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Evaluation of current and early production electronically controlled heavy-duty diesel engine emissions based on fuel property differences

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**Evaluation of Current and Early Production Electronically Controlled
Heavy-Duty Diesel Engine Emissions Based on Fuel Property Differences**

Varakala Shashidhar Reddy

Thesis submitted to

**The College of Engineering and Mineral Resources at
West Virginia University**

In partial fulfillment of the requirements

for the degree of

Master of Science

In

Mechanical Engineering

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ABSTRACT

Evaluation of Current and Early Production Electronically Controlled Heavy-Duty Diesel Engine Emissions Based on Fuel Property Differences

Varakala Shashidhar Reddy

Exhaust emissions emitted from heavy-duty diesel engines (HHDE) have been one of the contributors towards air pollution which indirectly have adverse effects on human health. This concern has made regulatory agencies impose stringent emissions standards in the United States and in many other countries. These increasingly stringent exhaust emissions levels have forced the HDDE manufacturers to focus largely on engine technology to reduce emissions levels to meet the regulatory standards.

Diesel fuel properties influence diesel engine emissions but how sensitive the engines are to these property changes is the objective of this study. To examine the influences, regulated emissions from two engines were measured which represented early and current electronically controlled HDDE production. Commercially available on-road diesel fuels were tested along with a biodiesel blended fuel. A 1992 Detroit Diesel Corporation (DDC) Series 60 and a 2004 Cummins ISM370 engines were used to evaluate the diesel fuel property effects using engine dynamometer cycles like the US Transient cycle also known as the Federal Transient Procedure (FTP) cycle, the European Stationary Cycle (ESC) which is a 13 mode steady state cycle and two on-road cycles. Only engine-out emissions were examined. To determine which fuel property influences emissions it was necessary to decouple the intercorrelation between fuel properties. This decoupling was achieved by using Pearson correlation coefficients. Additionally, statistical analysis software was used to create models that predicted engine specific emissions based on the fuel properties which were not correlated.

Results show that NO_x variation was as high as 16%, HC of 40%, PM of 44% and CO of 34% between fuels. However the levels of these variations were different for the two engines as the engines sensitivity to fuel property changes differed.

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1. INTRODUCTION

1.1. Prologue

Concern over the contributions of the exhaust emissions from HDDE on air quality has made the U.S. Environmental Protection Agency (EPA) and the California Air Resource Board (CARB) set stringent emissions levels. The regulated diesel emissions which are of major concern are the oxides of nitrogen (NO_x), which consists of nitric oxide (NO) and nitrogen dioxide (NO_2), particulate matter (PM), hydrocarbons (HC), carbon monoxide (CO) and non-methane hydrocarbons (NMHC). Emission standards according to the EPA and CARB from model year 1988 to 1998 are shown in Table 1-1 and model year 2004 and 2007 and later are shown in Table 1-2 for heavy-duty diesel trucks tested over the Transient Federal Testing Procedure (FTP) engine dynamometer cycle, with emissions defined in grams per brake-horsepower hour (g/bhp-hr) [1]. The 2007 and later standard has imposed regulations on diesel fuel limiting the sulfur content in on-highway diesel fuel from 500 to 15 ppm.

Table 1-1 EPA and CARB Emission Standards for Heavy-Duty Diesel Engines

Standards	Year	HC	CO	NO_x	PM	NMHC
EPA	1988	1.3	15.5	10.7	0.60	-
	1990	1.3	15.5	6.0	0.60	-
	1991	1.3	15.5	5.0	0.25	1.2
	1994	1.3	15.5	5.0	0.10	1.2
	1998	1.3	15.5	4.0	0.10	1.2
CARB	1987	1.3	15.5	6.0	0.6	-
	1991	1.3	15.5	5.0	0.25	1.2
	1994	1.3	15.5	5.0	0.1	1.2

Table 1-2 Emission Standards for 2004 and 2007 and Later

Year	Option	NMHC + NO_x	NMHC	CO	PM
2004*	1	2.4	n/a	15.5	0.1
	2	2.5	0.5	15.5	0.1
2007		NO_x	NMHC	CO	PM
		0.2	0.14	15.5	0.01

Over the past decade, with improving technology in the heavy-duty diesel engines, significant reductions in emissions have been achieved. However, application of technology would result in an improvement in either NO_x or particulate matter emissions and decrease in the other (NO_x PM trade off) along with an effect on fuel consumption. Although engine designs have a greater affect on the emissions than fuel quality, fuel does affect the emissions generated.

The implementation of in-use testing came into existence due to a court settlement reached between the EPA, US Department of Justice, CARB and the settling engine manufacturers (Caterpillar, Cummins, Detroit Diesel, Volvo, Mack and Navistar) over the issue of high NO_x emissions due to the control strategies employed by the engine manufacturers during cruising on highways [2]. The engine manufacturers used engine control software to control the fuel consumption so as to be more fuel efficient during which higher NO_x was produced.

West Virginia University (WVU) has assisted the settling engine manufacturers meet requirements of the Consent Decrees. A Mobile Emissions Measurement System (MEMS) was developed by WVU which was evaluated and procedures were developed for heavy-duty diesel-powered vehicle emissions which was later used to measure on-board emissions [2, 3, 4].

