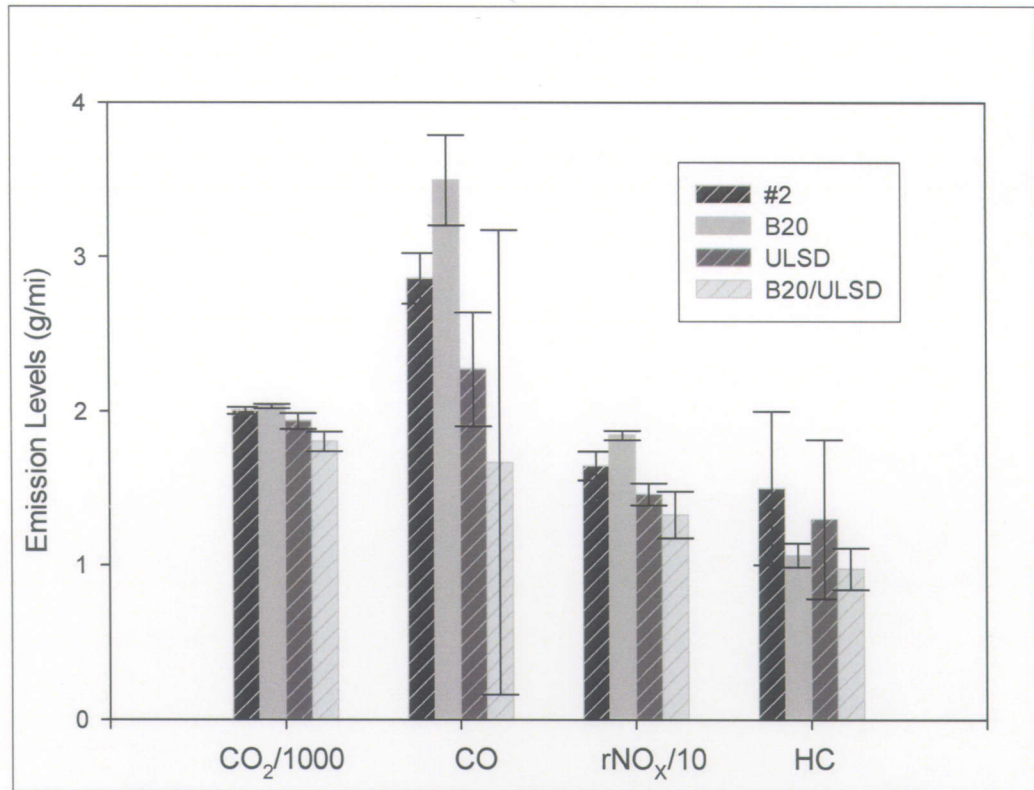


Figure 38: Gaseous Emission Summary for the Cummins ISB

Table 11 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 11: Alternative fuel reductions in emission levels for the T444E when compared to #2 diesel.

Cummins ISB	CO	rNO <sub>x</sub>	HC
<b>% Reduction</b>			
<b># 2 (g/mile)</b>	<b>2.9</b>	<b>17</b>	<b>1.5</b>
<b>B20</b>	<b>-22</b>	<b>-12</b>	<b>29</b>
<b>ULSD</b>	<b>21</b>	<b>11</b>	<b>13</b>
<b>ULSD/20% Bio</b>	<b>42</b>	<b>19</b>	<b>35</b>

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 39. 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.

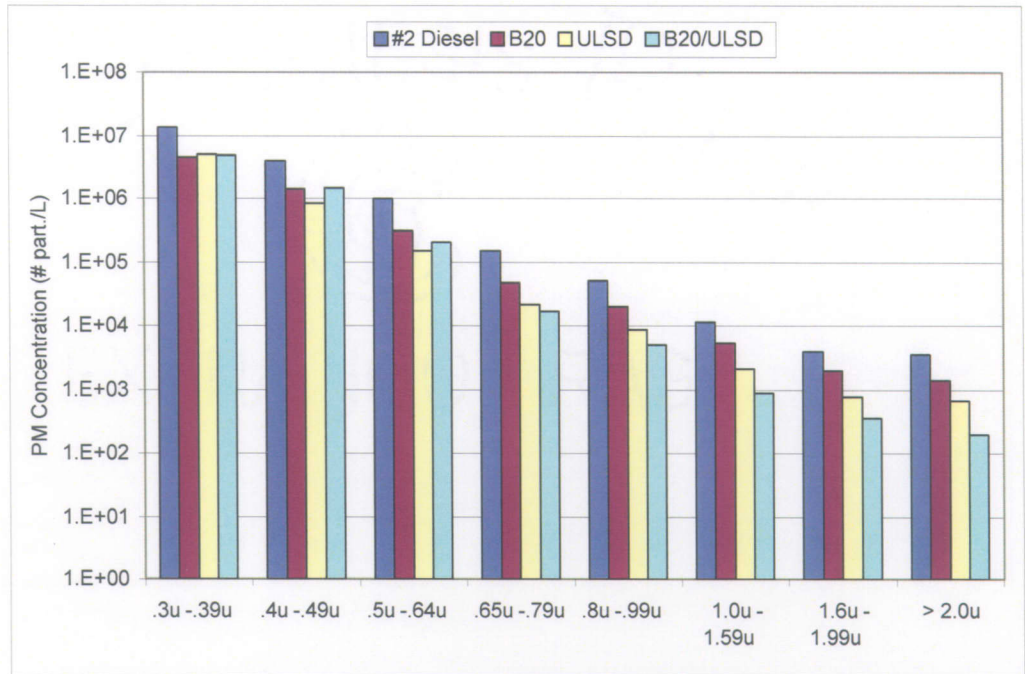


Figure 39: Average PM Concentrations for the Cummins ISB

The estimated mass of particulate matter shows similar results to Figure 39. For the Cummins ISB engine, the use of alternative fuels has shown to decrease the mass of PM emitted from the tailpipe.

Figure 40 below shows the PM mass reductions. The decrease ranges from 62% for the ULSD and B20/ULSD to 66% for the B20.

