ABSTRACT

BOOK, EMILY KATE. Particulate Matter Emissions from Diesel Engines Equipped with a Diesel Particulate Filter at Varying Temperatures, Loads, Fuels and Drive Cycles. (Under the direction of Dr. Tiegang Fang.)

The United States Environmental Protection Agency (EPA) has implemented emissions standards for manufactures to follow in an effort for producing efficient and clean diesel engines. The on-road diesel emission regulation for particulate matter (PM) restricts to 0.01 grams per brake-horsepower-hour (g/bhp-hr) and for nitrogen oxides (NO\textsubscript{x}) restricts to 0.02 g/bhp-hr. The current EPA regulations for PM are based on mass and to meet the regulations engine manufactures use a diesel particulate filter (DPF). PM has a wide range of impacts on the environment as well as human health and it is critical to minimize exposure to PM. Understanding PM emissions are an important step to reduce its impacts.

Two medium heavy-duty diesel trucks equipped with a DPF were tested at two ambient temperatures (70°F and 20°F), two fuels [ultra-low sulfur diesel (ULSD) and biodiesel (B20)], and two operating loads (a heavy and light weight) in a temperature controlled chassis dynamometer. The DPFs on the vehicles go through a clean out process, a regeneration, to remove the PM once it gets built up along the filter walls. Vehicle 1 was equipped with a NO\textsubscript{x} adsorber catalyst (NAC) in the aftertreatment system for NO\textsubscript{x} control and Vehicle 2 used a selective catalytic reduction (SCR) with urea. The test procedure included three driving cycles, a cold start with low transients (CSLT), the federal heavy-duty urban dynamometer driving schedule (UDDS), and a warm start with low transients (WSLT). All DPF active regenerations occurred during the UDDS cycle. PM emissions were measured second-by-second using an Aethalometer for black carbon (BC) concentrations and an Engine Exhaust Particle Sizer (EEPS) for particle count measurements between 5.6 and 560
nm. An analysis of variance (ANOVA) completed with the EEPS data showed that the DPF regeneration impacted the PM emissions during and after the DPF regeneration.

Vehicle 1 experienced increased BC and particle number concentrations during cold starts under cold ambient conditions, with concentrations two to three times higher than under warm starts at higher ambient temperatures. This vehicle also experienced decreased emissions when going from ULSD to B20, with an approximately 13% average decrease in PM number and an approximately 27% decrease in BC. Vehicle 2 had much lower emissions, with many of the BC and particle number measurements below detectable limits. Both vehicles did experience elevated emissions due to the DPF regeneration events. For the day after an active regeneration occurred both vehicles showed significant increases in particle number and BC for the CSLT drive cycle, with increases from 93 to 1380 percent for PM number emissions compared with tests following a day without an active regeneration. Vehicle 1 showed a decrease in PM emissions during the regeneration and a significant increase in PM emissions after a DPF regeneration. Vehicle 2 showed an increase of three orders of magnitude of PM emissions during the only DPF regeneration experienced. Both vehicles showed an increase in particle number count from the WSLT to the CSLT post-regeneration which was 38% for Vehicle 1 and 113% for Vehicle 2 while still maintaining PM emissions levels below the standards.

Nitrogen oxides (NO\textsubscript{x}), hydrocarbons (HC) and carbon monoxide (CO) emissions and fuel consumption data were also collected during this testing. Vehicle cold starts had the greatest impact on NO\textsubscript{x}, HC and CO emissions and fuel consumption and this impact was more significant at the colder ambient temperature. Vehicle cold starts attributed for a loss of fuel in miles per gallon by 29% and 35% for Vehicles 1 and 2, respectively.
Particulate Matter Emissions from Diesel Engines Equipped with a Diesel Particulate Filter at Varying Temperatures, Loads, Fuels and Drive Cycles

by
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DEDICATION

To my family, especially Dad.
BIOGRAPHY

Emily Kate Book was born on May 27, 1980 in New Albany, Indiana. She attended Purdue University in West Lafayette, Indiana to pursue a Bachelor of Science in Mechanical Engineering in 1998 and graduated in 2003. She began working at John Deere in Dubuque, Iowa in 2003. While working at John Deere she obtained a Master of Business Administration from Clarke College in Dubuque, Iowa in 2007. She then began working on a Master of Engineering in Engine Systems from the University of Wisconsin in Madison, Wisconsin and graduated in 2010. She took a leave of absence from John Deere to work on her Doctor of Philosophy in Mechanical Engineering at North Carolina State University with Dr. Tiegang Fang as her advisor in 2010. Her research work was done at the Environment Protection Agency in Research Triangle Park under the advisement of Dr. Richard Baldauf.
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1 INTRODUCTION

The U.S. Environmental Protection Agency (EPA) has regulations that limit the amount of emissions allowed into the environment through diesel engine exhaust. Two of the major pollutants that current heavy-duty diesel regulations focus on are particulate matter (PM) and oxides of nitrogen (NO\textsubscript{x}). The on-road diesel regulation for PM allows 0.01 grams per brake-horsepower-hour (g/bhp-hr) to be emitted. The regulation for NO\textsubscript{x} is 0.02 g/bhp-hr. The current EPA regulations for PM are based on mass. The European Union has instituted regulations for particle number (6E11 PN/km) in addition to standards for PM mass (0.005 g/km) and NO\textsubscript{x} (which currently varies depending on country in the EU) (European Union, 2012). Manufacturers have installed diesel particulate filters (DPFs) onto on-road vehicles with heavy-duty diesel engines in order to comply with the most recent PM emission standards from the EPA and EU. However, measurements have not been reported on how the DPF affects emissions under cold starts and cold ambient temperatures when operating on conventional diesel and biodiesel fuels.

1.1 MOTIVATION

The expectation of this research is to identify if diesel engines using the current technology do reduce PM emissions sufficiently under multiple operating conditions, and ensure that cold and/or high acceleration conditions do not result in unintended elevated exhaust concentrations. To do this, it is important to understand the impact that DPFs have on PM. If it is found that certain running conditions cause an increase or decrease in PM then changes can be made to the engine and aftertreatment system to run in conditions that minimize the PM being exhausted. When it is known what engine conditions result in high
PM emissions, strategies can be engineered to optimize engine performance while minimizing the negative impact on the environment and health conditions. It is important to improve public health by protecting people from local exposures where emissions occur. A reduction in exhaust emissions can lead to a reduced climate impact from diesel engine exhaust as well. If certain conditions are found that lead to higher emissions than expected with current knowledge, it could drive new emissions standards or revisions to existing standards by the EPA to further protect health and reduce climate impact.

PM is the only criteria pollutant regulated by the EPA that is not chemically defined. PM, however, has arguably the widest range of potential environmental impacts (Maricq et al, 2007). Adequate evidence from epidemiologic, controlled human exposures, and toxicological studies conclude that a causal relationship exists between short-term exposures to PM$_{2.5}$ and cardiovascular effects and mortality and a causal relationship is likely to exist between short-term exposures to PM$_{2.5}$ and respiratory effects. Evidence from epidemiologic and toxicological studies is enough to conclude that a causal relationship exists between long-term exposures to PM$_{2.5}$ and cardiovascular effects and mortality. A causal relationship is likely to exist between long-term exposures to PM$_{2.5}$ and respiratory effects. The causal relationship between long-term exposures to PM$_{2.5}$ and reproductive and developmental outcomes, and cancer is suggestive. Evidence from epidemiologic studies, controlled human exposure and toxicological studies is suggestive of a causal relationship between short-term exposures to PM10-2.5 and cardiovascular effects, respiratory effects and mortality. There is evidence that is suggestive of a causal relationship between short-term exposures to ultra-fine particles (UFPs) which are defined as particles that are 100 nm or less in diameter and
cardiovascular effects and respiratory effects (Health Effects Institute, 2013). As particle size becomes smaller, the total particle surface area increases. This allows surface chemistry to have a significant effect leading to the generation of oxidants. UFPs can cause recruitment of inflammatory cells which can release respiratory burst-derived oxidants that can induce mutations in exposed lungs (Donaldson K., 1997). Epidemiologic research has attributed elevated cardiovascular and respiratory morbidity and mortality to short-term and long-term diesel particles exposure (Ristovski, 2012). Diesel PM surface area and adsorbed organic compounds may be critical characteristics of PM that lead to the development of adverse respiratory health effects if sustained. The effects include inflammation, innate and acquired immunity, and oxidative stress. Particle size is a crucial parameter to consider when determining the respiratory and cardiovascular health impacts of diesel PM because the smaller particles, often defined as nanoparticles which are particles with a diameter of less than 50 nm, have greater access to the lungs and bloodstream (Ristovski, 2012). UFP’s are the dominate contributors to particle number concentrations in the atmosphere. Inhaled UFP’s differ from larger particles in their deposition patterns in the lung, their clearance mechanisms, and in their potential for translocation from the lung to other tissues in the body (Health Effects Institute, 2013). It was determined that surface area of the particulate in the lung was the best correlation of production of tumors and it was not particle mass, which means the smaller particles can be more harmful when they enter the lungs and blood.

Visibility has a direct significance to people’s enjoyment of daily activities and their overall sense of wellbeing. Psychological research has shown that people are emotionally affected by poor visual air quality such that their overall sense of wellbeing is diminished.
Visibility impairment is caused by light scattering and absorption by suspended particles and gases. PM is the overwhelming source of visibility impairment in both urban and remote areas (National Center for Environmental Assessment - RTP Division, 2009). A study done in China on cities with a population greater than 10 million from the period of 1973 to 2007 found a significant decrease in visibility (Chang, Song, & Liu, 2009). This was attributed to increases in PM from coal combustion, automobile exhaust, industry and certain natural factors as the major emissions sources.

Road transportation is responsible for nine percent of the global black carbon (BC). Of those emissions, diesel engines attributed to 99% of these (International Council for Clean Transportation, 2013). On a mass-equivalent basis, BC is 3,200 times more effective than carbon dioxide (CO₂), in causing climate impacts within 20 years (International Council for Clean Transportation, 2013). BC can be considered the most efficient visible light absorbing aerosol species. The atmosphere heats up due to absorption of solar radiation by BC. This exerts a direct global warming force that may be comparable to the forcing of the greenhouse gas methane (Kirchstetter, 2006). Considering the immediate warming impact of light absorbing aerosols, it has been suggested that controlling their emissions could slow down the rate of climate change (Kleeman, Chen, & Schauer, 2013). It is difficult to know exactly what distribution of climate change is caused by BC alone, therefore, changes to the entire emissions must be considered. A study that eliminated all fossil fuel soot suggested reduced surface air temperatures by 0.3-0.5 K, 13-16% of total net global warming (“Transportation’s Role in Reducing U.S. Greenhouse Gas Emissions,” 2010). The Intergovernmental Panel on Climate Change (IPCC) projects that global temperatures will raise between 2°F and 11.5°F.
by 2100, and global sea level will rise between 7 to 23 inches ("Transportation’s Role in Reducing U.S. Greenhouse Gas Emissions,” 2010). BC has been identified as the second largest contributor to climate change after CO$_2$ (Song, He, & Lei, 2012). Large amounts of BC in the atmosphere can impact precipitation patterns and decrease the amount of radiation that gets to the Earth’s surface and impact local agriculture (International Council for Clean Transportation, 2013). There are questions as to importance of dulling either BC or greenhouse gases in order to optimize the impact of the temperature effect and mitigating costs. The impact of CO$_2$ takes place over a limited range of infrared wavelengths and BC absorbs most of the visible light in its path which allows significant warming (Bond & Sun, 2005). Bond suggests that while BC control cannot counteract global warming, there is significance in reducing BC because in some areas it is an economical way to decrease radiative impact.

Diesel combustion includes both premixed and diffusion components. Diesel engines produce PM due to incomplete combustion. There are three different aerodynamic size categories of PM as described by (Kittelson, 1997), these include the coarse mode particles ranging from 1 to 10 µm. The accumulation mode particles range from 0.1 µm to 2.5 µm. The smallest particles are the nucleation mode particles range from 20 nm to 1000 nm, shown in Figure 1.1. The fuel injection is an important factor in the determination of the pollutant formation in diesel engines. Fuel is injected at a high velocity into the cylinder. The liquid fuel atomizes into small drops that vaporize and mix with air in high pressure and burn. The fuel distribution is non-uniform which leads to incomplete combustion. Carbonaceous soot is formed where the air to fuel ratio is low. NO$_x$ is created where the air
to fuel ratio is nearly stoichiometric and high temperatures are produced. When injection timing is retarded from an optimal fuel economy position, this can decrease NO\textsubscript{x} emissions. However if the timing is moved from the optimal combustion efficiency position, this will decrease the efficiency of the combustion which leads to greater PM. The closer to complete combustion the higher the temperatures and the greater the efficiency, which leads to an increase in NO\textsubscript{x} and a decrease in PM. The inverse relationship between NO\textsubscript{x} and PM, called the trade-off of PM and NO\textsubscript{x}, causes great challenges to decreasing overall emissions in diesel combustion and one of the reasons these pollutants are a major focus of EPA and EU regulations.
Figure 1.1 Diagram showing the typical aerodynamic diameter size distribution for PM with the three different size modes, nuclei, accumulation, and coarse (Kittelson, Watts, & Johnson, 2003)

Biodiesel is a renewable fuel produced from organic material such as vegetable oil, animal fat, or waste cooking oil, and can be used 100 percent organic material or a ratio of conventional and organic material. Biodiesel consists of the methyl esters of fatty acids that can be used to diversify energy sources and increase security of energy supply through reduced use of fossil fuels. Biodiesel has a noticeably different composition than the hydrocarbon content of fossil diesel. Some biodiesels can be used in diesel engines without any modification to the engine itself (Mazzoleni C., 2007). The amount of energy required to produce biodiesel from its feedstock is a fraction of the combustion energy produced by the
final product (Mazzoleni C., 2007). A study done in California on off-road vehicles without aftertreatment showed that BC emissions rates decrease with increasing content of biodiesel in fuel blends; however this study was conducted on a sample of one engine. Another study (Shah et al., 2013) without a DPF that included engine dynamometer testing, showed that biodiesel had up to 42% reduction of accumulation mode particles when compared to conventional diesel. Biodiesel, however, produced up to 11% more nucleation mode particles than the diesel. Shah attributed the higher accumulation mode particles with the diesel to the ratio difference of NO2/NOx between the two fuels and attributed the increase nucleation mode particles with the biodiesel to homogenous and heterogeneous nucleation which is attributed to the oxygen content in biodiesel.

The EPA conducted an analysis with statistical regression to correlate the concentration of biodiesel in conventional diesel fuel with changes in pollutants. This was done for a fleet of heavy-duty highway engines, none of which had a DPF. When looking at PM specifically, a reduction of 12% is shown with the B20 blend, Figure 1.2, (EPA, 2002). A drawback to biodiesel is a loss of heating value when compared to ultra-low sulfur diesel (ULSD) therefore it is expected that the brake specific fuel consumption (BSFC) increases. Biodiesel also has longer time at high-temperatures. Studies have shown that there is a NOx increase with biodiesel fuel (Durbin, Collins, Norbeck, & Smith, 2000). The NOx increase has been attributed to an inadvertent advance of fuel injection timing (Lapuerta, Armas, & Rodriguezfernandez, 2008). The advance in injection timing is due to the higher bulk modulus in the fuel blend in a mechanical injection pump. Biodiesel including B100 and blends reduces PM emission through oxygen content (Boehman, Song, & Alam, 2005). A
study with neat diesel, rapeseed methyl ester (B100) and a B30 with the neat diesel and rapeseed methyl ester were tested on a portable power generator without any exhaust aftertreatment. The B100 and the B30 produced less CO and total polycyclic aromatic hydrocarbons while the emissions of NO\textsubscript{x} and PM increased compared with petroleum diesel fuel per kWh (Sadiktsis, Koegler, Benham, & Bergval, 2014).

Figure ES-A
Average emission impacts of biodiesel for heavy-duty highway engines

![Graph showing emission impacts of biodiesel for heavy-duty highway engines](image)

**Figure 1.2** A comprehensive analysis of biodiesel impacts on exhaust emissions (EPA, 2002)

There are limited studies done on the effects of ambient temperature on PM emissions from heavy-duty diesel engines. For light-duty gasoline vehicles, a reduction in ambient temperature has been associated with increases in PM emissions (Nam et al., 2010). During colder temperatures, the engine is not running as efficiently as when the engine is at higher,
steady-state operating temperature. The emissions are higher because the 3-way catalyst has not yet reached its light off temperature. There are also concerns about testing PM emissions in cold temperatures in a laboratory setting. For example, if dilution air is cold, ice may form as warm humid exhaust emissions interact with the cold air in the dilution tunnel sampling system. Therefore, dilution air is heated. Uncertainties exist in the results from ambient temperature testing since the dilution air is not the same temperature as the tested ambient temperature used for the vehicle soak and running operations in the temperature-controlled chamber.