Prior to the in-use emissions testing requirements from the Consent Decrees, engine manufacturers were not concerned with fuel properties. Engine certification has always been performed with a fuel specified in the regulations. Now, manufacturers are required to do in-use testing and account for variability in fuels. A study by Gobble was motivated by the Consent Decrees, examined the effects of fuel properties on an engine which was tested on-road and later compared with the results obtained from the engine run by engine dynamometer [5]. The engine used for that study was a 1999 Ford B250 (International T444E). It was found that the commercially available on-road fuels had variations in the emissions emitted from the engine. But the question lies in whether it is the fuel properties or the engine technology that plays a vital role. This formed the motive for this research which studies the effect of fuel properties between older technology engines and a newer technology engine using six commercially available on-road diesel fuels.

A number of studies have identified important diesel fuel properties (cetane number, specific gravity, aromatics, sulfur and volatility) which influence the engine emissions. One of the difficulties faced by prior studies was that the fuel properties tend to be intercorrelated which poses a problem to identify a specific fuel property that directly influences emissions.

1.2. Objectives

The main objective of this study was to evaluate engine emissions from the commercially available diesel on early and current electronically controlled production HDDE. The engines were tested on dynamometer cycles like the FTP, ESC and an on-road cycles. The study looked into the aspect whether fuel properties have a considerable effect on low emission production engines or whether it's the technology which was the dominant factor for reduction in emissions.

The second objective was relating the effects of fuel properties on engine emissions. To examine that, it was pertinent to decouple the intercorrelation of fuel properties, which was achieved by using Pearson correlation method. Additionally, statistical analysis software was used to create models that predicted emissions which were engine specific based on the fuel properties which were not correlated.

The third objective was to test the advantages of using biodiesel blend with diesel fuel. A B20 blend was chosen for this study which consisted of 80% diesel fuel and remaining 20% of biodiesel which was tested on both engines to evaluate the influence of its properties on engine emissions.

2. LITERATURE REVIEW

2.1. Background

Diesel fuels composition mainly consists of hydrocarbons and to a lesser degree, organic compounds like sulfur, nitrogen and oxygen. Diesel fuels are influenced by crude source and method of refining. They are obtained from petroleum having a wide boiling range from 150-380°C. The hydrocarbons which are the major constituents are classified into three categories namely the normal paraffins which are straight-chain compounds (C_nH_{2n+2}), then the aromatic hydrocarbons and cycloparaffins also called as naphthenes (C_nH_{2n}) [6].

What makes one diesel fuel different from another is the proportion of paraffins, naphthenes and aromatic hydrocarbons. Paraffins are associated with lowest specific gravity and highest cetane numbers where as aromatics have higher specific gravity and boiling points but lower on cetane than the paraffins. Naphthenes on the other end have the highest specific gravity and boiling point and lowest cetane number.

Diesel fuel property qualities are specified by the standards in the respective countries like the ASTM D975 in the USA, EN 590 in the European Union and JIS K2204 in Japan and some of fuel properties are specific to the emissions regulations [7]. Most of the diesel fuels properties which are important are subjected to standards by which they are measured. The important properties which influenced combustion include cetane number, specific gravity, volatility and viscosity.

Normally fuel properties can be divided into two categories namely physical and chemical properties. Physical properties are measured using standard measurement methods to determine its property where as for the chemical property they are measured through interaction of a fuel with a standardized measurement apparatus. Some of the examples that fall under physical properties are the specific gravity, sulfur content, viscosity and volatility and examples for chemical properties are cetane number, flash point and lubricity.

The important diesel fuel properties that have an influence on emissions from heavy-duty diesel engines are as follows

- Cetane Number
- Specific Gravity
- Sulfur Content
- Volatility
- Aromatics

Cetane number is the measure of ease with which a fuel ignites when injected which influences ignition delay. High cetane number fuels are characterized by short ignition delay where as for low cetane number it is the converse. The ASTM D613 method is used to calculate the cetane number [7]. The cetane number of fuel is determined by comparing its ignition quality under standard operating conditions with two reference fuel (n-hexadecane or normal cetane and having a cetane number of 100 and a heptamethyl nonane having a cetane number of 15) using a Cooperative Fuel Research (CFR) single cylinder engine. The formula used to calculate is given below

$$\text{Cetane Number} = \% \text{ n-cetane} + 0.15 (\% \text{ heptamethyl nonane}) \quad \text{Equation (1)}$$

Specific gravity (relative density or RD) is the ratio of density of material to density of water which is measured using the ASTM 287 method [7]. In the USA, a common measure for density is expressed in degrees of API gravity which has an inverse relation with specific gravity, an arbitrary scale developed by the American Petroleum Institute. API gravity is measure using the ASTM 1298 method and calculated by the formula given below

$$^{\circ}\text{API gravity} = (141.5/\text{RD}) - 131.5 \quad \text{Equation (2)}$$

Sulfur is one of the contributors towards PM where sulfur trioxide (SO_3) binding with water forms sulfuric acid and sulfur dioxide (SO_2) emissions formed during combustion inside the engine. The resulting sulfur compounds have a negative environmental impact. In the early 1990's, sulfur level was restricted to 5000 ppm and later on environmental regulations further limited the sulfur content to 500 ppm and was termed low sulfur diesel. For the 2007 and later emissions standards the sulfur is reduced from 500 ppm to 15 ppm (termed ultra low sulfur diesel fuel). Effects of sulfur on engine emissions has been discussed

in many studies made on effect of fuel properties on engine emissions discussed later in this section. The ASTM D2622 or D5453 method is used to calculate the sulfur content [7].