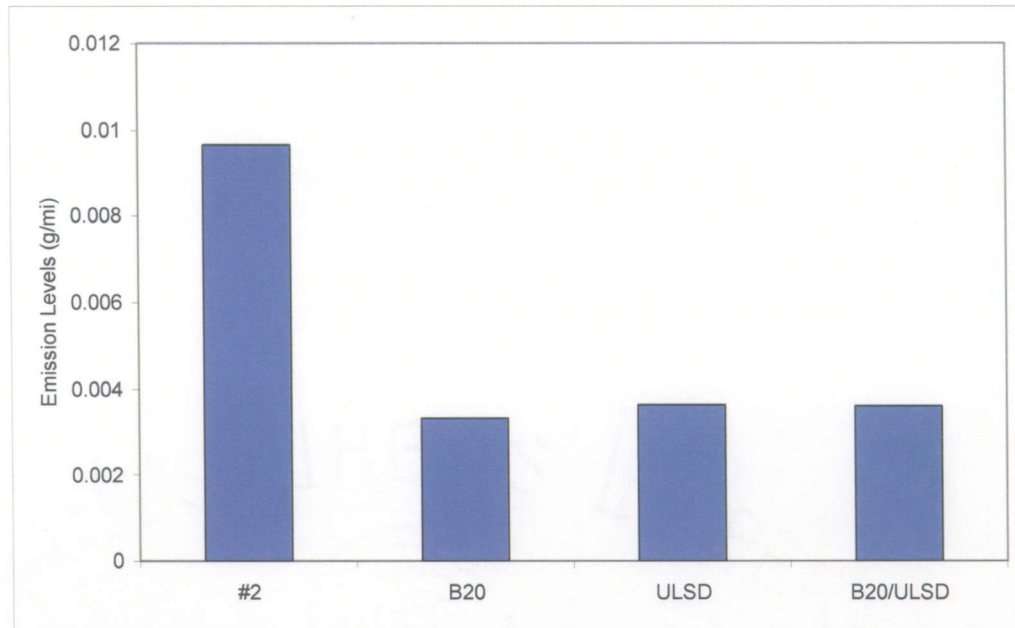


Figure 40: PM mass Estimations for the Cummins ISB

#### 4.3.4. Comparison to 2007 EPA Standards

A comparison of the alternative fuels test results to the 2007 US EPA standards are shown below in Table 12. 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 12 suggest that the use of alternative fuels do not have the potential alone to meet the 2007 EPA standards for NO<sub>x</sub> or HC emissions. The 1.2 g/bhp hr standard for NO<sub>x</sub> emissions is going to be phased down to 0.2 g/bhp hr by 2010. However

alternative fuels such as ULSD allow for NO<sub>x</sub> emission reduction technologies (such as NO<sub>x</sub> absorbers) to be used. #2 diesel contains too much sulfur in the fuel to be used with most NO<sub>x</sub> 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 chapter.

Table 12: Comparison of test results with 2007 standards

444	CO	rNO <sub>x</sub>	HC
	g/bhphr	g/bhphr	g/bhphr
<i>2007 Standard</i>	<i>15.5</i>	<i>1.20</i>	<i>0.14</i>
#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	rNO <sub>x</sub>	HC
	g/bhphr	g/bhphr	g/bhphr
<i>2007 Standard</i>	<i>15.5</i>	<i>0.20</i>	<i>0.14</i>
#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

#### 4.3.5. Alternative Fuels Global Warming Potential

The global warming potential for the three engines tested is shown below in Figure 41. For these calculations, both CO and THC emissions were approximated for have an Environmental index of 21. The equivalent grams per mile of CO<sub>2</sub> are plotted for each bus and alternative fuel. The figure shows that ULSD/20%Biodiesel blend has the lowest global warming potential.

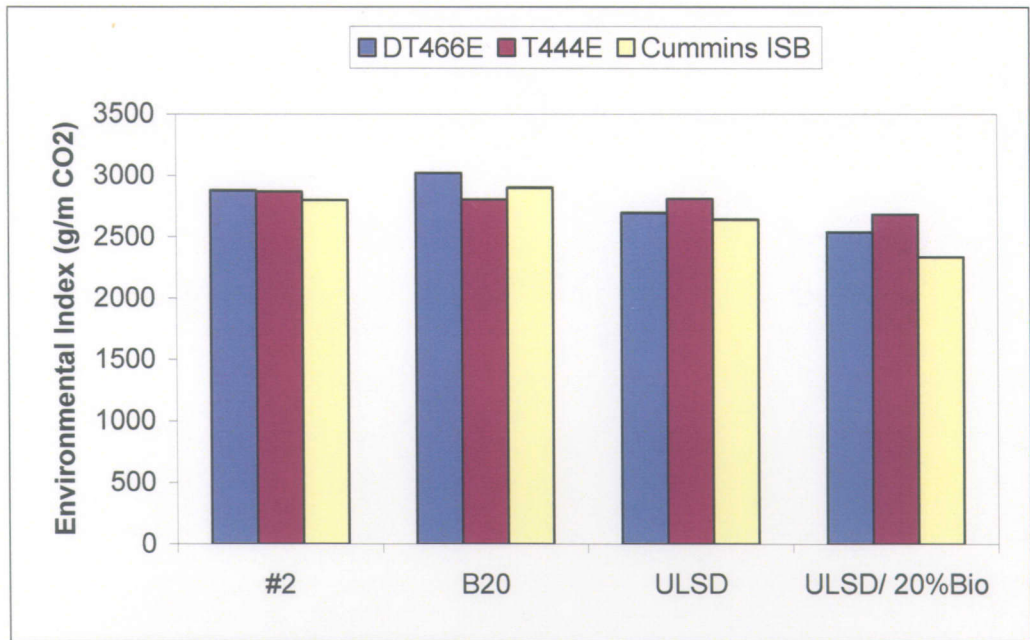


Figure 41: Alternative Fuel Study Global Warming Potentials

## **5. The Effect of Aftertreatment devices on Mobile Emissions**

### **5.1. 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 chapter 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<sub>x</sub> 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.

### **5.2. 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<sub>2</sub>, CO, CO<sub>2</sub>, 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 13 shows the test matrix for the aftreatment testing.

Table 13: Aftertreatment test matrix for each school bus

<b>Test</b>	<b>Strategy</b>	<b>Fuel Makeup</b>
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.