During a cold start for diesel engines, there is typically an increase in the amount of fuel injected to ensure a start. This causes an additional amount of fuel that is not participating in combustion; thus increasing incomplete combustion and PM emissions. Engines equipped with diesel oxidation catalysts (DOCs) to control emissions are also highly dependent on temperature. The catalysts temperature must be high enough to make certain an efficient conversion of pollutants occurs. This suggests that the emissions will increase during cold starts and in cold ambient conditions. A study was done varying temperatures at 23°C, -7°C and -20°C with two light-duty vehicles operating on conventional diesel fuel, one having a DPF and the other not. The results showed an increase in particle number concentration as the temperature decreased. The increase was between 71% and 73% with a reduction in temperature from 23°C to -20°C. This study on light duty diesel vehicles showed an influence of cold temperature during the cold start of the vehicle but insignificant effect on the PM emissions after the engine warmed up (Mohr 2004).
More studies have been conducted on the effect of ambient temperature on light-duty gasoline engines. The Kansas City Light-Duty Vehicle Emissions Study (KCVES) was the largest known study investigating light-duty gasoline PM emissions, including the impact of ambient temperature. Vehicle emission testing was completed during the summer and winter with vehicles operated at ambient temperatures. In this study, PM emissions increased exponentially as temperature decreased. PM emissions doubled for every 20°F drop in ambient temperature. These increases were independent of vehicle model year. This temperature effect was most noticeable during the initial starting of the vehicles. During cold conditions, combustion is inefficient, catalyst operation is inefficient and the vehicle has the tendency to run fuel rich (Nam et al., 2010). EPA maintains PM emission standards for gasoline vehicles. Improvements in the catalytic converter and better control of air to fuel mixture ratios for the engine intake designed for control of CO and HCs has also led to reductions of PM emissions from gasoline fueled vehicles. Well maintained, modern gasoline fueled vehicles emit far lower PM when compared to diesel fueled vehicles.

1.2 EMISSIONS CONTROL DEVICES

In 1981, when diesel particulate standards were first proposed, it was generally believed that filter based particulate removal systems would be developed in time to fulfill the future standards (Neeft, Makkee, & Moulijn, 1996). Particulate reduction techniques for diesel exhaust were initiated and in 1982 particulate standards for diesel engines were introduced (Neeft et al., 1996). Particulate standards were established in 1982 only for light-duty vehicles and not until 1990 for heavy-duty engines (Neeft et al., 1996). Between 1990 and 2010, a standard for diesel fuels for less than 500 ppm sulfur was in place and later
updated to ULSD with 15 ppm. Emissions standards that include regulations for CO, HC, PM, NO\(_x\) and PM were also phased in. Since 2010, in order to meet the most recent EPA regulation on PM emissions, a DPF is required for sufficient PM removal. DPFs are used in passenger cars in the European Union to meet similar standards (Mamakos, Martini, & Manfredi, 2013). In order to control and reduce the diesel emissions, engine manufactures are using different combinations of DOCs, DPFs, SCR, NO\(_x\) absorbers, and advanced fuel injection technologies.

### 1.2.1 DIESEL PARTICULATE FILTERS

A DPF has alternately plugged channels with porous ceramic walls. The exhaust gas is forced to pass through the porous walls, **Figure 1.3**. Solids get built up along the channel walls forming a layer of soot on the walls. This layer of soot continuously loads the DPF as the engine is operated. Before the filter is loaded enough to significantly affect the engine operation due to back pressure, the soot must be removed through regeneration. The DPFs need to be robust and have a controlled regeneration to clean out the filters. In general, four conditions must be met in order for the filter regeneration to be completed: 1) maximum temperature increase at minimum fuel expense, 2) the driver should not be involved, 3) there should be no additional noise, and 4) no additional by-products should be formed like CO, unburned hydrocarbons, and soot (van Setten B., Moulijn J., 2001). The regeneration can occur in a variety of ways. One strategy for regeneration is to increase exhaust temperatures by changing injection timing to burn off the particulate that has accumulated on the DPF. This “active” regeneration happens when the engine exhaust temperature gets high enough, usually above 1100°F, to oxidize the PM that is built up on the DPF walls. This exothermic
reaction begins at the inlet of the DPF where the soot layer is then lit off. More details are provided in Chapter 4. This is done when the engine management system forces the engine into the regeneration mode. These changes are not noticed by the driver. It is also possible for the DPF to undergo a passive regeneration, which is also not detected by the driver. Unless notified by a dashboard light indicator, the driver is not aware that a regeneration is happening. During passive regeneration, there is enough NOx to allow NO to NO2 oxidation reactions and oxidation of PM with NO2. A passive DPF regenerates itself without the intervention of on-board diagnostic and control systems. Passive regeneration occurs when the engine is running in ideal regeneration conditions and the particles are being burned off.

Currently, the DPF is the only technology that is able to demonstrate high levels of reduction for all types of diesel PM that concern environmental regulators, PM mass, UFPs and nano-sized particles, particle number and BC (Gladstein, 2013).
Figure 1.3 Exhaust flow (top) through the DOC and DPF and (bottom) details of the wall flow filter where the PM is trapped on the DPF walls (Gladstein, 2013)
The DPF lowers the PM mass emissions but the effect on particle number is less well understood. The mass emissions are dominated by the soot accumulation mode, which is efficiently trapped on the DPF but PM number concentrations can be dominated by nucleation particles which may be formed downstream of the DPF (Maricq et al, 2007). Since data is collected downstream of the DPF and after mixing with dilution air, the particles sampled are highly susceptible to being in the accumulation mode due to agglomeration in the exhaust and sampling system. The accumulation mode is in the 0.1-0.3 µm diameter range. This is where the carbonaceous agglomerates and associated adsorbed materials reside (Kittelson, 1997). There was a study done to learn about the DPF behavior with the use of biodiesel. In the study, results of the PM emissions showed that at the highest DPF temperature of the study, 450°C, there was an increase in PM emissions when compared to the second highest temperature tested, 425°C. This trend was true for both the diesel and biodiesel fuels (Buono D. Prati M.V., 2012).

A DPF is not the only part to the aftertreatment system. NO\textsubscript{x} is being regulated too; therefore NO\textsubscript{x} reduction devices are included on the vehicles. Vehicle 1 used for this test had an exhaust aftertreatment system that included a close-coupled catalyst, a NO\textsubscript{x} absorber (NAC), and a DPF. The 2.1 L close-coupled catalyst is made by Emitec. It takes the oxygen, hydrocarbons, and carbon monoxide from the exhaust and converts it to water and carbon dioxide. It is located close to the engine exhaust to benefit from the heat of the exhaust and optimize engine emissions during cold starts. The NAC converts NO\textsubscript{x} into barium nitrate during lean conditions which sticks to the surface of the substrate inside the absorber. The NAC uses a precious metal, commonly platinum, to help with nitrate formation. When the
surface is covered, the engine will switch to run in rich mode eliminating oxygen. This releases the barium nitrate and turns it into nitrogen gas and water vapor. The barium goes through a carbonate to nitrate conversion (Li, Roth, Dettling, & Beutel, 2001). It is not likely that a DPF regeneration and a NAC regeneration would occur at the same time because of the need for the lean conditions in the DPF regeneration (for soot oxidation) and rich conditions for the NAC.

It is challenging to evaluate in isolation the effects of each of the aftertreatment components and the fuel on PM emissions. The impact of the oxidation catalyst depends on factors such as fuel composition. It removes hydrocarbons that could otherwise condense on soot particles or nucleate as the exhaust subsequently cools. It also oxidizes \( \text{SO}_2 \) and \( \text{SO}_3 \). With water vapor this yields sulfuric acid which can promote nucleation or condense on soot. This leads to an interlinking effect between the catalyst and fuel sulfur level that alters the chemical makeup of diesel engine PM and affects the particle size distribution (Maricq et al, 2007).
2 EXPERIMENTAL APPARATUS

2.1 CHASSIS DYNAMOMETER

Dynamometers are useful during experimental studies so consistent drive cycles can be run under controlled sampling and vehicle operating conditions to allow for consistency and comparability between tests and studies. The same drive cycle can be run with the same atmospheric, sampling, and vehicle operating conditions. The ambient conditions and loads can be controlled and adjusted. The testing is not dependent on the unpredictable weather. Dynamometers are useful due to the capability to use instrumentation for data collection that needs to stay stationary. While there are some instruments that can travel with the vehicle, there is a limit to the number and type of instruments available when doing on-road testing. The drawbacks of using the dynamometer are that while the drive cycles do represent real world driving conditions, it may not exactly match what a vehicle would do on the road and some conditions (e.g. high speed, high acceleration/deceleration) cannot be conducted on a dynamometer. In addition, the particles that are collected in the dilution tunnel may not necessarily represent particles that would be present in the atmosphere from vehicle emissions. Conditions in the atmosphere like dilution and temperature changes between exhaust and ambient, cannot be fully simulated in a dynamometer system. In addition the amount of coagulation condensation, evaporation, and diffusion loss to tunnel walls may alter PM characteristics.
2.2 DILUTION TUNNEL

Testing in a dynamometer requires the need for a dilution tunnel. The exhaust used for PM analysis is taken from a dilution tunnel, after the dilution air and exhaust have been completely mixed. The dilution tunnel was insulated with double reflective insulation to prevent hot or cold spots. The dilution air used for this test was at the laboratory ambient conditions, this varied from the dynamometer ambient temperature during cold temperature (20°F) testing. The exhaust from the vehicle was connected to the dilution tunnel by extending the exhaust pipe on the truck as shown in Figure 2.1. The dilution tunnel is used to reduce the temperature and concentration of the exhaust before measurement by the instrumentation in an effort to measure emissions in a consistent and comparable manner. The exhaust particles directly from the tailpipe have differences from those sampled in a dilution tunnel and what is in the ambient atmosphere. The dilution tunnel is kept at a constant temperature, humidity and dilution ratio throughout testing while the atmosphere changes in temperature and humidity and is not controllable. The exhaust particles are impacted by these factors. When measuring PM for emission regulation purposes, temperature and humidity are set to specific values. Consistent results are difficult to obtain because, when PM is emitted, species are unstable and may be altered through a deposition of the particles to the dilution tunnel walls, change in size distribution caused by contact and interactions with other species in the exhaust at any time during the measurement process (Heywood, 1988). The dilution ratio for this testing was between 8:1 and 20:1. For comparison, the ambient conditions are closer to 1000:1 (Maricq et al, 2007).
2.3 ANALYZERS

There were six different analyzers that were taking data in order to better understand PM from the exhaust. These include an Engine Exhaust Particle Sizer (EEPS), an Environmental Condensation Particle Counter (ECPC), an AE-51 Micro Aethalometer, a Photoacoustic Extinctionmeter (PAX) 870 nm, a Photoacoustic Extinctionmeter (PAX) 532 nm, and a Cavity Attenuated Phase Shift (CAPS).

The EEPS 3090 measures particle size and count. This instrumentation is unique from the others in this study because it separates the particle count in specific size bins. The bin sizes are shown in Table 2.1. It measures emissions particles ranging from 5.6 to 560 nm aerodynamic diameter in real-time. It draws in exhaust where the particles are positively charged. These charged particles flow into measurement region of an electrode column. A positively charged voltage is applied to the electrode. This creates an electric field that repels the positively charged particles outward according to their electrical mobility. A particle with
lower electrical mobility strikes and electrometer lower in the stack, just as a particle with higher electrical mobility strikes an electrometer closer to the top (TSI incorporated, n.d.). A digital signal processor (DSP) is used to obtain the data, shown in Figure 2.2. The detection limit on the EEPS is dependent on the particle size and averaging time. For 1 second data collection at 5.6 nm it will detect approximately 550 particles per cubic centimeter. The specific detection limit is shown in the Figure 2.3. The EEPS displays real time data on its screen during data collection. When reporting particle size data for the EEPS, the data has been normalized. This is done to be able to compare data from the EEPS with other instrumentation that measures size particles that do not have the same size bin range. The data appears misleading if the size bin ranges are different and therefore is reported normalized. The limits of an EEPS is the size of the instrumentation. There needs to be sufficient space to set the EEPS up. It is also sensitive to vibration, therefore, it is important to ensure it is mounted on a stable surface.

Table 2.1 Size Bin Range for EEPS (nm)

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<th>5.6</th>
<th>6.04</th>
<th>6.98</th>
<th>8.06</th>
<th>9.31</th>
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<th>16.5</th>
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<td>60.4</td>
<td>69.8</td>
<td>80.6</td>
<td>93.1</td>
<td>107.5</td>
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<td>124.1</td>
<td>143.3</td>
<td>165.5</td>
<td>191.1</td>
<td>220.7</td>
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<td>339.8</td>
<td>392.4</td>
<td>453.2</td>
<td>523.3</td>
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</table>
Figure 2.2 Operation of the EEPS, particles are charged, where the particles strike the electrometer depends on the size of the particles (TSI incorporated, n.d.)
The ECPC 3783 measures particle count with optics. Particles are passed through humid air to form larger particles. The resulting droplets are passed through a laser beam and create a light pulse. Each particle pulse event is then detected and counted, schematic shown in Figure 2.4. Particles that are too small to scatter enough light to be detected are grown by condensing water on them. An external pump is used to continuously draw in the air sample. The ECPC uses water as its working fluid that has to be filled as needed. It measures particles as low as 7 nm. The efficiency is shown in Figure 2.5. The time it takes for the ECPC monitor reading to reach 95% of a concentration step change is less than 1 second. The particle diameter at which 50% of particles are detected is 7 nm. This instrumentation is ideal for atmospheric monitoring but because it requires an external pump and a water supply.
it is not ideal for mobility testing. While it provides a count of particles it does not determine the size of the particles and cannot detect particles as small as the EEPS. The main purpose for the use of ECPC in this experiment was to collect data alongside of the EEPS data for the use of Dr. Gayle Hagler at the EPA evaluating and comparing ambient air source sampling instruments. The EEPS and the ECPC both measure particle count therefore the results of the two instruments can be used to check data and make sure they have consistent trends even though different methods are being used to read the particle count.

**Figure 2.4** Description of the ECPC 3793 operation that uses a photodetector to determine particle count (ECPC product spec)
The AE-51 aethalometer is an instrument that measures BC using the rate of change in absorption of transmitted light due to a continuous collection of aerosol deposit on a filter. The sample is collected on a teflon coated glass fiber filter media. The filter change is simple and done on a daily basis. The measurement precision is +/- 0.1 µg BC/m³, 1 minute average at 150 mL/minute flow rate. The aethalometer is self-contained, pocket-sized and has flow control and data storage. This makes it easy to take data in any location. The data provided by the aethalometer contains a significant amount of noise that has to be filtered out before analyzing the data.

The PAX is an instrument that directly measures in-situ light absorption and scattering of aerosol particles. A Photoacoustic Extinctiometer (PAX) draws in a sample flow
with its internal vacuum pump to measure BC. It uses a modulated diode laser to measure light scattering and absorption. The flow is split between the nephelometer and the photoacoustic resonator for this measurement. The absorption method uses a laser beam through the aerosol stream. Absorbing particles heat up and produce heat waves that are detected with a microphone, shown in Figure 2.6. The 870 nm is a wavelength that is specific for black carbon particles and is best for large particles. Although the PAX 870nm and AE-51 use different methods to detect BC, the data can be compared to ensure both are giving consistent trends in the results.