Volatility of diesel fuel relates to the temperatures at which successive portions are distilled and then collected using standardized apparatus under controlled temperature which is measured by the ASTM D86 method [7]. In this method the fuel sample is placed in distilled apparatus and heated till the vapors are formed due to increase in temperatures which are later condensed and collected in cylinder marked with percentage of initial volume of liquid. The distillation temperatures of interest are the T50, T90 and T95.

Aromatics are normally referred to as total aromatics and are one of the important fuel properties on which many studies have been made to study the effect of it on engine emissions. The problems encountered during the studies were trying to decouple the intercorrelation between other properties which together influence the engine emissions. The ASTM D5186 method is used to measure the aromatic content [7].

Viscosity is defined as the resistance to flow, higher the viscosity greater is the resistance to flow and also decreases with increases in temperature. Viscosity is significant property which influences the atomization of fuel and lubricity of fuel [8]. Kinematic viscosity is defined as the ratio of dynamic viscosity to density of fuel. The ASTM standard used to measure is ASTM D445 [7].

Flash point of a fuel is defined as the temperature at which vapors from a combustible liquid ignite when exposed to a flame over the surface of the liquid. This is measured using the ASTM D93 method. Flash point is significant property to be measured which is important while handling and storing of fuels. A minimum flash point temperature is set by the standards, which is set to 38°C and any fuel below it indicates hazardous.

2.2. Previous Studies on Effect of Fuel Properties on Engine Emissions

The requirement to identify the significant fuel properties that have an affect on engine emissions has initiated many studies in this direction. Technologies incorporated by the engine manufacturers were the solution for reduction in emissions over the last 15 years. With the Consent Decrees and the requirement to perform in-use emissions testing, fuel

properties and fuel quality play a significant role in low emissions engines. The following studies discussed about significant fuel properties that influence the engine emissions.

A study by Cummins Engine Co. and Shell Oil Co. investigated the effect of diesel fuel properties in 1974 [6]. The study concluded that cetane number was the most significant diesel fuel property that had an effect on diesel emissions. The results showed that low cetane fuels resulted in higher hydrocarbons and oxides of nitrogen and conversely higher cetane fuels showed lower emissions. The fuels were tested on a 13-mode test with specially blended fuels to provide wide range in cetane number, specific gravity, aromatic content and volatility but were not commercially sold. Three production engines along with a prototype low emissions engines which was designed to meet 5 g/bhp-hr ($\text{NO}_x + \text{HC}$) were used for testing. Also, the study showed that the fuel properties alone do not provide a solution for major reduction in emissions it's the engine design that plays a vital role. Nevertheless it was recognized that with engine modifications for lower emissions the engines may become sensitive to fuel properties.

In 1979 a study was performed to examine the effects of fuel specific gravity, volatility, aromatics and sulfur content on particulates [9]. The test were performed using a naturally-aspirated, direct-injection diesel engine. The study concluded that with high aromatic and distillation temperature and low specific gravity the total mass of particulate matter was high.

Navistar completed a study in 1988 relating the effects of sulfur content on diesel emissions [10]. The study found similar trends for direct and indirect injection engines, with and without turbocharger apparatus. The sulfur content was varied from 0.05 to 0.29% by weight, and an increase in sulfur content increased the brake-specific PM emission from 0.06 to 0.07 g/bhp-hr. Increases in fuel sulfur content also increased the percent sulfate in TPM.

Southwest Research Institute conducted a study to investigate the effects of fuel composition on heavy duty diesel engine emissions in 1989 [11]. This was sponsored by the Coordinating Research Council to yield quantitative emissions data and emissions model to relate diesel fuel properties to emissions from modern heavy-duty diesel engines. The test were conducted over the EPA transient cycle using fuels in which three primary fuel properties, namely aromatics, volatility and sulfur were varied. The test fuels were not

commercially sold diesel fuels. One of the engines used for this study was a 14-liter Cummins Engine Co. NTCC 400 which met the 1988 CARB standards. The second one was an 11-liter DDC S60 and the third was a 7.3-liter Navistar International Corp. which was designed to meet the 1991 emissions standards.

The results were used to model transient composite emissions which were engine specific through multiple linear regression method. To decouple the intercorrelation of fuel properties, Pearson correlation coefficient analysis was used. A correlation coefficient greater than 0.90, implied a good correlation between the two properties. Along with this, emissions were also correlated with fuel properties so as to see any direct effect of fuel properties on emissions. The aromatic content had a significant effect on HC, CO, NO_x and particulate matter for all three engines. Volatility represented by T90 was significant for all emissions except on particulate matter for the DDC S60. Sulfur made a significant effect on particulate matter for all engines and on HC emissions except for NTCC 400 and in the case of NO_x and CO emissions it had no effect.