### 5.3. 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).



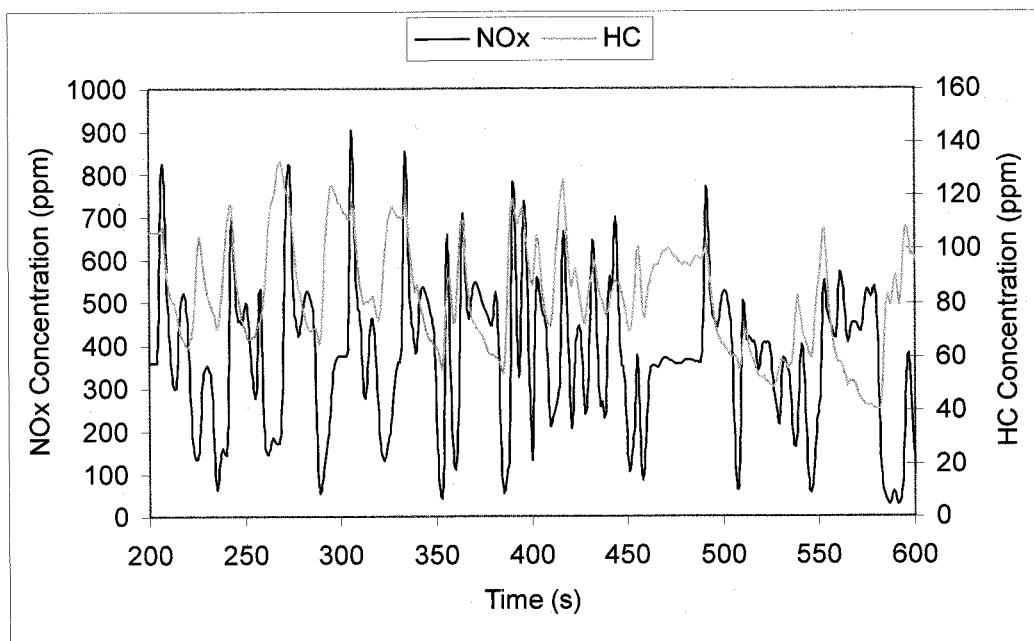


Figure 42: Raw Emissions results for a 400 second interval of the RUCSBC

### 5.3.1. Experimental Results – DT466E

The average results for the aftertreatment testing for the DT466E school bus are shown below in Figure 43. The error bars shown in the figure represent the standard deviation of the tests from the averages presented. 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<sub>x</sub> emissions using the engine specific correction factor show the best NO<sub>x</sub> 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%.

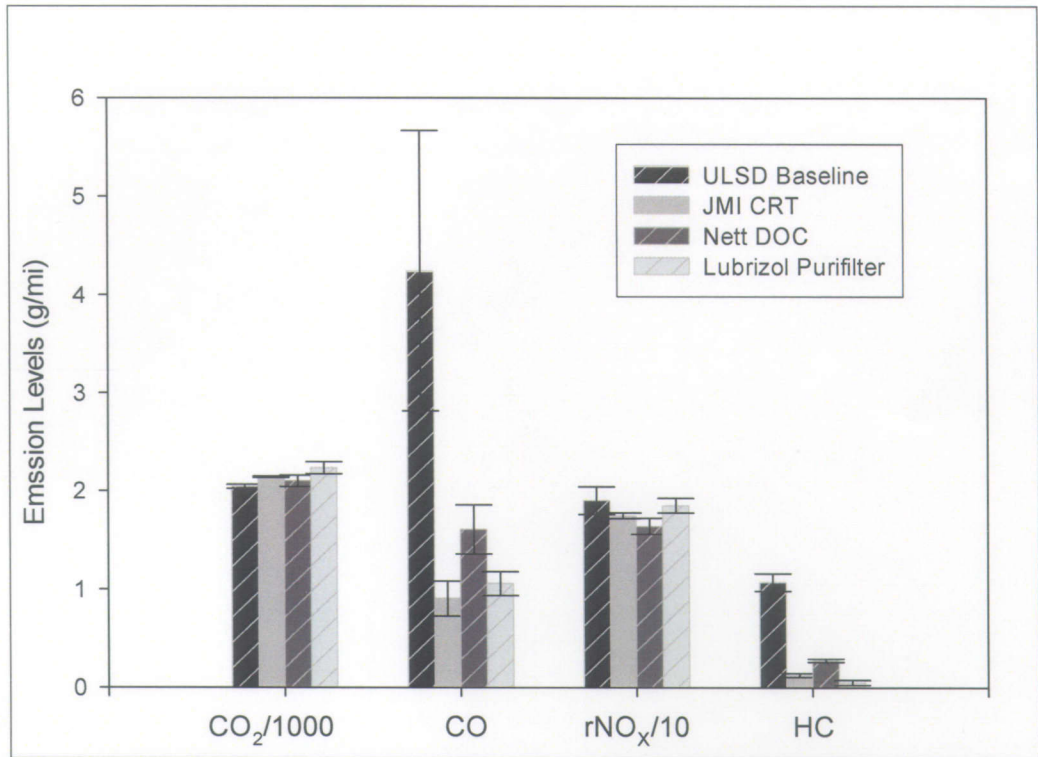


Figure 43: Aftertreatment Testing Results – DT466E

Table 9 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 14: Aftertreatment reductions in emission levels for the DT466E when compared to the ULSD baseline.

DT466E	CO	rNO <sub>x</sub>	HC
<b>% Reduction</b>			
<b>ULSD Baseline</b>	<b>4.2</b>	<b>19</b>	<b>1.1</b>
<b>JMI CRT</b>	<b>79</b>	<b>8</b>	<b>88</b>
<b>Nett DOC</b>	<b>62</b>	<b>14</b>	<b>74</b>
<b>Lubrizol Purifilter</b>			
	<b>75</b>	<b>3</b>	<b>95</b>

A summary of the PM as a function of bin size is shown below in Figure 44. 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.

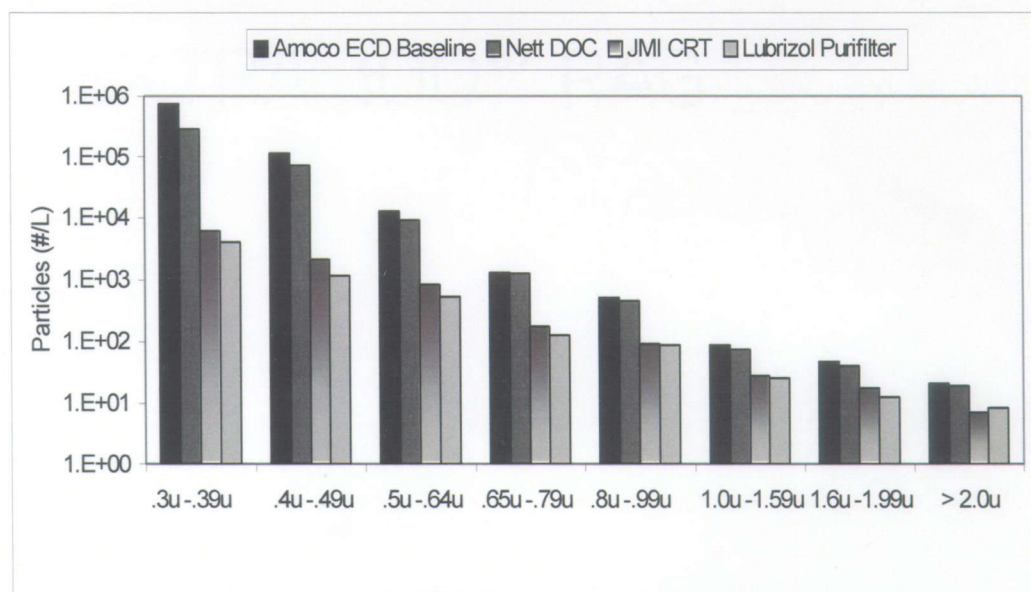


Figure 44: Average PM Concentrations for the DT466E

PM mass estimates show similar results. For the DT466E engine, the DOC from Nett reduced PM mass by 60%. The Lubrizol Purifilter and the JMI CRT both reduced PM by 99%.