**Figure 2.6** Description of operation of the PAX that uses scattering and absorption

The 532 nm is a wavelength that measures the visual range, typically what the human eye observes. This was used with the intent of trying to measure organic PM from the exhaust. This was used during the testing for experimental evaluation of the PAX. The PAX are new instruments and the specific PAX that were used were experimental versions. The primary reason for the use of this data collection was for experimental reasons for Dr. Mike
Hays at the EPA. While the PAX are easy to use, they are large and heavy instruments that need to be placed on a steady surface without vibrations that can affect the data. A visible (450 nm) absorption measurement instrument using Cavity Attenuated Phase Shift (CAPS) is used in order to read the NO₂ concentrations. This is necessary in order to subtract that data from the PAX 532 nm reading. The instrumentation is set up to record real-time second-by-second data along with the other instrumentation. The CAPS sensitivity is less than 1.5 parts per billion with a signal to noise ratio of 3 and does not require a conversion of NO₂ to other species for measurements. A set up of the instruments used for this experiment is shown in Figure 2.7.
Figure 2.7 (top) Inside the control room of the dynamometer with instrumentation and (bottom) schematic of dilution tunnel with instrumentation.
2.4 DRIVE CYCLES

The dynamometer drive cycles that were used for this testing comply with the 40 CFR Part 86 and Parts 1065 and 1066. The testing procedure includes three different drive cycles (Clark et al., 2003)

- Medium heavy-duty transient lower speed, a cold start with low transients (CSLT) lasting 319 seconds
- Federal heavy-duty urban dynamometer driving schedule (UDDS) lasting 1059 seconds
- Medium heavy-duty transient lower speed, a warm start with low transients (WSLT) lasting 319 seconds

The CSLT and the WSLT have the same engine speed trace. The difference between the tests is the engine has a minimum of 12 hour soak prior to the CSLT, and only a 20 min soak before the WSLT. There is a 20 minute soak of the vehicle between each of the tests as recommended by (Council, 2007). Figure 2.8 shows the engine speed trace for one day of testing. In an effort for consistent results, the vehicle must be pre-conditioned the day before a test. This is done to ensure the catalyst have the same starting point from test to test and for the vehicles adaptive learning curve. The pre-condition run consists of a full test cycle. When the test is complete, the engine is shut down and not run again until the next day for the CSLT, allowing for at least a 12 hour soak time at the ambient testing temperature within +/- 5°F.
Figure 2.8 Speed trace of the test cycles (top) medium heavy-duty transient lower speed cycle, used for a cold and warm start and (bottom) the federal heavy-duty urban dynamometer driving schedule
The CSLT is used in this study to represent driving around town when the vehicle is started for the first time that day or after a significant amount of time since the previous operation. The speed range is from zero to 29 mph. This test is done to see if there are any differences in emissions when the vehicle is started up and initially driven after a considerable delay since the prior time the engine has been run. When an engine is started and it is not warmed up, the combustion is not as efficient as when the engine is warmed up. Incomplete combustion is what causes PM and if cold conditions reduce the efficiency of combustion then it is important to know if cold starts cause an increase in PM. The UDDS is more representative of highway and urban arterial driving. The speed range is from zero to a maximum of 55 mph. This occurs after the engine is warmed up since the CSLT and WSLT are the same, comparing emissions between these drive cycles allows for a comparison to be made on the exhaust when the engine is cold and has been shut down for at least 12 hours versus when the engine has been started warm.

2.5 VEHICLES TESTED

Two vehicles were used for testing. Vehicle 1 is a 2011 class 2b (gross vehicle weight rating (GVWR) of 8,501 to 10,000 lbs) with a 6.7L Cummins engine. The aftertreatment includes a NO\textsubscript{x} catalyst adsorber, a close-coupled catalyst, and a DPF, Figure 2.9. Vehicle 2 is a 2011 class 5 (GVWR of 16,001 to 19,500 lbs) with a 6.7L Powerstroke engine. The aftertreatment includes selective catalyst reduction (SCR), a diesel oxidation catalyst and a DPF, Figure 2.10.
Figure 2.9 (top) Vehicle 1 and (bottom) vehicle 1 aftertreatment
Selective catalytic reduction (SCR)

Diesel Particulate Filter

Oxidation Catalyst

Figure 2.10 (top) Vehicle 2 and (bottom) vehicle 2 aftertreatment schematic
3 TEMPERATURE EFFECTS ON PARTICULATE EMISSIONS FROM DPF-EQUIPPED DIESEL TRUCKS OPERATING ON CONVENTIONAL AND BIODIESEL FUELS

3.1 ABSTRACT

Two medium heavy-duty diesel trucks equipped with a particulate filter (DPF) were tested at two ambient temperatures (70°F and 20°F), fuels [ultra-low sulfur diesel (ULSD) and biodiesel (B20)] and operating loads (a heavy and light weight). The fuel selection was based on the most popular fuels being used in the U.S. for these vehicle types. The test procedure included three driving cycles, a cold start with low transients (CSLT), the federal heavy-duty urban dynamometer driving schedule (UDDS), and a warm start with low transients (WSLT). Particulate matter (PM) emissions were measured second-by-second using an Aethalometer for black carbon (BC) concentrations and an Engine Exhaust Particle Sizer (EEPS) for particle count measurements between 5.6 and 560 nm. One vehicle experienced increased BC and particle number concentrations during cold starts under cold ambient conditions, with concentrations two to three times higher than under warm starts at higher ambient temperatures. The average particle count for the UDDS showed an opposite trend, with an approximately 27% decrease when ambient temperatures decreased from 70°F to 20°F. This vehicle also experienced decreased emissions when going from ULSD to B20, with an approximately 13% average decrease in PM number and an approximately 27% decrease in BC. The other vehicle tested had much lower emissions, with many of the BC and particle number measurements below detectable limits. However, both vehicles did experience elevated emissions from DPF regeneration events. All regeneration events occurred during the UDDS cycle. Slight increases in emissions were measured during the
WSLT cycles after the regeneration. However, the day after a regeneration occurred, following a 12-hour soak at ambient temperatures, both vehicles showed significant increases in particle number and BC for the CSLT drive cycle, with increases from 93 to 1380 percent for PM number emissions compared with tests following a day with no regeneration.

3.2 INTRODUCTION

Human exposure to airborne particles from diesel engine exhaust have been linked with a plethora of health concerns including acute irritant effects, respiratory symptoms, immunologic effects, lung inflammatory effects, cardiovascular health responses and cancer (Hesterberg et al., 2012) (C. A. et al. Pope III et al., 2002) (Thurston et al., 2009) (C. A. Pope III, Spengler, Raizenne, & Dockery, 1991). Epidemiologic research has attributed elevated cardiovascular and respiratory morbidity and mortality to short-term and long-term exposure to diesel particles (Ristovski, 2012). Diesel particulate matter (PM) surface area and adsorbed organic compounds can lead to the development of adverse respiratory health effects if sustained over time. The effects include inflammation, innate and acquired immunity, and oxidative stress. Many of these adverse health effects have been linked to the size of the particle. Particle size is defined by the aerodynamic diameter which represents the aerodynamic behavior of an irregularly shaped particle in terms of the diameter of an idealized spherical particle with unit density. Particle size based on aerodynamic behavior can influence the potential respiratory and cardiovascular health impacts of diesel PM because smaller particles have greater access to the lungs and bloodstream (Ristovski, 2012). Ultra-fine particles (UFP) are defined as PM with aerodynamic diameters less than 100 nm, a size fraction that dominates particle number emissions from diesel exhaust. Inhaled UFPs
differ from larger particles in their deposition patterns in the lungs, their clearance mechanisms, and in their potential for translocation from the lung to other tissues in the body, all of which contributes to the health concern for this class of PM (Health Effects Institute, 2013). A majority of PM emitted by diesel engine exhaust are in the UFP size range. A study reported that approximately 48% of particles emitted from a diesel engine were in the size range of 0-200 nm and approximately 35% were between 200 and 400 nm (Neer & Umit, 2006). In diesel exhaust, the nuclei mode consists of particles in the 5 to 50 nm diameter range. The majority of the particle mass from diesel emissions are in the accumulation mode with a diameter range of 100-300 nm (Kittelson, 1997).

Black carbon (BC), often referred to as soot, is formed by incomplete combustion and constitutes roughly 40% of PM mass emitted from diesel engines on average (Kittelson, 1997). BC strongly absorbs light. The climate effects of BC aerosols depend on physical and chemical properties and residence time and distribution in the atmosphere (Andreae Gelencer, A., 2006). High resolution transmission electron microscopy showed that the internal structure of combustion soot spherules depends on the chemical and thermal environment under which formation occurs and on the time allowed for annealing (Andreae Gelencer, A., 2006). BC can be considered the most efficient visible light absorbing aerosol species, promoting atmospheric heating due to absorption of solar radiation. This exerts a direct global warming force that may be comparable to the force of the greenhouse gas methane (Kirchstetter, 2006). Considering the immediate warming impact of light absorbing aerosols, controlling BC emissions could reduce the rate of climate change (Kleeman et al., 2013), although uncertainty exists on what contribution BC alone
makes. A study that modeled an elimination of all fossil fuel soot estimated a surface air temperature reduction of 0.3-0.5 K, which represents 13-16% of total net global warming ("Transportation’s Role in Reducing U.S. Greenhouse Gas Emissions,” 2010). BC emissions have also been implicated as a public health concern, particularly because these particles are present in the UFP size range; when particle size decreases, pulmonary deposition increases (Kittelson, 1997). BC has often been used as a surrogate for exposure to diesel exhaust because of its prevalence in diesel PM emission (Kirchstetter, 2006).

In the United States (US), the Environmental Protection Agency (EPA) has regulations that limit air pollution emissions from diesel engine exhaust, with two key pollutants being PM and oxides of nitrogen (NOx). The on-road diesel standard limits PM mass emissions to 0.01 grams per brake-horsepower-hour (g/bhp-hr) and 0.02 g/bhp-hr for NOx. The European Union (EU) has recently instituted regulations limiting emissions of particle number to 6.0E11 number/km, while maintaining mass-based limits of 0.005 g/km (EuropeanUnion, 2012). To meet these stringent US and EU emission standards, manufacturers now equip on-road, heavy-duty diesel vehicles with a diesel particulate filter (DPF). A DPF has alternately plugged channels with porous ceramic walls that the engine exhaust gas is forced to pass through. Solid particles get built up along the channel walls forming a layer of soot on the walls. This layer of soot continuously loads the DPF as the engine is operated. Before the filter is loaded enough to significantly affect the engine operation due to back pressure the filter must be cleaned. The cleaning of the filter is called a regeneration. It is difficult to determine the effects of the DPF in isolation on PM emissions due to other components in aftertreatment systems. The DPF substantially lowers PM mass
emissions, however, there is uncertainty on the number of regeneration events that occur during operation and the overall impact of the DPF on PM emissions.

While the addition of the DPF reduces total PM emissions, uncertainty remains on how the DPF performs during cold ambient temperatures, cold starts, accelerations, varying fuels and other engine operations. Diesel engines are operated all over the world in a variety of ambient conditions. Since cold ambient weather conditions and cold starts lead to highly elevated emissions from gasoline-powered vehicles operating with three-way catalysts (Nam et al., 2010), understanding how DPFs perform under cold conditions may have important implications on diesel PM emissions. No information has been identified on emissions from diesel engines with the new aftertreatment technology at temperatures less than 50°F.

The production of biodiesel has increased from 700 million gallons in 2008 to 1100 million gallons in 2011 (“U.S. Biodiesel Production,” 2012). Biodiesel is used to diversify energy sources and increase security of the domestic energy supply. Biodiesel has been shown to reduce PM by 10% for every 20% (volume) increase in biodiesel blend (e.g. a 40% reduction in PM can be achieved by an 80% biodiesel blend (EPA, 2002)) (Song et al., 2012). A study in California on off-road vehicles without aftertreatment showed that emissions rates of organic PM species decreased with increasing content of biodiesel in fuel blends (e.g. a 50% reduction achieved by a 25% biodiesel blend) (Kleeman et al., 2013). Other studies have shown that biodiesel emits less accumulation mode PM (0.1 µm < particle size < 2.5 µm) and has an increase in particles with small diameters (Kleeman et al., 2013). No studies have been identified that show the effects of biodiesel on emissions in cold ambient conditions. To address these uncertainties, a study was conducted to measure emissions from
heavy-duty vehicles equipped with DPFs under varying driving, ambient temperatures, and fuels to provide a greater understanding of the effects of the DPF on PM emissions.

3.3 EXPERIMENTAL METHOD

Air pollutant emissions were measured from two diesel vehicles equipped with DPFs operating over varying driving cycles with two ambient temperatures, two fuels, and two load conditions.

3.3.1 Testing Facility

This study used two fixed, chassis dynamometers: 1) a Burke-Porter, 48-inch, single-roll chassis dynamometer enclosed in a climate controlled chamber that allowed testing at ambient temperatures ranging from -20 to 110°F with a maximum of 12,000-pounds test weight and 2) a Renk, 72-inch single-roll electric chassis dynamometer operated at a temperature of 70°F with a maximum of 35,000-pounds test weight.

The PM sampling system conformed to the requirements of CFR Part 1065 testing standards for a Constant Volume Sampler (CVS) dilution tunnel system (CodeFederalRegulations1065, n.d.). The vehicles’ tailpipes were connected to the dilution tunnel with a flexible, stainless steel boot. Isokinetic probes were placed just greater than the required minimum 10 diameter lengths from the mixing plate, and used to collect sample air for PM analysis. Gaseous samples were collected less than 1-meter upstream from the isokinetic probes in the dilution tunnel.
3.3.2 Vehicles

The vehicle selection was made to fit within the size restrictions on the dynamometer and have two different engine manufactures. The vehicles were also chosen to be a good representation of what is currently being operated on the road. Two in-use vehicles were tested: 1) a class 2b vehicle (gross vehicle weight rating (GVWR) of 8,501 to 10,000 lbs (Quality, 2008)) Vehicle 1 2011 with a 6.7L Cummins engine and 22,062 miles and 2) a class 5 vehicle (GVWR of 16,001 to 19,500 lbs (Quality, 2008)) Vehicle 2 2011 with a 6.7L Powerstroke Vehicle 2 engine with 2,693 miles. Vehicle 1 exhaust aftertreatment system included a close coupled oxidation catalyst, a NO\textsubscript{x} absorber catalyst (NAC), and a DPF. The aftertreatment system for Vehicle 2 consisted of an oxidation catalyst, a selective catalytic reduction (SCR) system with urea injection for NO\textsubscript{x} control, and a DPF. The DPF on Vehicle 1 was 9.4L and manufactured by NGK. The DPF on Vehicle 2 was a Motorcraft DPF. The channels of the filter are alternately blocked so the engine exhaust is forced to pass through the filter medium and into the adjoining channels to exit the filter.

3.3.3 Fuel, Ambient Temperature, and Load Conditions

This study included two fuels, an ultra low sulfur diesel (ULSD) and a biodiesel blend. The biodiesel (B20) consisted of 80% of the ULSD with 20% of a soy-based biodiesel conforming to ASTM D6751-11b (purchased from Gage Products Company, Ferndale, Michigan). The fuel was stored in sealed 55 gallon steel drums in a temperature controlled fuel storage shed maintained at 55 +/- 2\textdegree F to minimize the loss of volatile components, the formation of condensation, and the growth of microbes in the fuel. A fuel change between the ULSD and B20 consisted of the following procedure. First the vehicle was warmed up
with a 10 minute idle, after which the fuel tank was bottom drained. The vehicle ignition was turned to run for 30 seconds and the fuel gauge reading of zero was confirmed. The tank was then filled to 40% of capacity with the new fuel and operated on the dynamometer over a high speed conditioning cycle. The tank was then drained, filled to 40% capacity with the test fuel, drained again and filled to 60% capacity with the test fuel. The vehicle and fuel temperature stabilized at the test temperature for 12-24 hours, after which the vehicle was operated on the dynamometer with three sets of WSLT-UDDS-WSLT cycles to condition the vehicle’s adaptive learning and exhaust aftertreatment systems with 2-5 minutes of shut off time in between the condition runs. After the condition runs, the vehicle sat idle for two minutes before shutting down.

The emission testing was conducted at ambient temperatures of 20°F and 70°F on the 48-inch roll dynamometer to represent winter and summer conditions, respectively. For each testing condition, a 12-hour vehicle soak time occurred at the ambient test temperature to within +/- 5°F.

Each truck was tested using both a heavy (laden) and a light (unladen) test weight. The laden case was calculated as 90% of the gross vehicle weight rating. The load was added to the vehicle on the dynamometer by increasing the friction load of the dynamometer roller. The unladen case was calculated as the actual vehicle curb weight plus 150 lbs which is the set weight for a single driver. Because of load limitations on the 48-inch roll dynamometer, only unladen conditions could be tested for Vehicle 2 at this facility. Thus, only unladen tests occurred at the 20°F and the 70°F test conditions for the Vehicle 2 and all laden tests were conducted on the 72-inch roll dynamometer at 70°F ambient temperatures. Vehicle 1 was
tested under laden and unladen conditions at both ambient temperatures on the 48-inch roll dynamometer. Since the instrumentation used in this study could not be moved between the two dynamometers, only tests conducted on the 48-inch roll dynamometer are reported in this paper.

3.3.4 Instrumentation

Two instruments collected second-by-second data reported in this paper. These included an Engine Exhaust Particle Sizer (EEPS) and an AE-51 Micro Aethalometer. The EEPS 3090 is manufactured by TSI in Shoreview, Minnesota and measures PM count and size at a 10 Hz sampling frequency. The MicroAethalometer AE51 is manufactured by AethLabs in San Francisco, California and measures BC.