Shell Research Ltd. and Thornton Research Centre studied the effect of fuel properties on particulates emissions in heavy-duty truck engines under transient operating conditions in 1991 [12]. The study concluded that sulfur content and fuel density had an effect on particulates emissions in the U.S. transient tests. The engine used for the testing was a pre-production 12-litre DDC S60 designed to meet the 1991 US emissions standards. The results showed that increasing sulfur content and fuel density increased the total particulate mass linearly. Another conclusion was that improved engine design had led to significant reductions in particulates which were larger than that seen due to effect of fuel properties. But for low emission production engines fuel quality would play a role.

Amoco Oil Co. and Navistar International Transportation Corp. studied the diesel fuel property effects on exhaust emissions from a heavy-duty diesel engine that met the 1994 emissions requirements in 1992 [13]. The study evolved around determining the effect of cetane number and aromatic on the engine which met the 1994 emissions standard in which no exhaust aftertreatment devices were used. The engine tested upon was a 1993 pre-production Navistar Smokeless Diesel DTA 466 model ES 210 using the EPA transient cycle. They found that increasing cetane number reduced all regulated diesel emissions and reducing

aromatic content reduced NO_x and particulate emissions. An important observation made in this study was it would be cost effective if only the cetane number was increased by using fuel additive rather than reducing the aromatic content. When compared to previous studies the effect of cetane in this study was more effective. Also the effect of API gravity was studied which had an effect on NO_x and PM (reduction in fuel density reduced NO_x and PM) but increased HC and CO emissions.

PM-fuel relations were analyzed by Shell Research Ltd in 1994 [14]. It was reported an increase in density and aromatic content increased brake-specific PM, and increasing cetane number generally decreased PM emission. Lowering the sulfur content of fuel from 0.037% weight to 0.023% weight reduced PM emission up to 12%, decreasing density reduced PM by 13%, and cetane increases reduced PM emission by 5% in a Euro-1 cycle.

Texaco, Inc. performed a study regarding the effects of diesel fuel on emissions in 1995 [15]. It was concluded fuels with higher cetane number generated lower NO_x emission levels than lower cetane number fuels when aromatic content was held constant. It was also noted there was little or no NO_x reduction when high cetane number fuels had their cetane numbers increased naturally or through additives. HC emissions were found to be unrelated to cetane number. PM emissions were not affected by cetane number fluctuations when under light and medium load, but under high load the PM emissions of higher cetane number fuels were greater than that of low cetane number fuels.

In 1996, a study by Indian Institute of Petroleum on diesel fuel quality and particulate emissions investigated the influence of fuel properties that had an influence on particulate emissions other than the sulfur content which was a significant effect on particulate emissions [16]. Results of various other studies showed that aromatic content had little influence on particulate emissions only in direct injection engines of modern design. This study came to a conclusion that density and oxygen content of the diesel fuel affected the particulates.

The Technical Research Centre of Finland studied the effects of physical and chemical properties of diesel fuel on NO_x emissions of heavy-duty diesel engines in 1997. The focus of this study was on separation of physical and chemical effects of the fuel on NO_x formation [17]. A Volvo DH10A-285 bus engine that met the Euro II emissions regulations, (CO 4.0 g/kWh, HC 1.1 g/kWh, NO_x 7.0g/kWh and particulates 0.15 g/kWh) was used for testing.

Four diesel fuels with different density and aromatic levels were used to study the effects of fuel on emissions. They also used reformulated fuels to study their effect on engine emissions. Regulated emissions data were collected over the ECE R49, the European 13-mode emission test cycle. The results concluded that 7-13% reduction was seen in reformulated fuels in which 75-90% of the total reduction was due to the physical (density, viscosity) and chemical (aromatics, cetane) properties.

WVU performed extensive studies relating to alternative fuels and their impact on engine emissions in 1999 [18, 19]. Fuels included low sulfur pump diesel, California pump diesel, Malaysian Fischer-Tropsch fuel, soy fuels and biodiesels. Emission reductions were as high as 60% for HC. NO_x was reduced in some instances by over 25% from low sulfur pump fuel, and increases from low sulfur were as high as 11%.

In 2000 the University of Tokushima conducted research on the effects of fuel properties on direct-injection diesel engines [20]. Cetane number and aromatic content were varied independently. It was shown for fuels of like aromatic content, decreasing the cetane number increased ignition delay, decreasing PM and increasing NO_x emission. High cetane number fuels were found to increase PM due to an increase in combustion duration. Aromatic content had little effect on combustion quality, but high aromatic content increased both NO_x and PM emissions. It was also concluded a raise in injection pressure made the effects of cetane number and aromatic content less significant.

A 2003 study performed by the Japan Automobile Research Institute tested 9 fuels, focusing on density and viscosity correlations [21]. The engine of focus was a common rail direct injection diesel, turbocharged and after-cooled. It was found that an increase in density increased brake-specific PM and decreased brake specific NO_x . An increase in density was also found to lower CO and THC emissions. Little conclusion was drawn on the effects of viscosity, other than an increase lead to an increase in Sauter mean diameter of the fuel spray, increasing PM.

2.3. Motivation

A part of the study made by Gible [5], who tested commercially available fuels on an engine to evaluate emissions it was determined that variations in engine emissions from in-use fuels were attributed to the differences in the properties of fuel. This was the motive for this study to evaluate emissions between an older technology engine and newer technology using commercially available fuels along with a biodiesel fuel.