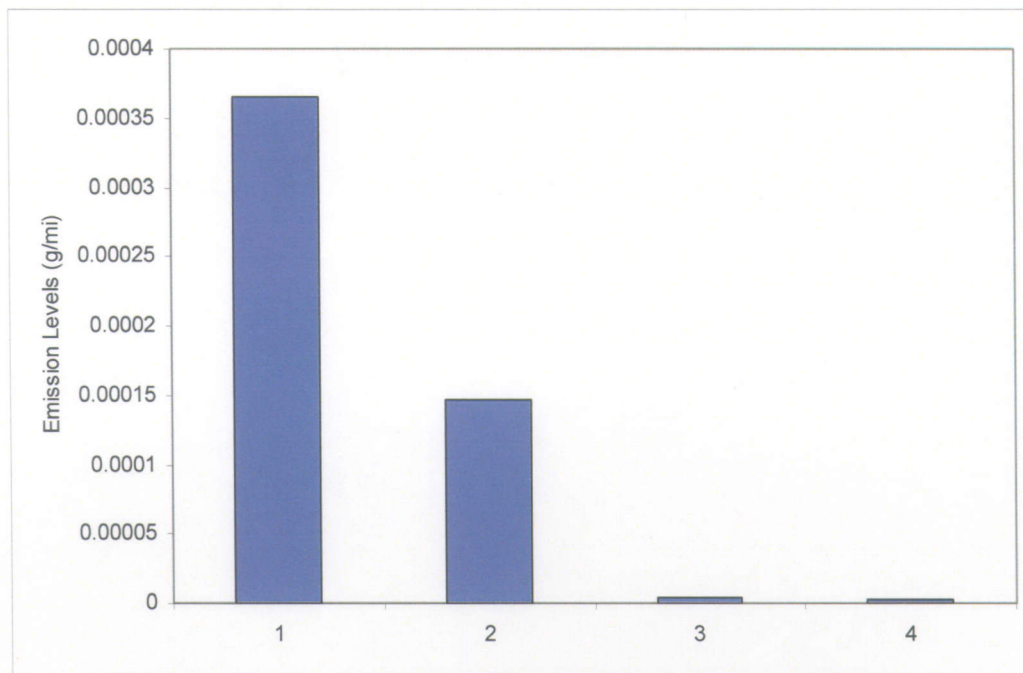


Figure 45: PM Mass Estimations for the DT466E

### 5.3.2. Experimental Results – T444E

Figure 46 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 Purifier reduced HC emissions by 54% while reducing CO emissions by 55%. The CRT resulted in 10% increase in corrected NO<sub>x</sub>, while the DOC had a much higher increase (28%) in terms of corrected NO<sub>x</sub>. The Purifier showed an 11% reduction in NO<sub>x</sub>.

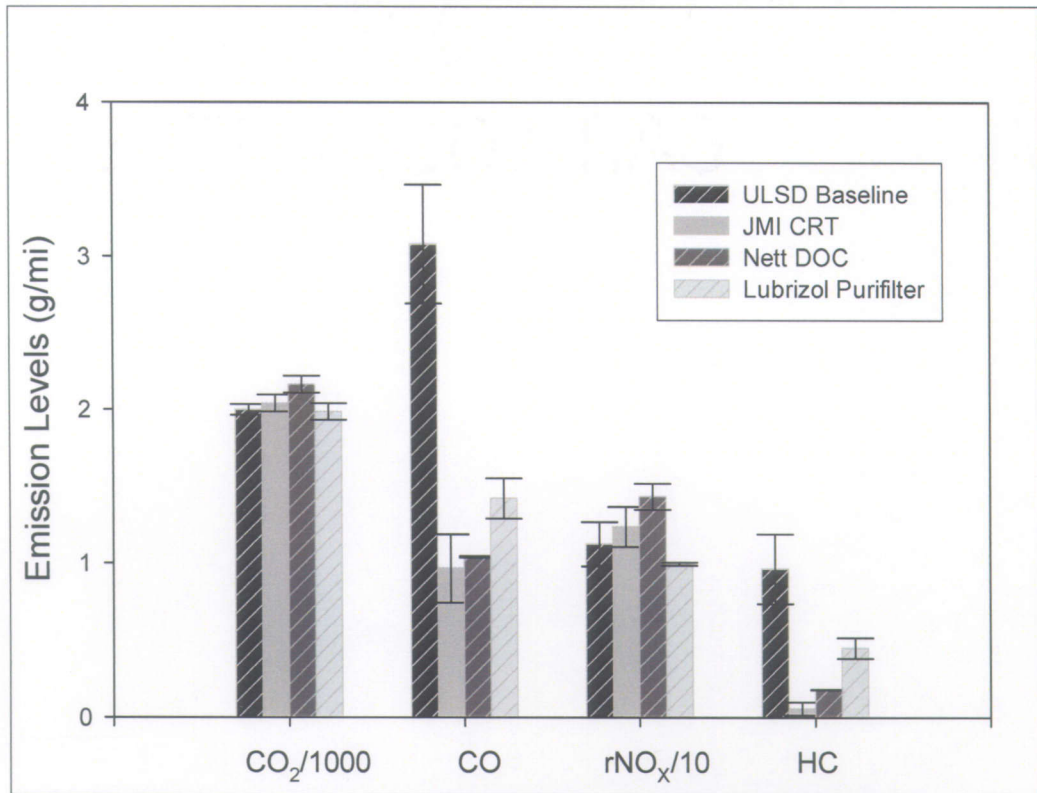


Figure 46: Gaseous emissions measurements for the T444E

Table 15: Aftertreatment reductions in emission levels for the T444E when compared to the ULSD baseline.

T444E	CO	rNO <sub>x</sub>	HC
<b>% Reduction</b>			
<b>ULSD Baseline</b>	<b>3.1</b>	<b>11</b>	<b>1.0</b>
<b>JMI CRT</b>	<b>69</b>	<b>-10</b>	<b>94</b>
<b>Nett DOC</b>	<b>66</b>	<b>-28</b>	<b>81</b>
<b>Lubrizol Purifilter</b>	<b>54</b>	<b>12</b>	<b>55</b>

The PM results for the school bus equipped with the T444E engine showed significant PM reductions with the use of a DPF. Figure 47 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.