The EEPS measures particle size and count in thirty-two size bins ranging from 5.6 to 560 nm aerodynamic diameter. The detection limit on the EEPS is dependent on the particle size and averaging time. The AE-51 is a small, portable instrument that measures black carbon by light absorption on a sample collected on a Teflon-coated, glass-fiber filter. The measurement precision is +/- 0.1 µg BC/m³, 1-minute time average at 150 mL/minute flow rate.

3.3.5 Test cycle

The drive cycles used in this test program complied with 40 CFR Part 86 and Parts 1065 and 1066 regulations (CodeFederalRegulations, n.d.). The drive cycles were completed with a human driving the predetermined schedule, with the same driver used for all of the testing. The test procedure included three different cycles: 1) a cold start with low transients (CSLT) lasting 319 seconds, 2) the federal heavy-duty urban dynamometer driving schedule
(UDDS) lasting 1059 seconds, and 3) a warm start with low transients (WSLT) lasting 319 seconds that duplicated the CSLT cycle. There was a 20-minute soak of the vehicle at the ambient test temperature between each of the three tests to allow time for instrumentation and dynamometer set-up between cycles. The CSLT and the WSLT have the same engine speed trace, the only difference between the tests was the 12-hour soak for the CSLT and only the 20-minute soak for the WSLT. A conditioning run was conducted prior to every change in the combination of fuel, temperature, load, and vehicle tested. The conditioning run consisted of a full test with all three drive cycles and included the minimum of 12-hour ambient test temperature soak. **Figure 3.1** shows the engine speed trace for one day of testing that included all three drive cycles. When the test was completed, the engine was shut down and not run again until the next day for the CSLT, allowing for the 12-hour soak time at the ambient testing temperature. Each of the combinations of fuel, temperature, load, and vehicle were run for at least three tests with all three drive cycles. Only one test was run each day. If a DPF regeneration occurred during a test, a fourth test was conducted for that fuel, temperature, load, and vehicle combination. Every condition on Vehicle 1 had a test cycle where a regeneration occurred; therefore, four tests were conducted for each condition on this vehicle. Vehicle 2 only had one regeneration during the testing.
Figure 3.1 Speed trace of the three test cycles including the 20-minute soak times. The initial 12-hour soak prior to the CSLT is not shown.

3.3.6 Test Schedule

A semi-randomized testing schedule was designed to reduce bias in the testing results while minimizing fuel and dynamometer changes. Table 3.1 shows the testing sequence. The grayed out weeks in Table 3.1 were conditions using the 72-inch roll dynamometer; data not reported in this paper.
Table 3.1 Schedule of test conditions. The order was semi-random to avoid bias yet minimize fuel/vehicle preparation and set-up.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Vehicle</th>
<th>Fuel</th>
<th>Ambient Temperature (°F)</th>
<th>Simulated Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>ULDS</td>
<td>70</td>
<td>Laden*</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Biodiesel</td>
<td>70</td>
<td>Laden</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Biodiesel</td>
<td>70</td>
<td>Unladen**</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Biodiesel</td>
<td>20</td>
<td>Unladen</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>Biodiesel</td>
<td>20</td>
<td>Laden</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>ULDS</td>
<td>20</td>
<td>Laden</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>ULDS</td>
<td>20</td>
<td>Unladen</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>ULDS</td>
<td>70</td>
<td>Unladen</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>ULDS</td>
<td>20</td>
<td>Unladen</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>Biodiesel</td>
<td>20</td>
<td>Unladen</td>
</tr>
<tr>
<td>11</td>
<td>2</td>
<td>Biodiesel</td>
<td>70</td>
<td>Unladen</td>
</tr>
<tr>
<td>12</td>
<td>2</td>
<td>Biodiesel</td>
<td>70</td>
<td>Laden</td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>ULDS</td>
<td>70</td>
<td>Laden</td>
</tr>
<tr>
<td>14</td>
<td>2</td>
<td>ULDS</td>
<td>70</td>
<td>Unladen</td>
</tr>
</tbody>
</table>

Notes: *Laden=90% Gross Vehicle Weight **Unladen=Vehicle Weight + 150 lbs

3.4 RESULTS

A summary of the emissions results averaged over each of the three driving cycles are shown in Table 3.2. The results showed that Vehicle 1 had generally higher PM emissions than Vehicle 2. Each of the Vehicle 1 drive cycles for all fuel, temperature and load combinations exceeded the EU standard for particle number of 9.65E11; however, the results of these tests were not directly comparable to the EU standards based on differences in drive cycle and measurement method. Both vehicles did meet the US and EU PM mass standards of 8 mg/mile and 10 mg/bhp-hr respectively, although, as with the particle number comparison, drive cycles were not directly comparable. Since regenerations had an influence
on emissions, results with and without regenerations were differentiated in this paper as “normal” (no regeneration) and “regeneration.” The active regenerations always occurred during the UDDS cycle. Initially, data for the CSLT, UDDS and the WSLT cycles were removed on the day the regeneration occurred. Further data analysis revealed that PM emissions were most affected for the CSLT cycle the day after the regeneration. Therefore, analysis for the “normal” operation represents data with removal of the UDDS and WSLT cycles the day of the regeneration event and for the CSLT on the day after the event. Vehicle 1 had an active regeneration for each of the testing conditions. Vehicle 2 had an active regeneration only once during the testing.
Table 3.2 Summary of average emission rates for each ambient temperature, fuel, load and drive cycle condition tested.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Temperature</th>
<th>Fuel</th>
<th>Load</th>
<th>Test Cycle</th>
<th>PM Count (#/mile)</th>
<th>BC (mg/mile)</th>
<th>PM Mass (mg/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle 1</td>
<td>70F</td>
<td>ULSD</td>
<td>Laden</td>
<td>CSLT</td>
<td>6.15E+12</td>
<td>1.1</td>
<td>3.48</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>UDDS</td>
<td>5.62E+12</td>
<td>1.8</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WSLT</td>
<td>6.26E+12</td>
<td>1.2</td>
<td>BDL*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unladen</td>
<td>CSLT</td>
<td>UDDS</td>
<td>7.24E+12</td>
<td>1.7</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unladen</td>
<td>CSLT</td>
<td>WSLT</td>
<td>5.68E+12</td>
<td>2.1</td>
<td>2.24</td>
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<td></td>
<td></td>
<td>Unladen</td>
<td>CSLT</td>
<td>UDDS</td>
<td>6.79E+12</td>
<td>1.6</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unladen</td>
<td>CSLT</td>
<td>WSLT</td>
<td>6.26E+12</td>
<td>1.2</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B20</td>
<td>Laden</td>
<td>CSLT</td>
<td>6.78E+12</td>
<td>0.9</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B20</td>
<td>Laden</td>
<td>UDDS</td>
<td>4.82E+12</td>
<td>1.2</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B20</td>
<td>Laden</td>
<td>WSLT</td>
<td>5.73E+12</td>
<td>1.0</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B20</td>
<td>Unladen</td>
<td>CSLT</td>
<td>5.62E+12</td>
<td>0.9</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B20</td>
<td>Unladen</td>
<td>UDDS</td>
<td>4.29E+12</td>
<td>1.2</td>
<td>1.36</td>
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<tr>
<td></td>
<td></td>
<td>B20</td>
<td>Unladen</td>
<td>WSLT</td>
<td>5.32E+12</td>
<td>1.0</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70F</td>
<td>ULSD</td>
<td>CSLT</td>
<td>1.08E+13</td>
<td>2.3</td>
<td>1.78</td>
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<td>70F</td>
<td>ULSD</td>
<td>UDDS</td>
<td>3.86E+12</td>
<td>0.7</td>
<td>0.41</td>
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<td>CSLT</td>
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<td>2.1</td>
<td>BDL</td>
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<td></td>
<td></td>
<td>20F</td>
<td>ULSD</td>
<td>UDDS</td>
<td>4.05E+12</td>
<td>0.8</td>
<td>0.74</td>
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<td></td>
<td></td>
<td>20F</td>
<td>ULSD</td>
<td>WSLT</td>
<td>5.55E+12</td>
<td>1.1</td>
<td>1.88</td>
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<td></td>
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<td>20F</td>
<td>B20</td>
<td>CSLT</td>
<td>9.71E+12</td>
<td>1.5</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
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<td>20F</td>
<td>B20</td>
<td>UDDS</td>
<td>3.32E+12</td>
<td>0.5</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20F</td>
<td>B20</td>
<td>WSLT</td>
<td>5.07E+12</td>
<td>0.8</td>
<td>BDL</td>
</tr>
<tr>
<td>Vehicle 2</td>
<td>70F</td>
<td>ULSD</td>
<td>Unladen</td>
<td>CSLT</td>
<td>2.25E+11</td>
<td>BDL</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70F</td>
<td>B20</td>
<td>CSLT</td>
<td>2.72E+11</td>
<td>BDL</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20F</td>
<td>ULSD</td>
<td>CSLT</td>
<td>2.99E+11</td>
<td>BDL</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20F</td>
<td>B20</td>
<td>CSLT</td>
<td>2.40E+11</td>
<td>BDL</td>
<td>BDL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>* Below Detectable Limit</td>
<td>Numbers reported without the effects of the regeneration</td>
<td></td>
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</tr>
</tbody>
</table>

Figures 3.2 and 3.3 provide comparisons of emissions results for BC and total PM number under the varying test drive cycles and conditions of fuel, temperature, and load for each vehicle separately. For these figures, the bars represent the maximum and minimum
emission rates, with the marker showing the average of the three runs. Figures 3.2a and 3.3a highlight the wide range in emissions during the vehicle cold start. Higher emissions occurred for both BC and PM number on the CSLT cycle on days after a regeneration event. Removing the data for the CSLT the day after the regeneration provided more consistent results as shown in Figures 3.2b and 3.3b. The UDDS was the only test cycle of the three that operated above 30 miles per hour (mph) and had the highest acceleration rates. An on-road study of nanoparticles emissions near highways in the Minneapolis area was completed (Kittelson et al., 2003). It was reported that elevated PM number concentrations were observed with higher vehicle speeds. The authors attributed these increased emissions to higher engine load, exhaust temperature, exhaust flow, and transient operations, although the dependence was stronger for spark ignition engines than diesel engines (Kittelson et al., 2003). The UDDS showed higher BC and PM number emission rates for the 70°F temperature compared to the 20°F. The relationship between higher engine speeds, exhaust temperature and flow, increased transient conditions and PM emissions could possibly attribute to why higher ambient temperatures produced higher PM emissions during the UDDS cycle compared with the CSLT and WSLT. However, it is not likely that increased ambient temperatures lead to increased particle count that was seen between 20°F and 70°F in the UDDS. This indicates that the DPF could possibly have a micro-imperfection or a small crack that could expand and contract with temperature. Thus, at the higher ambient temperature there are more particles allowed to get through the DPF when compared to the lower ambient temperature. The B20 produced lower PM emissions than the ULSD for each of the temperatures and drive cycles, which is consistent with other studies cited (EPA,
Comparing the CSLT to the WSLT revealed an increase in PM emissions for cold start conditions during colder ambient temperatures, with increases of two to three fold depending on the fuel and load conditions. Although the extent of this increase was not as elevated as increases seen for gasoline-powered passenger cars (Nam et al., 2010), these results indicate that increased cold start emissions do occur with the use of a DPF under colder temperature conditions, although this effect did not seem to be significant at the warmer temperature.

Results for Vehicle 2 shown in Figure 3.4 indicate similarities and differences with Vehicle 1. For Vehicle 2, only one regeneration event occurred during the study; however, this event had a significant impact on the CSLT PM emission rates the day after as shown by comparing Figures 3.4a and 3.4b, similar to the impact on the Vehicle 1. Aethalometer data for Vehicle 2 was below detection limits (0.1 µg/m³ reported by AethLabs) during the testing of normal driving conditions, with measurable levels only occurring during the regeneration event. Vehicle 2 did not emit significantly higher rates of PM during the cold start/cold temperature tests compared with Vehicle 1. In addition, Vehicle 2 did not experience higher PM emissions during high speed/high acceleration at higher ambient temperatures.

Figures 3.5 and 3.6 show the particle size distribution for Vehicle 1 and Vehicle 2 measured by the EEPS. Like the previously discussed data, the UDDS and the WSLT show more consistent results across the tested conditions than the CSLT for both vehicles. In general, higher PM number emissions occurred at 20°F, with a larger number in the UFP size bins. This increase in UFP may be a result of increased particle formation due to cold temperatures from decreased combustion efficiency, enhanced particle nucleation, and
decreased particle evaporation, as well as reduced efficiency of the DPF at cold start/cold temperature conditions. Previous studies identified that measured particle size distributions emitted from diesel engines did not include vehicles equipped with a DPF. Figure 3.5a shows that when comparing the fuels, the B20 produces a higher number of diameter particles than the ULSD. This is consistent with (Heikkila J., 2009) that stated biodiesel combustion emits less accumulation mode PM (0.1 µm < particle size < 2.5 µm) and has an increase in UFP particles, specifically particles less than 50 nm. This study was done with a rapeseed methyl ester on a heavy-duty diesel engine without a DPF. The UDDS and the WSLT results suggest that the fuel and load did not have a significant effect on the PM number. The results show that for UDDS and WSLT operations at 70°F, more UFP were generated than at 20°F. The majority of these particles ranged from 50 to 100 nm in diameter. For the CSLT, more particles were present around 10-20 nm in diameter, with higher overall particle emissions as well. In addition, the CSLT cycle suggested that vehicle load and ULSD also produced higher particle numbers than the other operating conditions. Cold ambient temperatures also produced higher particle numbers in the 10-20 nm size range, especially during the CSLT. This effect might be enhanced by biodiesel use as observed by (Buono D. Prati M.V., 2012), who observed that biodiesel reduced the temperature at which particulates were burned off in the DPF, leading to more PM emissions during passive regeneration.

When looking at the EEPS data for Vehicle 2 (Figure 3.6) only particles less than 14 nm were observed. Since primary BC particles are typically in the size range of 30 to 50 nm (Clague A.D.H. Wang T.K., Peng J.C.M., 1999), the particles measured in this study were
likely nucleated hydrocarbons and sulfate, explaining the lack of BC measured by the aethalometer for this vehicle.

The size distribution pattern for Vehicle 2 did not change with temperature, fuel or load. Increased numbers of particles occurred in the size bin between 9.31 nm and 10.8 nm. For each of the CSLT, UDDS and WSLT cycles, the largest amount of particles were from 20°F with ULSD fuel, followed by the 70°F B20, then the 20°F B20, with the 70°F B20 having the lowest numbers at these particle sizes. The CSLT, Figure 2.6a, shows the case where the active regeneration occurred during the 70°F B20 case, emitting particles between 25.5 and 143.3 nm.

The differing results between Vehicle 1 and Vehicle 2 suggest that the vehicle technology had a major impact on PM emissions. The primary technological difference between the two vehicles’ aftertreatment systems was the NOₓ reduction technology, with Vehicle 1 having a NOₓ absorber and Vehicle 2 an SCR with urea injection for NOₓ control. The regeneration frequency was also dramatically different between the vehicles, highlighted by regenerations taking place for each test condition by Vehicle 1 and only one regeneration over all of the test conditions for Vehicle 2. Although the frequency of regenerations differed greatly between vehicles, both vehicles showed an increase in particles during the CSLT the day after the regeneration event.
Figure 3.2 Aethalometer results for the Vehicle 1 (a) with the CSLT, UDDS and WSLT cycles removed the day of the regeneration event (b) with the UDDS and WSLT cycles removed the day of the regeneration event and the CSLT removed the day after the regeneration event. Note the scales are different in each figure.
Figure 3.3 EEPS results for the Vehicle 1 (a) with the CSLT, UDDS and WSLT cycles removed the day of the regeneration event (b) with the UDDS and WSLT cycles removed the day of the regeneration event and the CSLT removed the day after the regeneration event.

Note the scales are different in each figure.
Figure 3.4 EEPS results for the Vehicle 2 unladen (a) with the CSLT, UDDS and WSLT cycles removed the day of the regeneration event (b) with the UDDS and WSLT cycles removed the day of the regeneration event and the CSLT removed the day after the regeneration event. Note the scales are different in each figure.
Figure 3.5 EEPS size distribution results for the Vehicle 1 (a) CSLT (b) UDDS and (c) WSLT all with the CSLT, UDDS and WSLT cycles removed the day of the regeneration event.
**Figure 3.6** EEPS size distribution results for the Vehicle 2 unladen (a) CSLT, (b) UDDS, and (c) WSLT all with the CSLT, UDDS and WSLT cycles removed the day of the regeneration event.
(c)
3.5 CONCLUSIONS

Two diesel trucks underwent emissions testing to identify how vehicle technology, DPF aftertreatment, vehicle load, ambient temperature, fuel, and driving activity affect PM emissions. For one vehicle, PM emissions increased during cold starts under colder ambient temperature conditions, with BC values two- to three-times higher compared to warm driving operations. Colder ambient temperatures also increased the number of particles in the 10-20 nm size fraction. This vehicle also experienced PM number emissions increasing during warmer ambient temperatures and high speed and acceleration driving activity for particles in the 80-100 nm size range. Slight differences were observed under varying load conditions and fuel type, but these were not consistent across all operating conditions. Differences in emissions were most pronounced between the two vehicle technologies tested. The differences in vehicle aftertreatment technology seemed to significantly impact PM emissions, with the presence of a NOx absorber having higher emissions than a vehicle using SCR with urea injection for NOx control.