Gible tested commercially available fuels on a 1999 Ford B250 (International T444E) over the US transient FTP cycle, steady state and in-use testing. The test results showed differences in NO_x of 12%, PM of 50%, HC of 17% and CO of 40% between the tested fuels.

3. EXPERIMENTAL EQUIPMENT AND PROCEDURES

3.1. Introduction

The experimental equipment and procedures used for performing the testing were conducted at the Engine and Emissions Research Laboratory (EERL) at WVU which operates in compliance with CFR 40, Part 86, Subpart N [22]. A summary of the equipment and procedures used is given below.

3.2. Test Engines

3.2.1. Detroit Diesel Series 60

A turbocharged, direct-injected, in-line six cylinder DDC S60 engine was used for analyzing the exhaust emissions for this study using a DC dynamometer. Table 3-1 displays specifications of the engine and the engine can be seen in Figure 3-1. The engine was mapped from low to high engine speeds with wide open throttle on each fuel for torque and power curves and respective maps were used. Figure 3-2 represents one of the maps used for testing.

3.2.2. Cummins ISM 370

A turbocharged, direct injected in-line six cylinder Cummins ISM 370 was also used for analyzing the exhaust emissions for this study using a DC dynamometer. Table 3-1 displays more specifications of the engine and can be seen in Figure 3-3. The engine was mapped for torque and power curves on each fuel and Figure 3-4 represents a map curve.

Table 3-1 Engine Specifications

Engine Manufacturer	Detroit Diesel Corporation	Cummins
Engine Model, Year	DDC S60, 1992	Cummins ISM 370, 2004
Cylinders	6	6
Displacement, L	12.7 (775 CID)	10.8 (661 CID)
Power Rating (hp)	360	370
Torque Rating (ft-lb)	1450@1200 rpm	1450@1200rpm
Bore (mm) X Stroke (mm)	130 X 160	125 x 147
Compression Ratio	15:1	16.5:1
Air Handling	Turbocharged, Aftercooled	Turbocharged, Aftercooled
Exhaust Gas Recirculation (EGR)	N/A	Cooled EGR

Figure 3-1 1992, DDC S60

Figure 3-2 DDC S60 Engine Map

Figure 3-3 Cummins ISM 370 connected to the GE Engine Dynamometer

Figure 3-4 Cummins ISM 370 Engine Map

3.3. Engine Dynamometer

Dynamometers serve the purpose of loading the engines to simulate the load conditions used for engine dynamometer cycle testing. The dynamometer used for testing in this study at EERL was a General Electric direct current Model DYC 243 air cooled and is shown in Figure 3-3. The dynamometer has a capacity of absorbing up to 550hp and capable of motoring the engine up to 500hp. Once the dynamometer was coupled to the engine using Vulkan coupling and drive shaft, it was imperative to measure the torque which was achieved by using a load cell. The dynamometer was calibrated before the testing so as to make sure that it was in compliance with the testing procedures according to the CFR 40, Part 86, Subpart N. Engine speed was measured using a digital encoder mounted on the dynamometer.

3.4. Full Flow Dilution Tunnel

Whenever emission testing is performed it is important to simulate the real world conditions so as to analyze the effects of exhaust emissions on the environment. A full flow dilution tunnel serves the purpose of diluting the exhaust and preventing condensation by lowering of dewpoint of the dilute stream. The importance of preventing condensation is to avoid water droplets getting into sampling lines and affecting the analyzers and also to avoid absorption of gases such as NO₂.

The dilution tunnel at EERL was an 18 inch stainless steel and approximately 40 feet in length. A 75 hp blower was used to draw diluted engine exhaust through four critical flow venturis (one 400 scfm and three 1000scfm) with flow rates ranging from 400 to 3400 scfm and also provided a constant volume sampling (CVS) system. A mixing orifice was placed in the tunnel to assist in mixing of engine exhaust and dilution air. At 10 diameters downstream of the orifice the sampling probes were located to collect the dilute engine exhaust for analysis through heated sample lines (to prevent condensation) connected to analyzing instruments.

3.5. Critical Flow Venturi

The critical flow venturi (CFV) system used at WVU EERL was in compliance with the CFR 40, Part 86, Subpart N for the diluted exhaust flow. The laboratory used three venturis with a volume metric flow rate of 1000 scfm each and a 400 scfm to maintain a constant total flow rate. The CFV were based on the principle that the mass flow rate of a gas was maintained at a constant value once the gas flow reached sonic conditions. The mass flow through the venturi was calculated using the equation

$$Q = K_v \frac{P}{\sqrt{T}} \quad \text{Equation (3)}$$

Where Q was the mass flow rate (scfm), K_v was a calibration coefficient, P was the absolute pressure at the inlet of the venturi (in Hg), and T was the absolute temperature of the gas at the inlet of the venturi (°F). The flow rate used for this study was set to 2400 scfm.