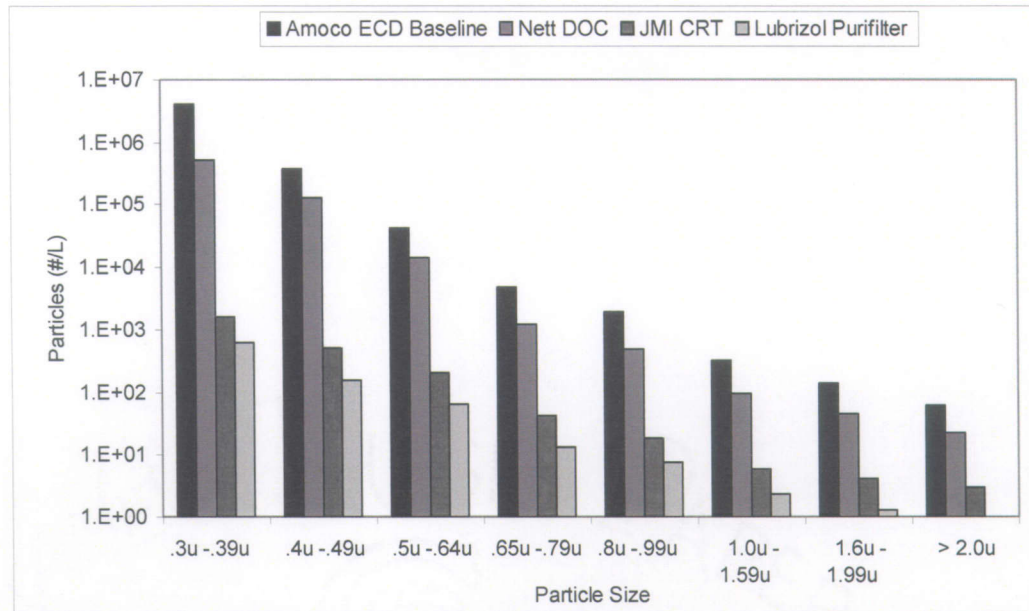


Figure 47: Average PM Concentrations for the T444E

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 48 shows that for the CRT and Purifier, virtually none of the PM from the school bus was emitted from the tailpipe.

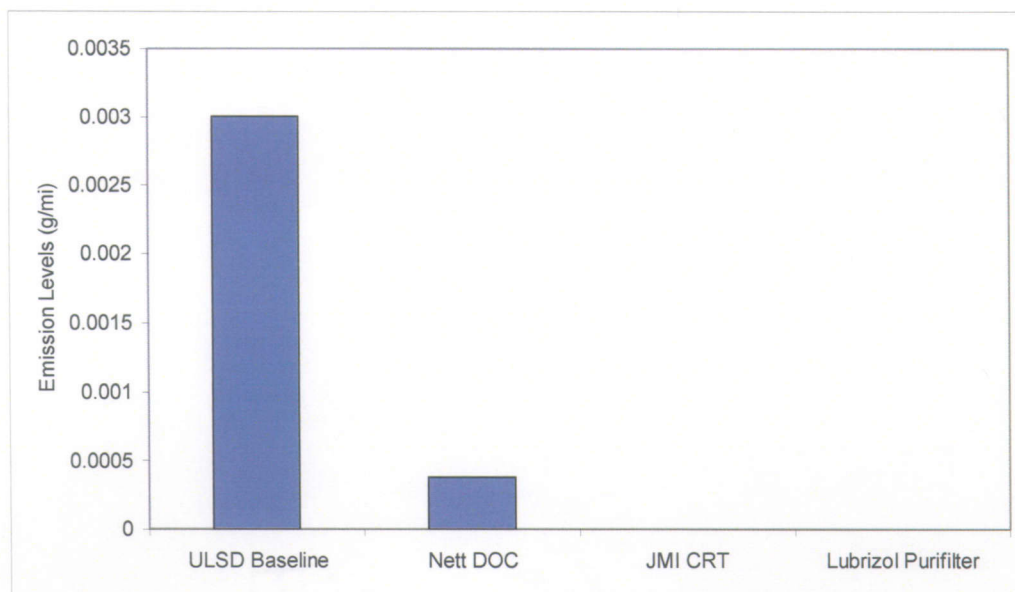


Figure 48: PM Mass Estimations for the T444E

### 5.3.3. Experimental Results – Cummins ISB

Testing for the Cummins ISB engine produced similar trends to the T444E; however CO reductions were not as significant. Figure 49 shows the gaseous emissions results for the Cummins ISB engine. The DOC reduced CO emissions by 39% and HC emissions by 81%. The Lubrizol Purifier 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 also not as effective 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.

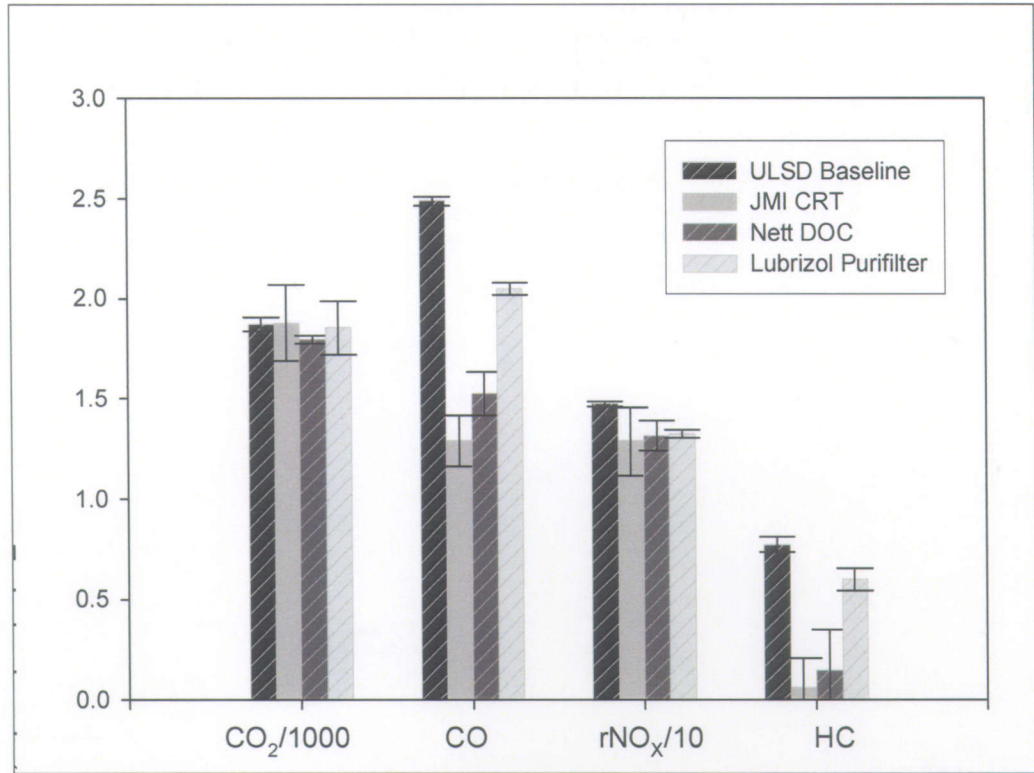


Figure 49: Gaseous emissions measurements for the Cummins ISB

Table 16: Aftertreatment reductions in emission levels for the Cummins ISB when compared to the ULSD baseline.