The average percentage change for the CSLT, UDDS and WSLT on Vehicle 1 show a decrease in particle count when going from ULSD to B20, with an approximately 13% average decrease in PM number and an approximately 27% decrease in BC. The average particle count for the UDDS shows an approximately 27% decrease when going from 70°F to 20°F. The day after a regeneration occurred, both Vehicle 1 and Vehicle 2 show a significant increase in particles for the CSLT, approximately 93% and 1380% for PM number emissions from Vehicle 1 and Vehicle 2 respectively. Vehicle 2 did not show any measurable BC under normal operation.
4 EFFECTS OF DIESEL PARTICULATE FILTER REGENERATION ON PARTICULATE EMISSIONS

4.1 ABSTRACT

Particle measurements were taken from the exhaust of two medium heavy-duty diesel trucks equipped with a diesel particulate filter (DPF). The operation was done on a chassis dynamometer with three test cycles, a cold start with low transients (CSLT), the federal heavy-duty urban dynamometer driving schedule (UDDS), and a warm start with low transients (WSLT). Factors varied during the tests included: ambient temperature (70°F and 20°F), fuel (ultra-low sulfur diesel (ULSD), and biodiesel (B20)) and operating load (a heavy and light weight). Particulate matter (PM) and black carbon (BC) were measured second-by-second using an engine exhaust particle sizer (EEPS) and an aethalometer, respectively. Active DPF regenerations occurred during the UDDS cycle for both trucks. An analysis of variance (ANOVA) showed the DPF regeneration impacted the PM emissions during and after the DPF regeneration. One truck that included a NO\textsubscript{x} adsorber catalyst (NAC) in the aftertreatment system showed a decrease in PM emissions during the regeneration and a significant increase in PM emissions after a DPF regeneration, both changes occurring to accumulation mode particles. The second truck, which used a selective catalytic reduction (SCR) with urea in the aftertreatment system for NO\textsubscript{x} control, showed an increase of three orders of magnitude of PM emissions, all in the nucleation mode during the DPF regeneration. This truck also showed an increase in both nucleation and accumulation mode particles after a DPF regeneration. Both vehicles showed an increase in particle number count from the WSLT to the CSLT post-regeneration which was 38% for the first truck and 113% for the second truck while still maintaining PM emissions levels below the standards.
4.2 INTRODUCTION

Health concerns have been attributed to human exposure to airborne particles from diesel engine exhaust including acute irritant effects, respiratory symptoms, immunologic effects, lung inflammatory effects, cardiovascular health responses and cancer (Hesterberg et al., 2012) (C. A. et al. Pope III et al., 2002) (Thurston et al., 2009)(C. A. Pope III et al., 1991). To meet the United States (US) and European Union (EU) emission standards, manufacturers equip on-road, heavy-duty diesel vehicles with a diesel particulate filter (DPF). The US and EU standards have PM mass-based limits. In addition, the EU has implemented particle number standards.

A DPF forces exhaust gas through alternately plugged channels with porous ceramic walls. The collection efficiency of the DPF depends on the size of the wall thickness and the mean pore diameter of the material. The wall flow DPFs can have a collection efficiency of 99% (Schenk, Mcdonald, & Laroo, 2001). The efficiency of the DPF is dependent on the amount of sulfur present in the fuel (United States EPA, 2000). The efficiency is also influenced by factors such as the size of the DPF, the exhaust gas flow rate and the amount of soot loading on the walls. A popular material for DPFs is cordierite. Another popular filter material is silicon carbide. Solid particles build up along the channel walls and form a layer of soot that continuously loads the DPF as the engine is operated. The DPF must be cleaned before filter loading causes enough back pressure to significantly impact engine operation. This cleaning process, called regeneration, can be active or passive. Active regeneration typically requires temperatures greater than 1100°F, the soot accumulated gets burned off by exothermic reactions. Engine parameters are changed to reach regeneration conditions. These
changes which are not detectable by the driver, can be done by retarding the fuel injection and having a post-injection. During an active regeneration the exhaust temperature is increased to increase the catalyst temperature. When the temperature is high enough soot combustion will start at the inlet of the DPF and the adjacent soot will ignite spontaneously (Neeft et al., 1996). The amount of soot collected before an active regeneration must not be too high or too low in order to keep the engine operation efficient and the DPF from being damaged. Passive regeneration occurs when operating conditions are ideal and the engine operation is not modified. During passive regeneration soot oxidation is done with NO\textsubscript{2} which only requires temperatures of 500°F compared to the soot oxidation strategy during an active regeneration that uses O\textsubscript{2} and requires temperatures of at least 950°F (Gorsmann, 2005). An active DPF regeneration is called a DPF regeneration unless otherwise specified.

The DPF is used to filter particulate matter (PM). PM from diesel engines can be separated into volatile and solid particles. These two different kinds of particles usually form separate modes in the number size distribution that are referred to as nucleation mode and accumulation mode particles. The nucleation mode particles are typically less than 20 to 25 nm in diameter and the accumulation mode particles are between 20 to 25 nm and 1000 nm in diameter (Kittelson, 1997). A study done on a light-duty vehicle equipped with a DPF showed that the majority of particle emissions were found in the first five minutes of the cold engine start driving cycle. The most significant amount of nucleation mode particles were observed during DPF regeneration (Mathis, Mohr, & Forss, 2004). Emissions from a DPF equipped EURO-4 diesel vehicle was studied in a test laboratory and on a high-speed test track using an engine exhaust particle sizer (EEPS) (Bergmann, Kirchner, Vogt, & Benter,
2009). The results reported that during the DPF regeneration the total PM number emissions of nucleation mode particles were 3-4 orders of magnitude higher compared to those emitted at the same speed without regeneration. The majority of the particles emitted during the DPF regeneration were found to be volatile. The levels of the accumulation mode particles were the same during regeneration. Note that DPF systems used for EURO-4 were typically not catalyzed, therefore it is unclear if comparisons can be made between emissions from EURO-4 vehicles and the vehicles used in this study.

While the DPF substantially lowers PM mass emissions, the effect on particle number during and after a regeneration is not well understood. While adding the DPF to a vehicle reduces total PM emissions, there is uncertainty about the impact of the DPF (i) before, during, and after, a regeneration, and (ii) during varying ambient conditions and different fuels. To address these uncertainties, this paper explores how PM emissions are affected from heavy-duty vehicles equipped with a DPF under varying driving schemes and ambient temperature conditions, and fuels.

4.3 EXPERIMENTAL METHODS

This study tested two medium heavy-duty diesel trucks in a temperature controlled chassis dynamometer. Two temperatures, (70°F and 20°F), two fuels, (ULSD and a 20% biodiesel blend (B20)), and two loads (laden (90% gross vehicle weight rating) and unladen (vehicle weight plus 150 pounds)) were tested on both vehicles. Vehicle 1 is a 2011 class 2b truck (gross vehicle weight rating (GVWR) of 8,501 to 10,000 lbs). It had a 6.7 L Cummins engine and started with 22,062 miles. This vehicle was chassis dynamometer certified. Vehicle 2 is a 2011 class 5 truck (GVWR of 16,001 to 19,500 lbs) with a 6.7L Powerstroke
engine with 2,693 miles. This testing was conducted using a chassis dynamometer, although this engine family was originally subject to heavy-duty diesel engine (HDDE) dynamometer emissions certification rather than chassis dynamometer certification. There are differences in emissions compliance provisions between engine and chassis dynamometer certified HDDEs. Complete details of this test set up and procedure are provided in Chapter 3.

The test cycle began with a 319 second drive cycle, a cold start with low transients (CSLT), the second drive cycle lasted 1059 seconds, the federal heavy-duty urban dynamometer driving schedule (UDDS), and the third drive cycle was the same as the CSLT with the exception of a warm engine, a warm start with low transients (WSLT). The test cycle included a 20-minute vehicle soak at the ambient testing temperature after the CSLT and the UDDS. After a complete test cycle, the engine was shut down to begin the minimum of 12-hour soak at ambient testing temperature.

To ensure consistent data, three tests with all three drive cycles were conducted for each of the combinations of fuel, temperature, load, and vehicle. Two instruments collected second-by-second data which include an EEPS 3090 (TSI, Shoreview, Minnesota, USA) and an AE-51 Micro Aethalometer (AethLabs, San Francisco, California, USA). The EEPS measures PM count and size between 5.6 and 560 nm. The MicroAethalometer AE-51 measures black carbon (BC). Only one test was run each day. If a DPF regeneration occurred during a test, a fourth test was conducted for that fuel, temperature, load, and vehicle combination. Each condition on Vehicle 1 had a DPF regeneration which always happened during the UDDS cycle. Vehicle 2 only had one condition where a DPF regeneration occurred, which also happened during the UDDS test cycle.
4.4 AFTERTREATMENT SYSTEMS AND DPF REGENERATIONS

The Vehicle 1 aftertreatment system included a close coupled oxidation catalyst, a NO\textsubscript{x} adsorber catalyst (NAC), and a DPF (NGK Automotive Ceramics, U.S.A, Inc.). The 2.1 L close coupled catalyst is made by Emitec, and takes the oxygen, hydrocarbons, and carbon monoxide from the exhaust and converts it to water and carbon dioxide. The NAC turns NO\textsubscript{x} into barium nitrate which sticks to the surface of the substrate inside the adsorber. Although the sulfur content in diesel fuel is being reduced, the amount that is present gets oxidized in either the diesel oxidation catalyst or the NAC. The sulfates reduce the storage capacity for the NO\textsubscript{x} and regeneration for sulfate requires temperatures in excess of 1100\textdegree F (Gill, Blakeman, Twigg, & Walker, 2004). When the surface becomes saturated, a NAC regeneration is required. The engine switches to a fuel rich condition, which can impact the PM emissions. This releases the barium nitrate and turns it into nitrogen and water vapor as it reacts with the precious metals. The cycle that the barium undergoes is carbonate to nitrate to carbonate which has been shown experimentally in the study (Li et al., 2001).

There was no dash board display stating that the aftertreatment was undergoing a DPF regeneration. Additionally, DPF regeneration did not occur after a specific amount of time or mileage, increasing the difficulty of prediction. The amount of soot in grams was monitored during operation with an AutoEnginuity reader/logger (AutoEnginuity L.L.C., Mesa, Arizona, USA), which confirmed that a regeneration was happening by measuring a soot decrease. The regeneration was also determined by monitoring the vehicle’s engine control module (ECM) for exhaust gas temperature that would increase to 1100\textdegree F and above.
compared with normal operating temperatures of 300°F to 500°F. Even with these measures, there was no clear indicator of when regeneration was first beginning.

The aftertreatment system in Vehicle 2 included an oxidation catalyst, a selective catalytic reduction (SCR) system for NO\textsubscript{x} control (which required urea injection), and a DPF. A regeneration event happened only once during testing while operating at 70°F with B20 and the unladen load condition, see Table 4.1 for the conditions where the regeneration occurred. The regeneration was determined by the same parameters as used for Vehicle 1. Vehicle 2 also did not have a dash board indicating the DPF regeneration. In addition to the difference in the frequency of the DPF regeneration for the vehicles, the SCR in Vehicle 2 does not have a separate regeneration for NO\textsubscript{x} where the NAC would regenerate at 70°F during every UDDS except when a DPF regeneration occurred in Vehicle 1.

Table 4.1 Vehicle conditions where DPF regenerations occurred

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Fuel</th>
<th>Ambient Temperature (°F)</th>
<th>Simulated Load</th>
<th>Number of Normal Operation Test Cycles</th>
<th>Number of DPF Regeneration during UDDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ULDS</td>
<td>70</td>
<td>Laden*</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Biodiesel</td>
<td>70</td>
<td>Laden</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Biodiesel</td>
<td>70</td>
<td>Unladen**</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Biodiesel</td>
<td>20</td>
<td>Unladen</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Biodiesel</td>
<td>20</td>
<td>Laden</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>ULDS</td>
<td>20</td>
<td>Laden</td>
<td>3</td>
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<tr>
<td></td>
<td>ULDS</td>
<td>20</td>
<td>Unladen</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>ULDS</td>
<td>70</td>
<td>Unladen</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>ULDS</td>
<td>20</td>
<td>Unladen</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Biodiesel</td>
<td>20</td>
<td>Unladen</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Biodiesel</td>
<td>70</td>
<td>Unladen</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>ULDS</td>
<td>70</td>
<td>Unladen</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

Notes: *Laden=90% Gross Vehicle Weight **Unladen=Vehicle Weight + 150 lbs
4.5 RESULTS AND DISCUSSION

4.5.1 Significance of Impact of DPF Regeneration

To gain a better understanding of changes to PM emissions it is necessary to understand the impact of DPF regenerations. A one way analysis of variance (ANOVA) was used to evaluate the emissions values that were collected from the EEPS on Vehicle 1. The second-by-second PM emissions values for each of the CSLT, UDDS, and WSLT were summed over the test time. For example, on the UDDS, the 1059 emission values (that were taken for the 1059 second test) were added for the 32 different UDDS tests (8 different test conditions and each condition was run 4 times). For the 32 values, 24 of these were considered normal operation values and 8 of these were regeneration values. The reason Vehicle 1 was chosen for the ANOVA was because a regeneration occurred for each of the conditions, and this was not the case for Vehicle 2. A separate analysis was completed for the CSLT, UDDS and the WSLT. Figure 4.1 shows the boxplot of the ANOVA.

For the data collected on the day the regeneration occurred, the CLST is called pre-regeneration, the UDDS is called regeneration (since all regenerations took place during this cycle) and the WSLT immediately following that UDDS is called post-regeneration. Initially, an ANOVA was done for the CSLT for normal operation and pre-regeneration. This would be the CSLT run prior to the UDDS run that included the regeneration. A p-value is the estimated probability of discarding the null hypothesis, where the null hypothesis is the probability of no difference between the factors being tested. For example, the probability that there is no difference in emissions when comparing normal operation versus DPF regeneration is being tested. If the value is less than 0.05, this suggests that the null
hypothesis is not true and that there is a statically significant difference between the two factors. The p-value for pre-regeneration and normal operation is 0.17, suggesting that there was not a significant difference in PM emissions during this cycle right before a regeneration (pre-regeneration). Realizing that the CSLT pre-regeneration was not impacted, an ANOVA was completed using the CSLT PM emissions values for normal operation and the day after the regeneration. This resulted in a p-value of 0.001. In addition to the CSLT the day after a regeneration having more PM emissions than normal operation, there is also more variance in the data, shown in Figure 4.1a. The p-value for the UDDS and the WSLT were both nearly zero (p < 1.27E-7), with the WSLT being the smallest. This clearly shows that the DPF regeneration impacts PM emissions during and after the event. The UDDS PM emissions during the regeneration were not only lower but had a smaller variance than the normal operation, shown in Figure 4.1b. The WSLT has increased PM emissions during a post-regeneration run, while the variance is not significantly different, as shown in Figure 4.1c.
Figure 4.1 ANOVA plots with EEPS data from Vehicle 1 for the (a) CSLT, (b) UDDS, and (c) WSLT. The center mark is the median, the edges of the box are the 25\textsuperscript{th} and the 75\textsuperscript{th} percentiles, the whiskers spread to the most extreme data values that are not considered outliers. All of the data used fell within these limits. The outliers are defined as 1.5 times the interquartile range away from the top or bottom of the box.
Normal Operation vs. Regeneration:

### CSLT

- **Normal Operation:**
  - Total Concentration: $1 \times 10^7$

- **Day After Regeneration:**
  - Total Concentration: $5 \times 10^7$

### UDDS

- **Normal Operation:**
  - Total Concentration: $2 \times 10^7$

- **Regeneration:**
  - Total Concentration: $6 \times 10^7$
Normal Operation

Post Regeneration

Total Concentration (#/cm³)

WSLT

x 10⁷
4.5.2 Vehicle 1 Results

4.5.2.1 UDDS Results
The DPF regenerations always occurred during the UDDS cycle. Figure 4.2 shows the UDDS and when the DPF regenerations occurred. The regeneration would not start until at least 500 seconds into the cycle during the highest acceleration, Figure 4.2 b. This indicated the exhaust needed to be at high temperature before the regeneration occurred. In the EEPS data in Figure 4.2 a and b, between 550 and 800 seconds, there is a decrease in PM emissions during regeneration, which occurred for all conditions. This decrease is more pronounced for the tests at 70°F than at 20°F. A possible explanation for the decrease in PM emissions during regeneration at 70°F is the lack of NAC regeneration during the DPF regeneration. Recall that a NAC regeneration occurred during the UDDS at 70°F for all cases except when a DPF regeneration occurred and that a NAC regeneration requires additional fuel injection. This, however, does not provide an explanation for the decrease seen at 20°F since NAC regeneration did not occur at all at 20°F. It is seen from Figure 4.2 there is a difference in PM emissions for 20°F and 70°F. The aethalometer results in Figure 4.2 show the DPF regeneration had the same impact on BC as it does for PM emissions. The particle size distribution shows a decrease in UDDS PM emissions in the accumulation mode particles (see Figure 4.3). This indicated that the accumulation mode particles are influenced by DPF regeneration and the nucleation mode particles are not.
Figure 4.2 Second-by-second results for Vehicle 1 during the UDDS cycle for laden (L), unladen (UL), ULSD, B20, 70°F and 20°F for (a) EEPS data averaged without a DPF regeneration (b) EEPS data during a DPF regeneration (c) aethalometer data averaged without a DPF regeneration (d) aethalometer data during a DPF regeneration.
(a)

(b)

Spike goes to 9.8E6 #/cm³

DPF Regeneration
Figure 4.3 EEPS average size distributions for Vehicle 1 during the UDDS cycle averaged for normal operation non-regenerations cycles and for DPF regeneration for laden (L) and unladen (UL), 70°F and 20°F (a) with ULSD (b) with B20.
4.5.2.2 **WSLT Results**

The WSLT was run 20 minutes after completing the UDDS. During the 20 minute soak, the vehicle remained at test temperature with the engine off. The WSLT results show that after the regeneration, referred to as post-regeneration, there was a sizeable increase in the accumulation mode particles, as shown in [Figure 4.4](#), which is consistent with (Campbell, Peckham, Symonds, Parkinson, & Finch, 2006). This may be attributed to a clean DPF because when the DPF is cleaned the efficiency decreases. The biggest contribution to the increase in emissions particles occurs at the first major acceleration within the first 50 seconds of the WSLT (see [Figure 4.5](#)). The DPF regeneration had the same impact on BC emissions as particle number. The average increase in PM emissions between normal operation and post-regeneration during the WSLT is approximately 108%. 