3.6. Gaseous Emission Sampling System

The gaseous sampling system at the WVU EERL consists of heated sampling probes, heated sampling lines, heated pumps, heated filters, a chiller unit and gas analyzers. Stainless steel sampling probes were placed radially in the sampling plane at 10 diameters down the orifice of the dilution tunnel to sample required proportion of the diluted exhaust to the analyzers through pumps. Four probes are used – one each for HC, NO_x , NO_x2 and CO/CO₂. According to the CFR 40, Part 86, Subpart N, the temperatures of the heated sample lines were held constant by temperature controllers (HC – 375±20°F, NO_x – 235±20 °F, CO/CO₂ – 235±20°F) to prevent condensation in the sample lines. The heated sample for HC analyzer was maintained at higher temperature than the other lines to insure that heavy hydrocarbons did not condense in the sample line. The CO/CO₂ sample was pumped through a Dominic Hunter compressed air dryer to remove moisture from the sample.

3.7. Exhaust Gas Analyzers

The emissions analyzer bench at the WVU EERL contained analyzers manufactured by Rosemount Analytical, Inc, Horiba and Eco Physics as shown in Figure 3-5, which were capable of measuring HC, CO, CO₂ and NO_x. Also included in the bench was a Beckman NO_x efficiency tester, used for testing the converter efficiency in the NO_x analyzer. The following sections discuss in brief about the principle of operation and their specifications.

3.8. Hydrocarbon (HC) Analyzer

A Rosemount Model 402 Heated Flame Ionization Detector was used to measure the hydrocarbon concentration of the engine exhaust. A flame ionization detector operates on the principle of using polarized electrodes to collect positive ions. A regulated flow of the sample gas was introduced to the instrument. The sample then passed through a flame, fueled by a combination of 40% - 60 % hydrogen and helium. As the sample passed through the flame, hydrocarbons initiate an ionization process in which electrons and positive ions were produced. Electrons went to the positive electrode (anode), while the positive ions migrated to the negative electrode (cathode). A small ionization current, which was proportional to the concentration of carbon atoms passed between the two electrodes. An amplified analog voltage is read which was proportional to the current being generated. The Model 402 measured concentrations ranging from 1 to 5,000 ppm which was selected using a multiplier switch located in the front of the analyzer.

3.9. Oxides of Nitrogen (NO_x) Analyzer

A Rosemount Model 955 heated chemiluminescent analyzer was used to measure the NO_x in the exhaust mixture. Chemiluminescence is a process of photon emission during a chemical reaction which results when NO reacts with Ozone (O₃). Ozone (O₃) was generated by the ultraviolet irradiation of oxygen in a quartz tube. Excess O₃ was present to ensure complete reaction and to minimize quenching effects. A photo-multiplier tube enhanced the light intensity, where a photo-detector converted into voltage proportional to the number of NO molecules in the sample. Sample pressure and flow rate was carefully monitored before and after testing to ensure proper readings. An analog output voltage between 0-5V was

measured representing the zero and full scale calibration gas concentration. It is known that a significant portion of NO_x in diesel exhaust can be NO_2 . Therefore, the Model 955 reduced NO_2 in the sample to NO through the use of a NO_2 -to- NO converter. The NO produced in the converter was then reacted with O_3 in the same manner as the original NO in the sample to give a total NO_x measurement. If only a NO measurement was desired, then the analyzer could have been switched to NO mode, in which the sample bypassed the converter. The Model 955 analyzer could measure NO_x concentrations in full-scale ranges from 10 to 10000ppm. Along with the Rosemount Model 955, an Eco Physics NO_x analyzer was also used.

3.10. Carbon Monoxide (CO) and Carbon Dioxide (CO_2) Analyzer

A Horiba AIA-210 non-dispersive infrared analyzer (NDIR) was used to measure CO and CO_2 concentrations. The principle of operation is based on infrared absorption spectrum of gases. The analyzer passes infrared radiation through two cells; one cell containing reference gas and the other containing the sampling gas. At certain frequencies in the infrared spectrum, the energy associated with photon coincides with that required to change a molecule from one quantized energy level to another. At those frequencies a gas will absorb radiation.

Figure 3-5 Analyzer Bench

3.11. Bag Sampling

Dilute and background gas samples were collected in 80-liter Tedlar bags at the WVU EERL for integrated emission analysis. Dilute bag samples were drawn from the probe located at the sampling plane through Teflon tubing. The background sample of conditioned air were drawn upstream of the dilution tunnel before the introduction of exhaust in the dilution tunnel.

The bags were analyzed using the same emissions analyzers described previously, recorded through the data acquisition system (which is discussed in the following section in this chapter) and then evacuated. Background measurements were subtracted from the exhaust measurements to account for exhaust constituents present in the ambient dilution air.

3.12. Fuel and Air Flow Metering

Accurate measurement of fuel and air flow is a pertinent part of engine emissions testing. Engine air intake flow, exhaust flow, and fuel flow must be set accordingly. Fuel metering in the WVU EERL were done with a Max Machinery, Inc. Max Model 710 fuel conditioning system. The fuel measurements were obtained through data acquisition computer which was interfaced with the fuel system for accurate measurements. The fuel measurement system consists of a constant volume fuel tank, fueling supply and return lines, fuel pump, fuel meter, and heat exchanger. The intake air flow rate to the engine was measured using a Meriam Instruments laminar flow element (LFE). The differential pressure across the LFE, along with the absolute pressure, temperature and relative humidity (Omega, HX52) of the air at the inlet, was measured and related to the flow. The intake pressure was adjusted with a butterfly valve placed upstream of the laminar flow element. Likewise, a butterfly valve was placed in the exhaust piping close to the engine to adjust exhaust backpressure to the manufacturer's specification.