Cummins ISB	CO	rNO <sub>x</sub>	HC
<b>% Reduction</b>			
<b>ULSD Baseline</b>	<b>3.1</b>	<b>11</b>	<b>1.0</b>
<b>JMI CRT</b>	<b>48</b>	<b>13</b>	<b>92</b>
<b>Nett DOC</b>	<b>39</b>	<b>11</b>	<b>81</b>
<b>Lubrizol Purifilter</b>	<b>18</b>	<b>10</b>	<b>22</b>

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 50 below shows the PM concentrations as a function



of bin size.

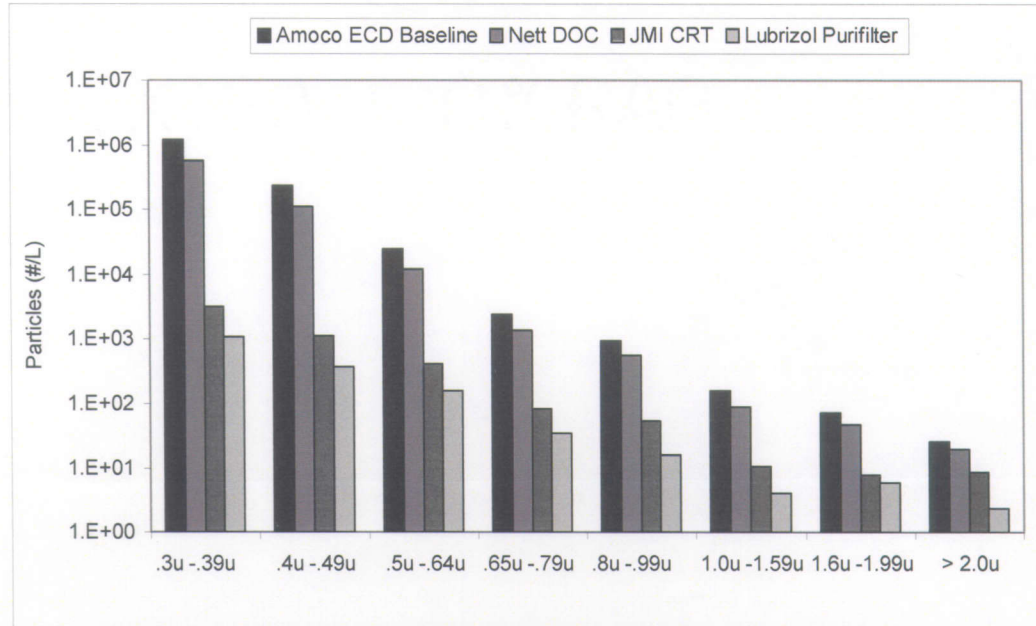


Figure 50: Average PM Concentrations for the Cummins ISB

Estimated PM mass emissions when using a DPF showed similar results 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 Purifier.