Figure 4.4 EEPS average size distributions for Vehicle 1 during the WSLT cycle averaged for normal operation cycles and for cycles right after a DPF regeneration for laden (L) and unladen (UL), 70°F and 20°F (a) with ULSD (b) with B20.
Figure 4.5 Second-by-second results for Vehicle 1 during the WSLT cycle for laden (L), unladen (UL), ULSD, B20, 70°F and 20°F for (a) EEPS data averaged without post-regeneration cycle (b) EEPS data for cycle right after a regeneration (post-regeneration) (c) aethalometer data averaged without post-regeneration cycle (d) aethalometer data for cycle right after a regeneration (post-regeneration). Note the scales are different.
4.5.2.3 CSLT Results

To understand the impact of a DPF regeneration, it is important to consider the PM emissions when the DPF walls are clean, just after it has gone through a regeneration (post-regeneration), after a layer of soot has formed on the walls (normal operation) and after multiple layers of soot have formed, immediately prior to a regeneration (pre-regeneration). Figure 4.6 makes this comparison for Vehicle 1 with CSLT PM emissions for these three cases. The general trend is the accumulation mode particles increased post-regeneration and slightly decreased pre-regeneration, with PM emission levels for normal operation in between. During pre-regeneration the DPF is presumed to have the greatest amount of soot loading along the filter walls. The effect is an increase in DPF efficiency and reduction of PM emissions. The amount of soot present in the DPF appeared to have more of an impact on particles in the accumulation mode than the nucleation mode, as shown in Figure 4.6. This figure also showed a large increase in PM emission for accumulation mode particles post-regeneration, when the DPF has just been cleaned. The average increase between normal operation and post-regeneration is approximately 93% as reported in Chapter 3. This effect is more evident with ULSD than with B20. A difference between the CSLT and UDDS is that during the regeneration there was a decrease in PM emissions seen in UDDS and the PM emissions increased the day after regeneration for the CSLT. This could be attributed to the DPF being cleaned which allowed more particles to pass through because the efficiency of the DPF is dependent on the soot layer on the walls.

The substantial increase in PM emissions is seen at the first major acceleration in the speed trace, shown in Figure 4.7 a and b. After about 150 seconds into the cycle, there is not
a significant difference between the normal operation and post-regeneration operation. This is consistent with a study done on a passenger diesel vehicle equipped with a DPF, stating that accumulation mode increase lasted for approximately 200 seconds (Campbell et al., 2006). Aethalometer data in Figure 4.7 c and d show the same trend as the EEPS data. Engine acceleration after an engine cold start with a regenerated DPF results in an increase in PM emissions. The particle number count in the CSLT post-regeneration is greater than the particle number count in the WSLT post-regeneration, the increase is on average 38% greater.
Figure 4.6 EEPS average size distributions for Vehicle 1 during the CSLT cycle right before a regeneration (pre-regen) the day after a regeneration (post-regen) and average of other days of operation (normal operation) for laden (L) and unladen (UL), 70°F and 20°F (a) with ULSD (b) with B20.
**Figure 4.7** Second-by-second results for Vehicle 1 during the CSLT cycle for laden (L), unladen (UL), ULSD, B20, 70°F and 20°F for (a) EEPS data averaged without the day after a regeneration (b) EEPS data the day after a regeneration (c) aethalometer data averaged without the day after a regeneration (d) aethalometer data the day after a regeneration. Note the scales are different.
4.5.3 Vehicle 2 Results

Vehicle 2 had a regeneration event during one condition only: at an ambient temperature of 70°F, B20 fuel and unladen operation. While data collection was the same on both vehicles, using the EEPS and aethalometer, the amount of BC in the exhaust was below the detectable limit of the instrument (0.1 µg/m³) for Vehicle 2. Therefore, only the EEPS results for the one condition where the regeneration occurred is reported. Size distribution data for Vehicle 1 and Vehicle 2 are shown in Figure 4.8.

Figure 4.8a shows that during the actual regeneration, there was a large increase in the nucleation mode particles. This is not consistent with the results from Vehicle 1. During the regeneration on Vehicle 1 there was a decrease in the PM emissions in the accumulation mode particles and the nucleation mode particles were not significantly impacted. A possible explanation for the lack of decrease in accumulation mode particles on Vehicle 2 is that Vehicle 2 had a trivial amount of accumulation particles during normal operation, meaning it would be difficult at best to know if accumulation particles decrease during DPF regeneration. The trend of increased nucleation mode particles seen in Vehicle 2 is consistent with other studies (Mathis et al., 2004) (Bergmann et al., 2009) (Beatrice, Iorio, Guido, & Napolitano, 2012) (Campbell et al., 2006). In these studies, the vehicles used were equipped with DPFs. None of the studies had additional NOx catalysts systems because the vehicles used were either EURO-5 or earlier. NOx catalyst systems are not used in Europe prior to EURO-6. A possible explanation for the increase in nucleation mode particles proposed by (Mathis et al., 2004) is that, at increased exhaust temperatures, the volatile compounds could desorb from the exhaust system and dilution tunnel and be involved in the formation of
nucleation mode particles. Depending on the washcoat used in the aftertreatment, a significant amount of sulfates can be stored in the DPF (Kittelson et al., 2006) (Herner et al., 2011). Sulfate release takes place during high temperatures which are experienced during DPF regeneration. Therefore the increase in the nucleation mode particles could be the release of the stored sulfate. There is a lack of excess of oxygen for semivolatile organic compounds (SVOC) oxidation during a DPF regeneration, therefore, the SVOCs could be the contributor to the increase particles in the nucleation mode. While it is known that dilution ratio, temperature and residence time have effects on the nucleation of particles, it is noteworthy that the nucleation mode particles show different trends for Vehicle 1 and 2 when other testing conditions were kept the same. A possible factor that may contribute to the difference between the two vehicles is the impact of the DPF catalyst. The details on what the catalysts are for the DPFs is unknown. If the DPFs had different catalysts, the reactions during the DPF regeneration may not be the same. The stoichiometry of the DPF regeneration could also be a contributor if it is different for the two vehicles. The exhaust temperature was reviewed for both vehicles during a DPF regeneration by looking at the ECM data. Both of the trucks reached maximum temperatures of approximately 1200°F. Another possible reason for the differences in the emissions during regeneration is the differences in the way the vehicles were certified. Vehicle 1 was chassis dynamometer certified and Vehicle 2 was engine dynamometer certified. The compliance requirement differences between engine and chassis dynamometer could drive a different engine calibration and emissions control system design between the two vehicles. The WSLT showed an increase in particles in both the nucleation and accumulation mode, for the run
immediately following the regeneration (post-regeneration) on Vehicle 2, Figure 4.8b there was an approximately 600% increase in particles between the normal operation and the WSLT post regeneration. Figure 4.8c shows a consistent trend with both vehicles. The day after the regeneration, there was an increase in particles in the accumulation mode, consistent with the study by (Campbell et al., 2006). The particles in the nucleation mode were not affected the day after a regeneration for either vehicle. The increase in particles for the post-regeneration in the CSLT is approximately 1380% for Vehicle 2 as reported in Chapter 3. There is an approximately 113% increase in particle number count when comparing the WSLT to the CSLT post-regeneration for Vehicle 2.
**Figure 4.8** EEPS size distribution results for Vehicle 2 and Vehicle 1 averaged normal operation data, unladen with B20 at 70°F (a) with the DPF regeneration run for the UDDS, (b) with the run immediately following the DPF regeneration, post-regeneration, for the WSLT and (c) with the run the day after a regeneration for the CSLT. Note the scales are different.
The second-by-second data on the CSLT for Vehicle 2 showed the same trend as Vehicle 1. There is an increase in PM emissions that occurs within the first 50 seconds of the cycle, Figure 4.9c. The regeneration on Vehicle 2 occurred a little later in the UDDS cycle starting around 700 seconds, Figure 4.9a. The WSLT for Vehicle 2 showed similar results as Vehicle 1 with an increase in particles within the first 50 seconds of the cycle, at the first significant acceleration, Figure 4.9b. While there were increases seen in PM emissions either during and/or after of the DPF regeneration, both vehicles stayed below the emissions standards, shown in Table 4.2.
**Figure 4.9** EEPS second-by-second results for Vehicle 2 averaged normal operation data, unladen with B20 at 70°F (a) with the regeneration run for the UDDS, (b) with the run immediately following the regeneration, post-regeneration, for the WSLT and (c) with the run the day after a regeneration for the CSLT.
(c)
4.6 CONCLUSION

The DPF regeneration had an impact on the PM and BC emissions not only during the DPF regeneration but also during vehicle operation following the regeneration. The DPF regeneration for both vehicles occurred only in the UDDS cycle, and initiated during the high acceleration/high speed portion of the test cycle which indicated that DPF regeneration required high exhaust temperatures. Vehicle 1 PM emissions were reduced during the DPF regeneration, while Vehicle 2 emissions increased which is more consistent with current DPF regeneration studies. Vehicle 2 emissions in the nucleation mode increased by 3 orders of magnitude during DPF regeneration.

The PM and BC emissions were elevated during vehicle operation over the next two test cycles conducted after the DPF regeneration while still staying below the PM emissions.
standards. The most significant increase occurred with the first engine acceleration of these test cycles. After the second test cycle (CSLT), PM emissions returned to values representing normal operations not affected by DPF regeneration. The CSLT showed PM emission differences for the different fuels with the B20 having lower PM emissions. For both vehicles, the CSLT produced the greatest PM emission values. The increase in particle number count from the WSLT to the CSLT post-regeneration for Vehicle 1 and 2 was 38% and 113%, respectively. Further research is required to confirm the reasons for increases in the nucleation mode particles for one vehicle and accumulation mode particles in the other and the influence of NOx control systems on PM emissions. Taking measurements with the EEPS before and after the aftertreatment, getting data on multiple DPF regenerations on Vehicle 2, and being able to control when the DPF regeneration occurred could provide insight into this research.
5 FUEL CONSUMPTION AND GASEOUS EMISSIONS

5.1 ABSTRACT

Two heavy-duty diesel trucks that were both equipped with a diesel particulate filter (DPF) and NO\textsubscript{x} control were tested in a temperature controlled chassis dynamometer. Vehicle 1 had a NO\textsubscript{x} adsorber catalyst (NAC) and Vehicle 2 had selective catalyst reduction (SCR) for NO\textsubscript{x} control. Nitrogen oxides (NO\textsubscript{x}), hydrocarbons (HC) and carbon monoxides (CO) emissions and fuel consumption data were collected during a test cycle that included a low transient cycle with a cold start (C SLT) and warm start (W SLT) and the federal heavy-duty urban dynamometer driving schedule (UDDS). A biodiesel blend (B20) and ultra-low sulfur diesel (ULSD) were tested at two ambient temperatures (20°F and 70°F) and two vehicle operating loads (heavy and light). Vehicle cold starts had the greatest impact on NO\textsubscript{x}, HC and CO emissions and fuel consumption with this impact more pronounced at the colder ambient temperature. Vehicle cold starts attributed for a loss in miles per gallon by 29% and 35% for Vehicle 1 and 2, respectively. The NO\textsubscript{x}, HC, and CO emissions increased between 62-330% for the vehicle cold start. DPF regeneration and ambient temperatures also increased fuel consumption and gaseous emissions.

5.2 INTRODUCTION

Diesel engines are preferred over gasoline engines for heavy-duty applications because of reliability, high torque, higher energy density, less maintenance and high fuel efficiency (MacLean & Lave, 2003). The United States Environmental Protection Agency (EPA) instituted regulations to be implemented in 2010 that required a diesel particulate filter (DPF) in order to maintain the level of allowed particulate matter (PM) in the exhaust of
diesel engines. The DPF requires regeneration, a clean out process that changes the engine operating conditions to increase exhaust temperatures. Typically this is done by adding a post fuel injection to increase the exhaust temperature to correspondingly increase the temperature of the catalyst in the DPF. The EPA has instituted regulations that limit the amount of nitrogen oxides (NO\textsubscript{x}) in the exhaust to 0.02 grams per brake-horsepower-hour (g/bhp-hr). Therefore, the aftertreatment includes a combination of DPF, NO\textsubscript{x} adsorber catalysts (NAC) or selective catalytic reduction (SCR), and SO\textsubscript{x} (sulfur oxides) traps. Sulfur poisons the catalysts used in the aftertreatment; therefore the efficiency of the aftertreatment depends on the amount of sulfur in the fuel (United States EPA, 2000). The use of alternative fuels, like biodiesel, can be used as renewable energy source and generally have lower sulfur content (depending on the base fuel).

Two popular methods of NO\textsubscript{x} control include a NAC and a SCR that uses urea injection. The NAC oxidizes the NO in the exhaust to NO\textsubscript{2} with a platinum catalyst during lean operations. NO\textsubscript{2} then reacts with barium carbonate and is converted into barium nitrate. After the barium carbonate is completely converted to barium nitrate a regeneration is required (Brijesh & Sreedhara, 2013). SCR uses urea, (NH\textsubscript{2})\textsubscript{2}CO, and injects into the exhaust to react with NO resulting in N\textsubscript{2} and H\textsubscript{2}O (Brijesh & Sreedhara, 2013). Urea heats up and decomposes to NH\textsubscript{3} and HNCO, isocyanic acid, which is stable in the gas phase (Koebel, Elsener, & Kleemann, 2000). However, at extremely low and high temperatures isocyanic acid emissions may be significant. The urea requires an additional tank and injection system to provide the urea to the engine exhaust. The aqueous urea solutions have high freezing point, for example a 32.5% urea concentration has a freezing point of 12°F (Koebel et al.,
Urea must also have a precise injection strategy in order to prevent ammonia slip. The entire system must operate efficiently, including the additional fuel injections required for regenerations of the aftertreatment. While studies have evaluated emissions effects with biodiesel, fuel consumption, DPFs with regeneration, and temperature effects (Myung et al., 2013) (Shah et al., 2013) (Beatrice et al., 2012) (McCarthy, Rasul, & Moazzem, 2011) (Mathis et al., 2004), a collective look at these systems impacts on fuel consumption has not been done to our knowledge. A study completed at the EPA shows the impact of fuel consumption with ultra-low sulfur diesel, and biodiesel blend with 20% of a soy-based biodiesel (B20), with two vehicles: one with DPF and a NAC and the other with DPF and SCR. Details on the test and set up are in Chapter 3. Efficient fuel economy is important. One of the purposes of the emissions regulations is to improve fuel economy, which is necessary to keep overall fuel use as low as possible. If more fuel is required to lower PM emissions, the impacts of the production and usage of the additional fuel needs to be considered.