3.13. Instrumentation Control and Data Acquisition

The laboratory data collected in this experiment was obtained using the software and data acquisition hardware of the WVU EERL which is shown in Figure 3-6. The data was collected using a signal conditioning backplane with Analog Devices 3B system modules and

RTI-815 analog-to-digital converter data acquisition boards housed inside of the computer [23]. The data was recorded in ADC code. It was later reduced using in-house software to convert it into engineering units.

Figure 3-6 Data Acquisition and PM Sampling

3.14. PM Sampling

A proportional sampling of the diluted exhaust passes through a filter holder containing a primary and a secondary T60A20 70mm Pallflex fluorocarbon coated glass filter shown in Figure 3-6. The sample was drawn from the dilution tunnel at the sampling plane at the same location as the gaseous emissions lines. The maximum filter face temperature was maintained below 125°F during testing per the requirements of the CFR 40, Part 86. Filters were preconditioned for a minimum of an hour in a temperature and humidity controlled environment with temperature maintained at $71.6 \pm 5^\circ\text{F}$ and relative humidity of $45 \pm 8\%$. A Mettler Toledo UMX2 microbalance shown in Figure 3-7, with a resolution of $0.1\mu\text{g}$ was used for filter weighing. Prior to each weighing session, a calibration was performed and reference filters were weighed. Two reference filters were weighed and used for a month to

check for varying room conditions. The reference filters were subjected to a maximum weight change of 40 micrograms.

Following each test, the filters were conditioned to chamber conditions for minimum of an hour before being finally weighed. Background PM data was collected at the end of each day and background PM weight was subtracted from the total PM weight for each cycle.

In the case of steady state cycles, a solenoid controlled bypass system was setup to maintain a constant sample flow through the secondary dilution tunnel for the duration of the test. During the stabilization phase, a large replaceable fibrous filter was used to collect PM.

Figure 3-7 Mettler Toledo UMX2 Microbalance

3.15. Tapered Element Oscillating Microbalance (TEOM)

A Rupprecht & Patashnick Co., Inc. TEOM Series 1105, Diesel Particulate Mass Monitor was used in this experiment to acquire the real time PM data, shown in Figure 3-8. The TEOM incorporated a tapered element which was mounted at the wide end and a Pallflex TX 40 filter on the other narrow free end. The tapered element was mounted between two field plates to induce and control oscillation. A LED and phototransistor system was used to measure the frequency of the tapered element in the form of AC signal. The signal was amplified and converted to a mass value using a microprocessor algorithm. A sample of 2.0 lpm was drawn from the secondary dilution tunnel and the real time PM data was collected

Figure 3-8 Tapered Element Oscillating Microbalance

3.16. Quality Control and Quality Assurance Procedures

Laboratory checks were performed in accordance with CFR 40 Part 86, Subpart N including propane injections, NO_x efficiency, interference checks for analyzers and pressure leak and temperature checks for heated lines. Interference checks were made in order to insure that the analyzers were not affected by other sample gases. Oxygen interference and water interference tests were performed on the hydrocarbon and CO analyzer respectively. Pure oxygen was supplied to check the percentage of oxygen interference in the hydrocarbon analyzer. As specified by CFR Title 40 part 86 subpart N the percentage of oxygen interference should be less than 3% in a hydrocarbon analyzer. For the water and CO₂ interference test on CO analyzer, 3% CO₂ gas was passed through a water bubbler unit to the CO analyzer. As specified by CFR Title 40 part 86, the analyzer response should not be more than 1% of full scale for ranges above 300 ppm or more than 3 ppm on ranges below 300 ppm.

3.17. Calibration of Analyzers

Calibration procedures utilized by the WVU EERL were in accordance with the requirements of CFR 40, Part 86, Subpart N. The gases used to calibrate the exhaust analyzers were certified by the supplier to have an accuracy of 1%, traceable to NIST. No gas bottle was

used if the pressure dropped below 250 psig. The calibration gases were checked with Standard Reference Material (SRM) bottles to see if the bottles were named properly. All exhaust gas analyzers were calibrated using ranges of operation that were in accordance with the engine being tested. These calibrations were performed before each series of tests and after any instrument maintenance was been performed. A 10-point calibration procedure was carried out using a 10-point gas divider. The divider accurately produced varying concentration of component gas in 10% increments by mixing the span gas with a balance zero reference gas. The instrument readings were allowed to stabilize at each measurement point and a computer averaged (100 points) reading of the instrument response was recorded. These data points and corresponding gas concentrations were fitted to with up to a third degree polynomial and constituted that particular analyzer's calibration data file. The calibration gases used are shown in

Table 3-2 Calibration Gases Used for Testing

Calibration Gases	DDC S60	Cummins ISM 370
HC (ppm)	10	10
NO _x (ppm)	508	171.3, 350.6
Low CO (ppm)	500	49.98
High CO (ppm)	979	250.3
CO ₂ (ppm)	40110	48110

3.18. Propane Injections

To verify the accuracy of the CFV-CVS system, propane injections were performed where propane was injected into the dilution tunnel at a known rate using a Horiba Model 201B propane kit. The amount of propane injected was compared with the calculated amount indicated by a hydrocarbon analyzer. The difference between the volumes of propane injected to recovered measure by the analyzer must be lower than 2%. Three successive injections which fell within the 2% with not more than 0.5% differences between successive injections were considered valid to ensure accuracy of the CFV- CVS.