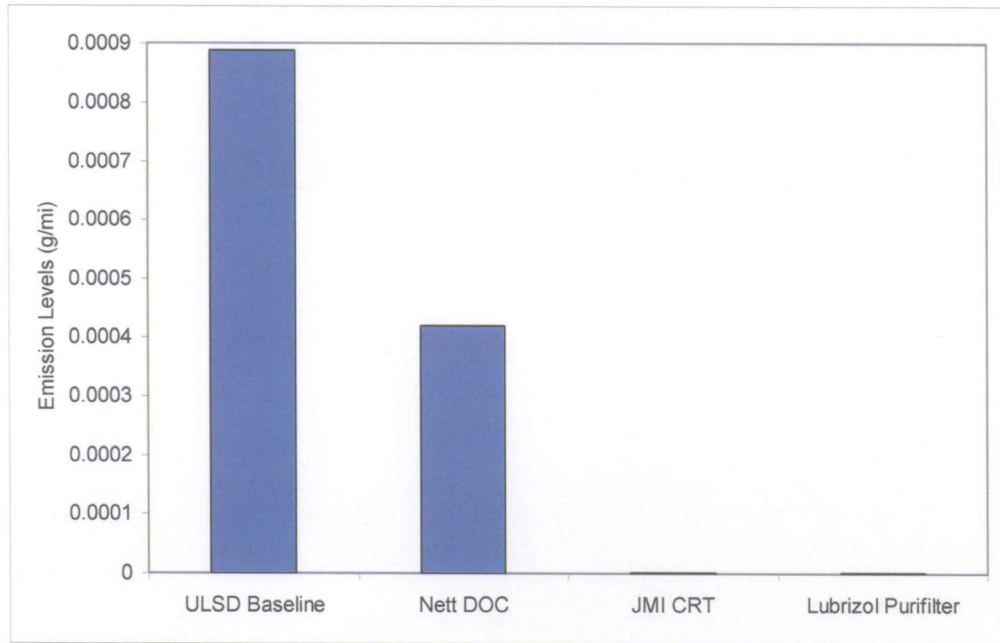


Figure 51: PM Mass Estimations for the Cummins ISB

### 5.3.4. Investigation of NO and NO<sub>2</sub> Emissions

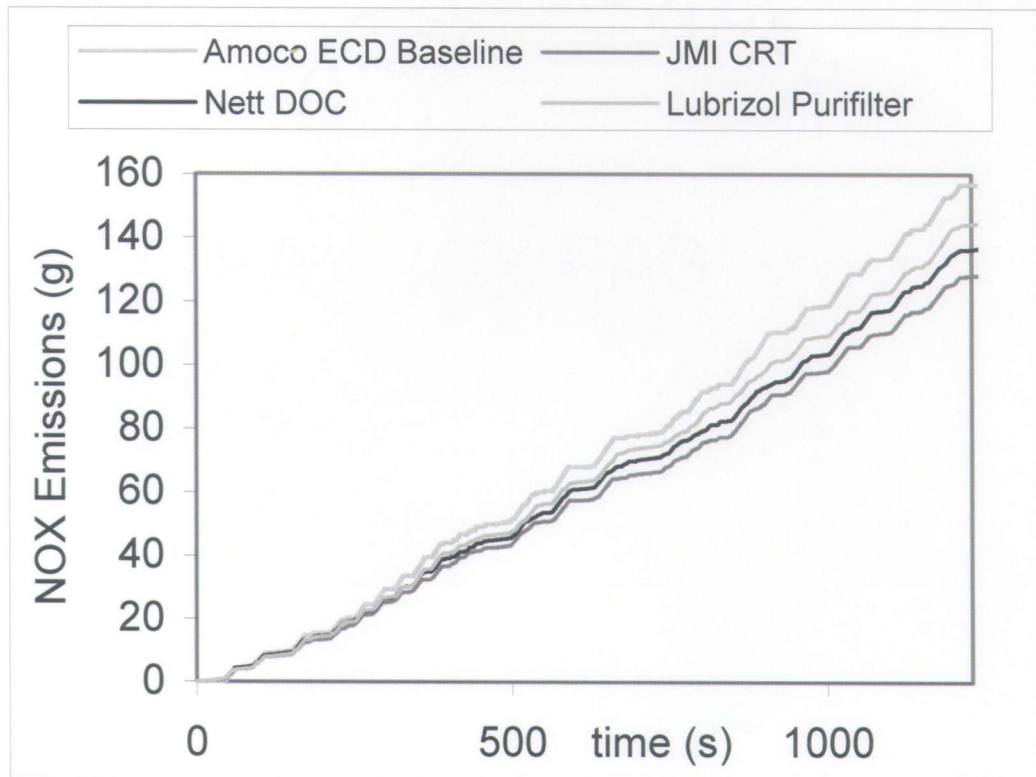


Figure 52: Total cumulative NO<sub>x</sub> emissions for the DT466E during a single RUCSBC test.

In order to examine the chemistry of the catalyst for the three

aftertreatment technologies, the  $\text{NO}_x$  emissions were further analyzed. Figure 52 is a cumulative plot of total  $\text{NO}_x$  emissions for the DT466E engine with the baseline fuel, DOC, CRT, and Purifier, respectively. The figure represents the total accumulation of  $\text{NO}_x$  emissions in grams as a function of time during the single cycle of the RUCSBC.  $\text{NO}_x$  emissions are primarily a mixture of NO and  $\text{NO}_2$ . Of these two gases, NO emissions are typically much higher than  $\text{NO}_2$  emissions. Figure 53 and Figure 54 below show the breakdown of each constituent for the DT466E.

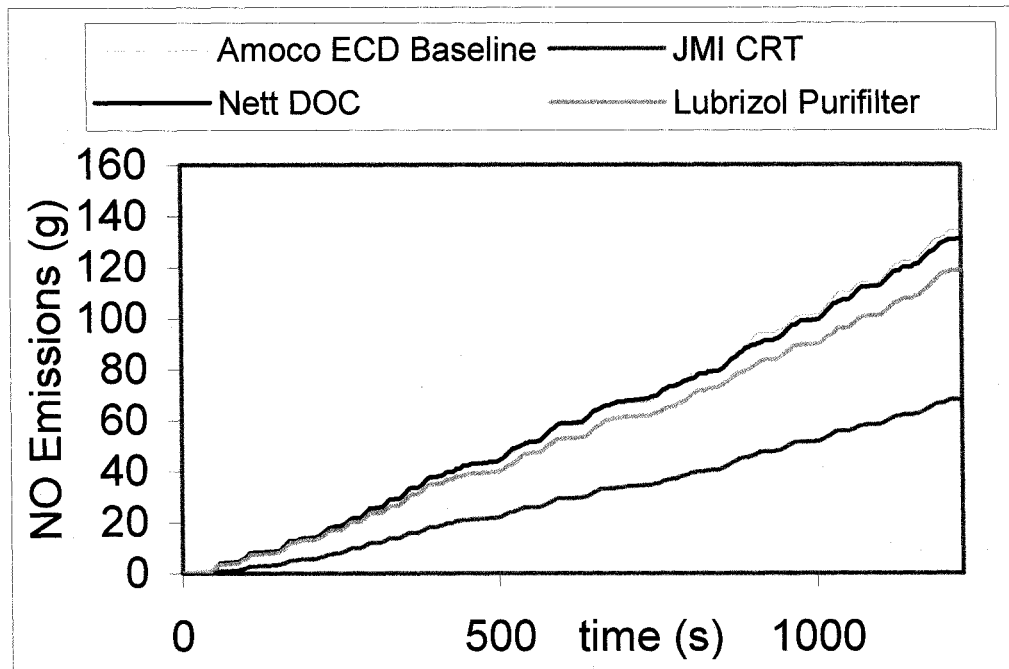


Figure 53: Total cumulative NO emissions for the DT466E bus during a single RUCSCB test.

As shown in Figure 53, NO emissions were the lowest for the experiments performed using the CRT. Conversely, the Nett DOC shows little reduction in NO.