5.3 EXPERIMENTAL METHODS

Two medium heavy-duty vehicles were tested in a temperature controlled chassis dynamometer. Vehicle 1 is a 2011 class 2b truck (gross vehicle weight rating (GVWR) of 8,501 to 10,000 lbs) with a 6.7 L Cummins engine and 22,062 miles. This vehicle was chassis dynamometer certified. Vehicle 2 is a 2011 class 5 truck (GVWR of 16,001 to 19,500 lbs) with a 6.7L Powerstroke engine with 2,693 miles. The two fuels used during the experiment were ULSD and B20. Flash point is the lowest temperature that allows the fuel to vaporize so that it will ignite when an ignition source is exposed. The flash point for both
ULSD and B20 were very similar. The viscosity of fuel is important in the diesel engine because the fuel is the source of lubrication for the engine. Viscosity is also important because it has an impact on the fuel injection. Higher viscosity leads to worse fuel atomization because it can cause less vaporization, increased droplet sizes, and narrower injection spray angle (Hoekman, Broch, Robbins, Ceniceros, & Nataraj, 2012). This leads to less efficient combustion which attributes to an increase in emissions. There is not a significant difference in the viscosity between the two fuels. The cloud point temperature of fuel is the maximum temperature where a cloud of wax crystals appear in a liquid when it is cooled during a standard test procedure. The temperature when a gel formation occurs that prevents the fuel from being poured is the pour point. The cold filter plugging point (CFPP) happens before the pour point because of the growth of the solids and agglomerates (Torres-Jimenez et al., 2011). The undesirable solids not only cause issues in the filter but also cause issues in the fuel lines. A lower cloud point is desired to avoid clogging. The cetane number of a fuel indicates the length of the delay between when the fuel is injected and when combustion begins. A higher cetane number results in a shorter delay time. The cetane number for the B20 used is slightly higher than the ULSD. A study showed that NOx decreased with increasing cetane number and attributed it to the reduction in ignition delay and the quantity of premixed fuel (Ladommatos, Parsi, & Knowles, 1996). Composition of these fuels were analyzed at Southwest Research Institute with the results shown in Table 5.1. The SCR used in Vehicle 2 requires a diesel exhaust fluid (DEF), a mix of urea and water. The DEF used was by Motorcraft (Dearborn, Michigan, USA) and filled at the
beginning of the testing only. The DEF has a boiling point of 220°F and a freezing point of 10°F.

**Table 5.1** Fuel properties for the ULSD and B20

<table>
<thead>
<tr>
<th>Property</th>
<th>ASTM Method</th>
<th>Fuel 1 = B0</th>
<th>Fuel 2 = B20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flash Point, °C, min</td>
<td>D93</td>
<td>85</td>
<td>86</td>
</tr>
<tr>
<td>Water and Sediment, volume%, max</td>
<td>D2709</td>
<td>&lt;0.005</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Viscosity, mm²/s at 40°C</td>
<td>D445</td>
<td>2.639</td>
<td>2.864</td>
</tr>
<tr>
<td>Sulfur ppm</td>
<td>D5453</td>
<td>10.4</td>
<td>8.9</td>
</tr>
<tr>
<td>Ash Content, mass %, max</td>
<td>D482</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Copper Corrosion, 3 h at 50°C, max</td>
<td>D130</td>
<td>1A</td>
<td>1A</td>
</tr>
<tr>
<td>Cetane Number</td>
<td>D613</td>
<td>44.8</td>
<td>47</td>
</tr>
<tr>
<td>Cetane Index</td>
<td>D976-80</td>
<td>46.5</td>
<td>47.7</td>
</tr>
<tr>
<td>Cloud Point, °C max or LTFT/CFPP, °C, max</td>
<td>D2500</td>
<td>-31.7</td>
<td>-20.6</td>
</tr>
<tr>
<td>Biodiesel Type</td>
<td></td>
<td></td>
<td>Soy based Biodiesel conforming to ASTM D6751-11b</td>
</tr>
</tbody>
</table>

*Unless specified otherwise above, Fuel 1 (B0) shall conform to ASTM D975 No. 2-D S-15. Fuel 2 (B20) is a blend of Fuel 1 (B0) and a soy based biodiesel conforming to ASTM D6751-11b.*

The testing cycle included a cold and warm start with low transients (CSLT and WSLT) and the federal heavy-duty urban dynamometer driving schedule (UDDS). Two temperatures, (70°F and 20°F), two fuels, (ULSD and a 20% biodiesel blend (B20)), and two loads (laden (90% gross vehicle weight rating) and unladen (vehicle weight plus 150 pounds)) were tested on both vehicles. The NO\textsubscript{x} data was collected using a 600 CLD Analyzer that used chemiluminescence to measure NO, NO\textsubscript{2} and NO\textsubscript{x}. The sample line for the measurement was heated to 140°F to ensure that there was not moisture in the sample line. Moisture can cause an erroneous measurements because of the interactions with H\textsubscript{2}O.
The hydrocarbons (HC) were measured using a Flame Ionization Detection (FID) 600 with a heated sample line of 235°F (according to (CodeFederalRegulations1065, n.d.)) to ensure that HC does not adhere to PM. Carbon monoxide (CO) was measured with a non-dispersive infrared (NDIR) analyzer with unheated sample lines as CO does not adhere to particles and does not react with H₂O. All of these analyzers are manufactured by California Analytical Instruments (Orange, California, U.S.A.). The second-by-second data was averaged over the test cycle. The gaseous data was collected approximately 4 meters downstream of the PM data collection (which is described in Chapter 3).

5.4 RESULTS AND DISCUSSION

5.4.1 FUEL CONSUMPTION

To determine if there was an impact on the fuel consumption from the NAC regeneration, DPF regeneration, ULSD versus B20, ambient temperature, vehicle cold start and vehicle load, a one way analysis of variance (ANOVA) was conducted. The 32 test conditions were used for Vehicle 1; three tests at normal operation plus one test for the DPF regeneration for all 8 conditions. Fuel consumption values were used for the UDDS cycle only to determine the impact on the NAC and DPF regenerations since the UDDS was the only test cycle that experienced a DPF regeneration. The NAC regeneration included 12 regeneration values and 20 values for normal operation. The DPF regeneration had 8 values that were DPF regeneration and 24 values were normal operation. In each of these ANOVA’s completed half of the values were with ULSD and the other half with B20. The ANOVA for the ULSD versus B20, cold starts, and different ambient temperatures still included 32
values, 16 of the BSFC values were with ULSD and the other 16 were with B20. The fuel consumption values were the averages over the CSLT, UDDS and WSLT. The boxplots below show the first, second and third quartiles shown with notches. The notches are calculated with the median (q2), and the first (q1) and third (q3) quartile. The endpoint of the notches are \( q_{2} +/- 1.57 \times (q_{3} - q_{1}) / \sqrt{n} \), where \( n \) is the number of fuel consumption values. The two medians are significantly different if the intervals of the notches do not overlap. If the sample size is small the notches may go beyond the end of the box (the first and third quartile).

**Figure 5.1** below shows the ANOVA results for Vehicle 1. These results show that fuel consumption is increased during DPF regeneration, cold ambient conditions and cold starts. In order for the NAC regeneration to take place, fuel rich conditions must occur, however, the NAC regeneration did not occur during cold ambient conditions. This shows that the cold ambient temperatures have more of an effect on fuel consumption than the NAC regeneration. **Figure 5.1a** shows that when NAC regeneration occurred during the UDDS there was an increased in miles per gallon which is because the comparing normal operation in this case was done at 20°F and the NAC regeneration was at 70°F except when a DPF regeneration occurred (p-value of 0.0002). **Figure 5.1b** shows that DPF regeneration significantly increases the fuel consumption (p-value < 0.0001). **Figure 5.1c** shows that there is not a significant difference (p-value = 0.6) in fuel consumption for the ULSD versus the B20. The 20°F ambient temperature consumes more fuel than the 70°F ambient temperatures (p-value = 0.0002) as shown in **Figure 5.1d. Figure 5.1e** shows that a vehicle cold start significantly impacts the fuel consumption (p-value < 0.0001). The only difference
between the CSLT and the WSLT test cycle is the minimum of 12 hour test ambient temperature soak of the vehicle.
Figure 5.1 ANOVA plots to determine effects of fuel consumption on Vehicle 1 for (a) NAC regeneration (b) DPF regeneration (c) ULSD versus B20 (d) temperature and (e) start condition
Vehicle 1 Start

Fuel Consumption (mpg)

CSLT  WSLT
For Vehicle 2 only the unladen case was run because of the dynamometer limitations, there are only 16 values that were used for the ANOVA. **Figure 5.2a** shows that the one DPF regeneration observed on Vehicle 2 (which was at 70°F with B20) had fewer miles per gallon than the average of all other runs (p-value = 0.02). There was not an impact on fuel consumption when considering ULSD and B20 (p-value = 0.9). Temperature did have an impact on fuel consumption for Vehicle 2 (p-value < 0.0001), **Figure 5.2b**. Similar to Vehicle 1, Vehicle 2 fuel consumption was not impacted by 20°F ambient temperature when compared to 70°F. A study done on an engine dynamometer with a DPF showed an increase in fuel consumption when comparing low sulfur diesel to non-blended biomass-to-liquids biodiesel fuels (Wang, Liu, Tian, Liu, & Zhang, 2012). This study only considered steady state operation. Another study was done to determine the effects on engine emissions and fuel consumption while a DPF was loaded with soot (Lapuerta, Rodríguez-Fernández, & Oliva, 2012) and found that brake specific fuel consumption (BSFC) was increased significantly, even surpassing the impact of the pump losses expected for the increase in back pressure on the engine due to the soot build up. This was explained by the increased engine thermal losses because of the hotter exhaust temperature and increased heat transferred to the coolant and the environment. **Figure 5.2c** shows the impact of the vehicle cold start, similar to Vehicle 1, Vehicle 2 had a significant increase in fuel consumption with a cold start. See **Table 5.2** for the average fuel consumption values that include three normal operations and the cycle with the DPF regeneration when applicable.
Figure 5.2 ANOVA results for Vehicle 2 for (a) DPF regeneration (b) temperature and (c) start condition
Normal Operation
8.5
9
9.5
10
10.5
11
11.5
12

Vehicle 2 DPF Regeneration
Fuel Consumption (mpg)

Vehicle 2 Temperature
Fuel Consumption (mpg)
Table 5.2 Average miles per gallon for each test condition (UDDS reports average of normal operation and DPF regeneration)

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Temperature</th>
<th>Fuel Type</th>
<th>Condition</th>
<th>CSLT (mpg)</th>
<th>UDDS (mpg)</th>
<th>UDDS DPF Regeneration (mpg)</th>
<th>WSLT (mpg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle 1</td>
<td>70 °F</td>
<td>ULSD</td>
<td>Laden</td>
<td>7.10</td>
<td>11.43</td>
<td>8.78</td>
<td>9.23</td>
</tr>
<tr>
<td></td>
<td>70 °F</td>
<td>ULSD</td>
<td>Unladen</td>
<td>7.36</td>
<td>12.11</td>
<td>8.97</td>
<td>9.66</td>
</tr>
<tr>
<td></td>
<td>70 °F</td>
<td>B20</td>
<td>Laden</td>
<td>7.09</td>
<td>12.08</td>
<td>9.81</td>
<td>9.33</td>
</tr>
<tr>
<td></td>
<td>70 °F</td>
<td>B20</td>
<td>Unladen</td>
<td>7.52</td>
<td>11.99</td>
<td>8.68</td>
<td>9.79</td>
</tr>
<tr>
<td></td>
<td>20 °F</td>
<td>ULSD</td>
<td>Laden</td>
<td>5.62</td>
<td>11.11</td>
<td>8.19</td>
<td>8.75</td>
</tr>
<tr>
<td></td>
<td>20 °F</td>
<td>ULSD</td>
<td>Unladen</td>
<td>5.73</td>
<td>11.26</td>
<td>8.12</td>
<td>9.03</td>
</tr>
<tr>
<td></td>
<td>20 °F</td>
<td>B20</td>
<td>Laden</td>
<td>5.75</td>
<td>10.89</td>
<td>8.11</td>
<td>8.43</td>
</tr>
<tr>
<td></td>
<td>20 °F</td>
<td>B20</td>
<td>Unladen</td>
<td>5.72</td>
<td>11.11</td>
<td>8.12</td>
<td>8.71</td>
</tr>
<tr>
<td>Vehicle 2</td>
<td>70 °F</td>
<td>ULSD</td>
<td>Unladen</td>
<td>7.25</td>
<td>12.01</td>
<td>10.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>70 °F</td>
<td>B20</td>
<td>Unladen</td>
<td>7.26</td>
<td>11.03</td>
<td>8.67</td>
<td>9.92</td>
</tr>
<tr>
<td></td>
<td>20 °F</td>
<td>ULSD</td>
<td>Unladen</td>
<td>5.30</td>
<td>10.28</td>
<td>9.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20 °F</td>
<td>B20</td>
<td>Unladen</td>
<td>5.22</td>
<td>10.27</td>
<td>9.18</td>
<td></td>
</tr>
</tbody>
</table>

Fuel consumption increase with cold temperatures can be attributed to incomplete combustion in the cylinder and an increase in fuel injection to ensure starting at cold temperatures. The fuel consumption increase with cold start is consistent with the study by (Bielaczyc, Szczotka, & Woodburn, 2011). The ambient temperature has more of an impact on vehicle cold starts than warm starts. The average decrease in miles per gallon for the CSLT when going from 70°F to 20°F is 21% and 27% for Vehicle 1 and 2, respectively and for the WSLT it is 8 and 9% for Vehicle 1 and 2, respectively. When the fuel is not at operating temperature the atomization process is impeded and the engine will therefore inject more fuel which attributes to this increase in fuel consumption (Heywood, 1988). The decrease in miles per gallon for Vehicle 1 when comparing WSLT to CSLT is 29% and
Vehicle 2 is 35%. During an active DPF regeneration exhaust temperatures are increased from normal operating exhaust temperatures of 300°F – 500°F to above 1100°F in order to get the soot oxidized and burned off by exothermic reactions. A common way to increase the exhaust temperature is to add a post-injection which causes an increase in fuel consumption. The average decrease in miles per gallon when comparing the UDDS average without DPF regeneration and the UDDS with the DPF regeneration occurred for Vehicle 1 is 31%. The one condition for Vehicle 2 had a decrease in miles per gallon of 27%.

5.4.2 GASEOUS EMISSIONS

Figures 5.3 – 5.8 below show the averages of the data for the normal operation (except where DPF regeneration is specified) and the error bars represent the maximum and minimum values. For both vehicles, 20°F ambient temperature produced an increase in NOₓ when compared to 70°F, as shown in Figure 5.3. This trend is more prevalent in Vehicle 2 (SCR equipped) than Vehicle 1 (NAC equipped). The CSLT has more NOₓ emissions than the WSLT which is attributed to the catalyst in the aftertreatment not being at operating temperature. The increase in NOₓ at 20°F for Vehicle 2 is not surprising because urea will not hydrolyse and ammonia will not be generated at temperatures below 320°F (Walker et al., 2003). The soy based B20 did not have a significant impact on NOₓ. One study on two different biodiesels found that for the same testing conditions on an engine dynamometer one blend of biodiesel that used beef, pork and sheep tallow and canola oil methyl ester had 14% reduction in NOₓ emissions and the other biodiesel that used chicken tallow and waste cooking oil methyl ester had a 17% increase in NOₓ emissions (McCarthy et al., 2011). Another study showed an increase in NOₓ emissions with the use of B10, B20 and B50
without PM or NO\textsubscript{x} aftertreatment (Agarwal, Sinha, & Agarwal, 2006). A study that included four light heavy-duty diesel vehicles and used four different fuels (diesel, B20, B100 and a synthetic blend) resulted in neither a significant increase or decrease in NO\textsubscript{x} emissions (Durbin et al., 2000) which is consistent with these results. In Figure 5.4, the UDDS compared normal operation to operation when a DPF regeneration took place. Vehicle 1 showed during the UDDS with the DPF regeneration much higher NO\textsubscript{x} emissions were present than without a DPF regeneration. Vehicle 2 did not experience a change in NO\textsubscript{x} emissions, although only one DPF regeneration occurred.
Figure 5.3 NO\textsubscript{x} values for Vehicle 1 and 2 comparing the different conditions with the CSLT and the WSLT (laden load was not run on Vehicle 2)
Figure 5.4 NO\textsubscript{x} values for Vehicle 1 and 2 comparing the different conditions during the UDDS for the average of normal operation and DPF regeneration (laden load was not run on Vehicle 2).

Vehicle cold starts result in higher HC and CO emissions because at cold starts the fuel is not up to operating temperature which leads to increased fuel viscosity, the intake air temperature is low along with the engine components not being at operating temperature (Bielaczyc et al., 2011). All of these factors reduce combustion efficiency which increases the HC and CO. Figure 5.5 shows that CSLT produces more HC emissions than the WSLT. This trend can be attributed to the additional fuel used during cold conditions to ensure a
start. In addition the catalyst does not operate at the optimized temperature during start conditions. The “x” on the chart indicates no data for that condition. Figure 5.6 shows that for Vehicle 2 at 70°F the normal operation has less HC then during a DPF regeneration. For Vehicle 1 the normal operation has higher HC than during a DPF regeneration for 70°F. This is the opposite trend of what is seen at 20°F. This could be because at 70°F the DPF is closer to regeneration temperature than at 20°F so there is less “additional” fuel added to increase the exhaust temperature.
Figure 5.5 HC values for Vehicle 1 and 2 comparing the different conditions with the CSLT and the WSLT (laden load was not run on Vehicle 2)
Figure 5.6 HC values for Vehicle 1 and 2 comparing the different conditions during the UDDS for the average of normal operation and DPF regeneration (laden load was not run on Vehicle 2)

Figure 5.7 shows CO emissions for both vehicles. While temperature did not significantly impact Vehicle 1, there was an increase in CO for Vehicle 2 for 20°F compared to 70°F. There is an insignificant amount of CO during the WSLT. Figure 5.8 shows during a DPF regeneration for Vehicle 1 there was not a significant amount of CO at 70°F. At 20°F CO was only measurable during a DPF regeneration. Vehicle 2 only produced measureable
CO at 20°F for normal operation, at 70°F there was small amount of CO only during the regeneration but not measured during normal operation.

Figure 5.7 CO values for Vehicle 1 and 2 comparing the different conditions with the CSLT and the WSLT (laden load was not run on Vehicle 2)
Figure 5.8 CO values for Vehicle 1 and 2 comparing the different conditions during the UDDS for the average of normal operation and DPF regeneration (laden load was not run on Vehicle 2)

A 2004 study found emissions of NO$_x$, HC and CO increased during a DPF regeneration for a diesel four cylinder passenger car equipped with a DPF (Dwyer et al., 2010). Vehicle cold starts increased NO$_x$, HC and CO emissions when compared to warm starts. The average increase from WSLT to CSLT for NO$_x$ is 1.5-fold, HC increase is 3.3-fold, and based off of the minimum detectable limit (MDL) of CO the increase was 4.6-fold for Vehicle 1. For Vehicle 2 from a WSLT to a CSLT NO$_x$ average increase is 62%, HC
increase is 1.7-fold, and based off of the MDL of CO the increase was 6.8-fold for Vehicle 2. These results are aligned with other studies (Bielaczyc et al., 2011; Brijesh & Sreedhara, 2013; Myung et al., 2013). This is attributed to incomplete combustion due to the engine temperature not being warmed up and the aftertreatment not yet reached light-off temperature for the catalyst to be operating optimally. The lubrication has not had time to warm up which prevents the engine from working at optimal conditions as well. Although this trend is consistent for both 70°F and 20°F the trend is more prevalent at 20°F. When the air is cold the density increases and can cause an increase in delay of ignition (Bielaczyc et al., 2011).

5.5 CONCLUSIONS

Fuel consumption data was collected and exhaust emissions were measured from two vehicles operating on a chassis dynamometer with different operating conditions to gain an understanding of the effects of DPF-equipped vehicles. When considering the different parameters (vehicle cold starts, ambient temperatures, DPF regeneration, NAC regeneration, vehicle load and fuel), vehicle cold starts, ambient temperature and DPF regeneration significantly impacted the fuel consumption of the vehicles. Vehicle cold starts attributed for a loss in miles per gallon by 29% and 35% for Vehicle 1 and 2, respectively. Ambient temperature also impacted fuel consumption but did not have as much of an impact as the vehicle cold starts. DPF regeneration is completed with a cost in fuel. Comparing normal operation to DPF regeneration the vehicles had a decrease in miles per gallon of, 31% and 27% for Vehicle 1 and 2, respectively.

Emissions of NO\textsubscript{x}, HC and CO were measured during the testing. NO\textsubscript{x} average increase was 1.5-fold, HC was 3.3-fold, and CO was 4.6-fold (based off of MDL) for Vehicle
1 for a cold start. For Vehicle 2 the NO\textsubscript{x} average increase was 62%, HC increase was 1.7-fold, and CO increase was 6.8-fold (based off of MDL) for a cold start. CO measurements were below the MDL during the WSLT. During a DPF regeneration NO\textsubscript{x}, HC and CO were increased when compared to normal operation for all cases except for Vehicle 1 at 70\textdegree F for HC and CO.

Understanding the impacts of the differences between the two vehicles’ fuel consumption and gaseous emissions on national inventories is difficult because the strategy of DPF regeneration, NAC regeneration (for Vehicle 1 only) and SCR strategy (for Vehicle 2 only) are not public knowledge. To gain a better understanding, measurements should be taken before and after the DPF. This was not possible in this study because the vehicles in this test were rented and could not be altered.

Please note that these are preliminary results and the conclusions do not necessarily reflect those of the EPA.
6 CONCLUSIONS

The goal of this research was to determine the effects that a DPF has on diesel engine exhaust with varying ambient conditions, fuels, drive cycles, and loads. Two heavy-duty trucks with diesel engines were tested in a temperature controlled chassis dynamometer for a seven month period. This research is motivated by the human health impacts and environmental influence that PM emissions have. Along with PM emissions, fuel consumption data and gaseous emissions were collected. Consistent trends were seen with the different instrumentation used for data collection. The EEPS and the ECPC showed consistent results for PM count. The same trends were also observed for BC with the PAX 870 nm and Aethalometer.

6.1 VEHICLE 1

For Vehicle 1 the following conclusions can be drawn.

1. PM emissions increased during cold starts under colder ambient temperature conditions, with BC values two- to three-times higher compared to warm driving operations. Colder ambient temperatures increased the number of particles in the 10-20 nm size range.

2. PM number emissions increased during warmer ambient temperatures and high speed and acceleration driving activity for particles in the 80-100 nm size range.

3. The average percentage change for the CSLT, UDDS and WSLT decreased in particle count when going from ULSD to B20, with an approximately 13% average decrease in PM number and an approximately 27% decrease in BC.

4. PM emissions decreased during the DPF regeneration.
5. The NO\textsubscript{x} average increased 1.5-fold and HC 3.3-fold for a vehicle cold start over a warm start.

6.2 VEHICLE 2

For Vehicle 2 the following conclusions can be made.

1. No measureable BC was detected under normal operation.
2. PM emissions increased during DPF regeneration.
3. A trend for ULSD versus B20 was not observed.
4. Emissions in the nucleation mode increased by 3 orders of magnitude during DPF regeneration.
5. The NO\textsubscript{x} average increased 62%, HC increased 1.7-fold when a cold start occurs versus a warm start.

6.3 COMPARISON OF VEHICLES

Differences in emissions were most pronounced between the two vehicle technologies tested. The differences in vehicle aftertreatment technology seemed to significantly impact PM emissions, with the presence of a NO\textsubscript{x} absorber having higher emissions than a vehicle using SCR with urea injection for NO\textsubscript{x} control. The day after a regeneration occurred, both vehicles show a significant increase in particles for the CSLT, approximately 93% and 1380% for PM number emissions from Vehicle 1 and Vehicle 2, respectively.

The DPF regeneration had an impact on the PM and BC emissions not only during the DPF regeneration but also during vehicle operation following the regeneration. The DPF regeneration for both vehicles occurred only in the UDDS cycle, and initiated during the high
acceleration/high speed portion of the test cycle. The most significant increase occurred with the first engine acceleration of these test cycles, while still staying below the PM emissions standards. The increase in particle number count from the WSLT to the CSLT post-regeneration for Vehicle 1 and 2 was 38% and 113%, respectively.

Vehicle cold starts, ambient temperature and DPF regeneration significantly impacted the fuel consumption of the vehicles. Vehicle cold starts attributed for a loss in miles per gallon by 29% and 35% for Vehicle 1 and 2, respectively. Comparing normal operation to DPF regeneration the vehicles had a decrease of fuel consumption in miles per gallon of, 31% and 27% for Vehicle 1 and 2, respectively.

During a DPF regeneration NO\textsubscript{x}, HC and CO were increased when compared to normal operation for all cases except for Vehicle 1 at 70°F for HC and CO (note that the gaseous emissions results conclusions do not necessarily reflect those of the EPA).

6.4 FUTURE WORK

To gain a deeper understanding of this experiment, specific engine operations could be investigated over a 1, 5, 10 or 30 second period where the size distribution is studied and analyzed to see what impact engine acceleration and deceleration have on PM size distribution. This specific investigation could also be done right before and after a DPF regeneration to see if differences exist between the size distribution before during and after a DPF regeneration.

To go beyond this specific experiment and gain a better understanding of PM emissions, PM measurements should be taken before and after the DPF. In addition an experiment where the DPF regenerations could be controlled could provide insight on DPF
regeneration by being able to know exactly how long a DPF regeneration is occurring. Then an analysis could be done on how fast the filter gets cleaned out and what the impacts are when the DPF regeneration is stopped when the filter is not completely cleaned, for example if a driver came to the destination and turned the vehicle off in the middle of a DPF regeneration. Different materials of the DPF could be investigated in the trucks to see if there are significant changes due to ambient temperature, fuels, loads or drive cycles on PM emissions. A broader range of temperatures could be investigated to determine the relationship between temperature and emissions and to know if it is linear or exponential. This study could also be done at varied altitudes to see what the influence of the decreased air has on the aftertreatment. Steady state operation of the trucks could provide insight on how the DPF is loaded with PM. All of this work could be investigated that could lead to a deeper understanding of diesel engine PM emissions that could provide the knowledge necessary to mitigate the human health and environmental impacts of PM emissions.
7 REFERENCES


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8 APPENDICES
8.1 R Code to Import Aethalometer Data

```r
###Import and Select Times from Dyno files
rm(list = ls()) ## removes any objects in workspace.

####################################################
#EPA Computer
setwd("C:\Documents and Settings\ebook\Desktop\Test R Script") #Change to folder you are working in

#Personal Computer
#setwd("C:\Users\EmilyKate\Desktop\R Data Files")

sampledate<-"2013-05-02" ## NEED TO CHANGE each time I run
time1<as.POSIXct(paste("2013-05-02 9:50:19"))
time2<as.POSIXct(paste("2013-05-02 9:55:59"))
time3<as.POSIXct(paste("2013-05-02 10:15:49"))
time4<as.POSIXct(paste("2013-05-02 10:33:59"))
time5<as.POSIXct(paste("2013-05-02 10:53:37"))
time6<as.POSIXct(paste("2013-05-02 10:58:59"))

# Personal Computer
#setwd("C:\Users\EmilyKate\Desktop\R Data Files")

fnames<-dir()

dat<-read.csv(fnames[1],skip=9, sep="","
#dat<-dat[,1:4]

dat[,1]<as.POSIXct(strptime(paste(dat[,1]),"%Y/%m/%d %H:%M:%S")) ## POSIXct changed to date
coldstart<-dat[which(dat[,1]>=time1&dat[,1]<=time2),]
coldstart[nrow(coldstart)+1,]<-NA
udds<-dat[which(dat[,1]>=time3&dat[,1]<=time4),]
udds[nrow(udds)+1,]<-NA
warmstart<-dat[which(dat[,1]>time5&dat[,1]<=time6),]

outdata<-rbind(coldstart, udds, warmstart)

outfile<-paste0("AETH_",sampledate,".csv")
write.csv(outdata, outfile) # to get rid of first col row.names=False
```
8.2 R Code to Import EEPS Data

## Import and Select Times from Dyno files

rm(list = ls()) # removes any objects in workspace.

# Change to folder you are working in
setwd("C:\Documents and Settings\ebook\Desktop\Test R Script")
sampledate<-"2013-05-02" # NEED TO CHANGE each time I run
time1<as.POSIXct(paste(sampledate, "9:50:19"))
time2<as.POSIXct(paste(sampledate, "9:55:59"))
time3<as.POSIXct(paste(sampledate, "10:15:49"))
time4<as.POSIXct(paste(sampledate, "10:33:59"))
time5<as.POSIXct(paste(sampledate, "10:53:37"))
time6<as.POSIXct(paste(sampledate, "10:58:59"))

fnames<-dir()
bins<-c(6.04,6.98,8.06,9.31,10.8,12.4,14.3,16.5,19.1,22.1,25.5,29.4,34,39.2,45.3,52.3,60.4,69.8,80.6,93.1,107.5,124.1,143.3,165.5,191.1,220.7,254.8,294.3,339.8,392.4,453.2,523.3) # calling the bin sizes
corfactor<-bins # creating variable
for (i in 1:length(bins)-1)) {
    corfactor[i]<-log10(bins[i+1]/1000)-log10(bins[i]/1000)
}
corfactor[32]<-corfactor[31]
dat<-read.table(fnames[1],skip=15, sep=",")
dat<-dat[,1:33] # cuts off data to the right of columns
dat[,1]<-as.POSIXct(paste(sampledate, dat[,1])) # POSIXct changed to date
class(dat[,1]) # check to see what the class

cormat<-matrix(corfactor,nrow=nrow(dat), ncol=length(corfactor), byrow=TRUE) # create matrix of correction factors

dat_cor<-dat # creating a variable
dat_cor[,2:32]<-dat[,2:32]*cormat # creates the corrected values in matrix
dat_cor$totalparticles<-apply(dat_cor[,2:32],1,sum)
colnames(dat_cor)
coldstart<-dat_cor[which(dat_cor[,1]>=time1&dat_cor[,1]<=time2),]
coldstart[nrow(coldstart)+1,]<-NA
udds<-dat_cor[which(dat_cor[,1]>=time3&dat_cor[,1]<=time4),]
udds[nrow(udds)+1,]<-NA
warmstart<-dat_cor[which(dat_cor[,1]>=time5&dat_cor[,1]<=time6),]
outdata<-rbind(coldstart,udds,warmstart)
outfile<-paste0("EEPS_",sampledate,".csv")
8.3  R Code to Import ECPC Data

##Import and Select Times from Dyno files

rm(list = ls() ) ## removes any objects in workspace.

#############################################

#EPA Computer
setwd("C:\Documents and Settings\ebook\Desktop\Test R Script") #Change to folder you are working in

#Home Computer
#setwd("C:\Users\EmilyKate\Desktop\R Data Files")

sampledate<="2013-05-02" ## NEED TO CHANGE each time I run
time1<as.POSIXct(paste(sampledate, "9:50:19"))
time2<as.POSIXct(paste(sampledate, "9:55:59"))
time3<as.POSIXct(paste(sampledate, "10:15:49"))
time4<as.POSIXct(paste(sampledate, "10:33:59"))
time5<as.POSIXct(paste(sampledate, "10:53:37"))
time6<as.POSIXct(paste(sampledate, "10:58:59"))

fnames<-dir()

dat<-read.csv(fnames[1],skip=18, sep="", header=FALSE)
dat<-dat[,1:4]

dat[,1]<-as.POSIXct(strptime(paste(sampledate,dat[,1]),"%Y-%m-%d %H:%M:%S"))

class(dat[,1])

coldstart<-dat[which(dat[,1]>=time1&dat[,1]<=time2),]
coldstart[nrow(coldstart)+1,]<-NA
udds<-dat[which(dat[,1]>=time3&dat[,1]<=time4),]
udds[nrow(udds)+1,]<-NA
warmstart<-dat[which(dat[,1]>=time5&dat[,1]<=time6),]

outdata<-rbind(coldstart, udds, warmstart)

outfile<-paste0("EPC_",sampledate,".csv")
write.csv(outdata, outfile) # to get rid of first col row.names=False
8.4 MATLAB Code for ANOVA results

%Figure 5.1a
anova(UDDS,NACRegeneration)
title('Vehicle 1 NAC Regeneration')
ylabel('Fuel Consumption (mpg)')

%Figure 5.1b
anova(UDDS,Operation)
title('Vehicle 1 DFP Regeneration')
ylabel('Fuel Consumption (mpg)')

%Figure 5.1c
anova(averageBSFC,Fuel)
title('Vehicle 1 Fuel')
ylabel('Fuel Consumption (mpg)')

%Figure 5.1d
anova(averageBSFC,Temperature)
title('Vehicle 1 Temperature')
ylabel('Fuel Consumption (mpg)')
xlabel('Temperature (F)')