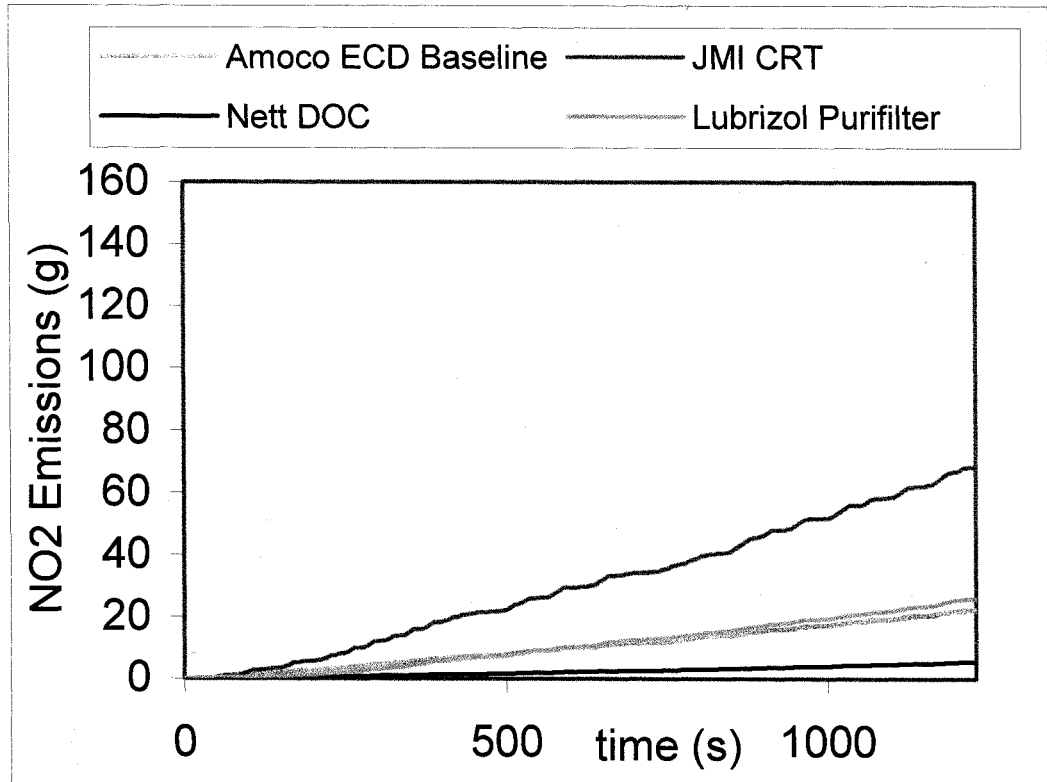


Figure 54: Total cumulative NO<sub>2</sub> emissions for the DT466E bus during a single RUCSCB test

The Johnson Matthey CRT and Lubrizol Purifilter processes require the conversion of NO to NO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions but not NO emissions.

### 5.3.5. Comparison to 2007 EPA Standards

A comparison of the alternative fuels test results to the 2007 US EPA standards are shown below in Table 12. 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 12 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<sub>x</sub> emissions to below the standard. The 1.2 g/bhp hr standard for NO<sub>x</sub> 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<sub>x</sub> absorber can potentially reduce both HC, PM, and NO<sub>x</sub> emissions simultaneously.

Table 17: Comparison of test results with 2007 standards

444	CO	rNOx	HC
	g/bhphr	g/bhphr	g/bhphr
<i>2007 Standard</i>	<i>15.5</i>	<i>1.20</i>	<i>0.14</i>
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	rNOx	HC
	g/bhphr	g/bhphr	g/bhphr
<i>2007 Standard</i>	<i>15.5</i>	<i>0.20</i>	<i>0.14</i>
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

### 5.3.6. Aftertreatment Global Warming Potentials

The global warming potential for the three engines tested is shown below in Figure 55Figure 41. For these calculations, both CO and THC emissions were approximated for have an Environmental Index of 21. PM emissions are not calculated as part of the Environmental Index. The equivalent grams per mile of CO<sub>2</sub> are plotted for each bus and alternative fuel. The figure shows that the Nett DOC has the lowest GWP for the DT466E and Cummins ISB engines. The JMI CRT has the lowest GWP for the T-444E.

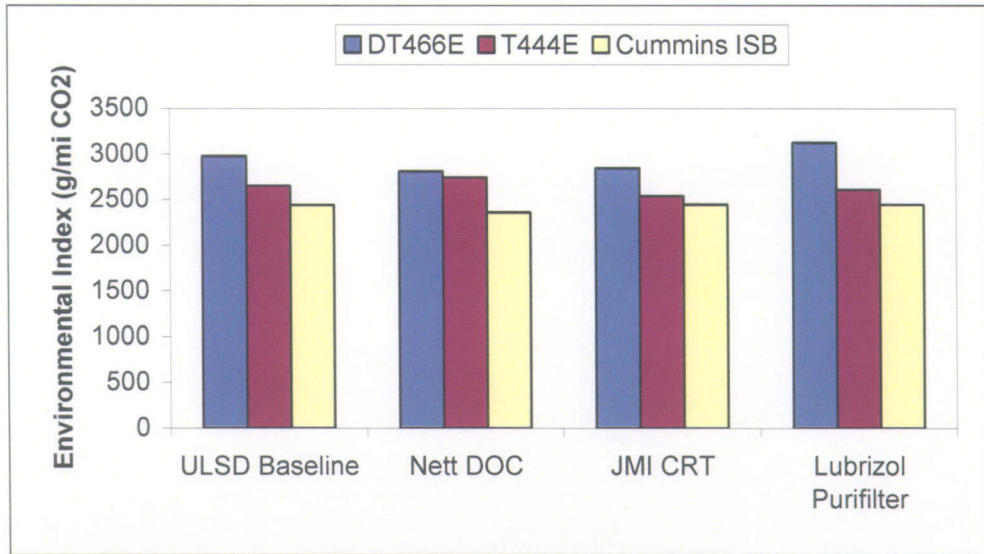


Figure 55: Aftertreatment Global Warming Potentials

## **6. 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<sub>x</sub> emissions were corrected for temperature and humidity using an engine specific correction factor developed from a school bus idle study.

### **6.1. Mobile Testing**

#### **6.1.1. 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<sub>x</sub> emissions were slightly affected by the alternative fuels tested. However, ULSD and B20/ULSD allow for use of NO<sub>x</sub> reduction technologies.



- The two International engines showed an increase or slight decrease in corrected NO<sub>x</sub> 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 > PM<sub>0.3</sub>) by 26% for the DT466E.
- B20 and ULSD decreased PM emissions (for PM > PM<sub>0.3</sub>) by 4% and 18%, respectively, for the DT466E.
- No effect of alternative fuels on CO emissions was observed for the DT466E.
- Global Warming Potentials show that the use of the ULSD/20% Biodiesel has the lowest equivalent grams per mile CO<sub>2</sub> for the alternative fuels tested using the RUCSBC.

#### **6.1.2. 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<sub>x</sub> emissions are not significantly lowered using any of the three technologies.
- NO emissions are lowered using the JMI CRT. However, NO<sub>2</sub> emissions rise as part of the catalytic chemistry used to lower HC, CO and PM. The SC17L from Lubrizol showed only slightly elevated NO<sub>2</sub> emissions.
- NO<sub>x</sub> emissions using the Nett Catalytic Muffler are reduced by an average of 6%. Only the NO<sub>2</sub> constituent of the NO<sub>x</sub> 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.
- Global Warming Potentials show that DOC from NETT Technologies has the overall lowest equivalent grams per mile of CO<sub>2</sub> for use of the an aftertreatment following the RUCSBC. PM is not evaluated in this calculation.

## **6.2. Future Work**

The results presented in this thesis represent the final phase of mobile school bus emissions testing. Further work will be performed investigating PM concentrations within the cabin of the school bus. Experiments will be performed using the RUCSBC and the buses from the emissions study. Ambient PM analyzers will be installed inside the cabin and along the track in order to establish

background PM concentrations.

In efforts to promote the use of biodiesel, a recycling vehicle from Atlantic County will be tested using B20. Combined with the results from the school bus study, a paper will be published to show the emissions effects of biodiesel, with an emphasis on NO<sub>x</sub> emissions.

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