3.19. NO_x Efficiency Test

This test was performed to ensure efficiency of the converter in the NO_x analyzer in efficiently converting NO₂ to NO such that the chemiluminescent detector can properly measure NO_x. The Rosemount Analytical Model 955 NO/ NO_x analyzer does not detect NO₂, because it does not undergo the reaction with O₃ as NO. Therefore the NO₂ has to be converted to NO through the NO₂ to NO converter. This converter was checked at a monthly basis in EERL using a known concentration of NO gas. This efficiency test was also performed on the Eco Physics NO_x analyzer used during testing.

4. TEST CYCLES

For emissions certifications of on-road diesel engines the engines are tested on the US transient (FTP) cycle. Additionally, engine manufacturers most now exercise their engines over the ESC cycle as part of the certification test procedure. Along with these standard cycles, on-road cycles were also used to study fuel effect from those cycles.

4.1. Federal Transient Procedure (FTP)

One of the prominent transient cycles used to test HDDE to analyze emissions that simulates closely to that of the real-time on-road conditions is the FTP. FTP simulates the styles of urban and freeway driving cycles. FTP is based on Urban Dynamometer Driving Schedule (UDDS) for HDDE.

The FTP cycle is divided into four phases to completely simulate the various driving situations on road. The four phases included are the New York Non Freeway (NYNF) phase which represents light urban traffic with frequent stops, the Los Angeles Non Freeway (LANF) phase which represent busy urban traffic with few stops, the Los Angeles Freeway (LAFY) phase that simulates the busy freeway traffic and the last phase is the NYNF phase [24].

The FTP input file consisted of set points which was generated from the percentages of engine speeds and torques from the engine map generated from on each fuel. The emissions were reported on a brake specific basis to account for the variety of engine sizes. For testing purpose a minimum of three hot starts cycles were carried out. The test duration for each hot start consisted of 40 minutes of which the first 20 minutes consisted of soak time where the engine was not running and next 20 minutes where engine was running. Figure 4-1 shows target engine speed versus time and Figure 4-2 shows target engine torque verses time trace for the FTP cycle adapted to the DDC Series 60 based on the information from the DDC Series 60 engine map.

Figure 4-1 Engine Speed versus Time for the FTP Cycle for a DDC S60

Figure 4-2 Engine Torque versus Time for the FTP Cycle for a DDC S60

4.2. European Stationary Cycle (ESC)

The ESC is a 13-mode, steady state cycle which is used for emissions certification. The engine is tested on an engine dynamometer over a sequence of steady-state modes as shown in Table 4-1, which was one of the input files used for this testing. The engine was operated for a set time in each mode, where engine speed and load changes were first allowed to stabilize before the gas data and PM data was collected. The specified speed is held to within ± 50 rpm and the specified torque $\pm 2\%$ of the maximum torque at the test speed. Particulate matter emissions were sampled on one filter over the 13 mode. The weighted emissions were expressed in brake specific units and for individual mode in terms of g/mode for gas data. The engine was mapped on each fuel and the percentage engine speed and torque

values were recorded which was later used to configure the set points for the input file. One such representative input file generated is attached in Appendix A.

Table 4-1 Example Set Points for 13-Mode ESC for a DDC S60

Mode	Engine Speed	Load	Weighing Factor (%)
1	600	0	15
2	1200	1310	10
3	1423	619	10
4	1423	929	8
5	1200	655	5
6	1200	983	5
7	1200	328	5
8	1423	1238	9
9	1423	310	10
10	1645	1142	8
11	1645	286	5
12	1645	857	5
13	1645	571	5

Figure 4-3 Example ESC Set Points and Weighing Factors

4.3. On-Road Cycles

4.3.1. Bruceton Mills, WV

This route is designated by SAB2BM which was used in MEMS Phase-II as an on-road route for testing. The actual route consists of an outbound and return journey. The outbound journey will be discussed. This route originated from the former WVU facility close to Sabraton entrance ramp on I-68 east, and continues onto I-68 where a climb of 5% grade exists, followed by up and down grades to Bruceton Mills, WV. The distance traveled on this route is 39.7 miles with speed limit of 70 mph on the interstate [3]. Figure 4-4 displays the engine speed and torque values versus time for the SAB2BM cycle. The speed and torque setpoints used for this cycle were taken from a 1994, DDCS60 engine with maximum torque rating being the same as the DDCS60 used for this testing but a slightly higher power of 400hp. The setpoints used from 1994, DDC S60 are closely matched by 1992 DDC S60 during cycle comparisons. Hence the setpoints were used for on-road cycle which represents a real time conditions.

Figure 4-4 Engine Speed and Torque versus Time for the SAB2BM Route Cycle

4.3.2. ISM HH4

The ISM HH4 was an engine-dynamometer cycle, recreated from a normal duty cycle of a Heavy Hauler which was taken from in-field data. The engine speed, torque and other parameters were acquired using a data acquisition system connected to the ECM. This cycle was recreated so that the cycles were of shorter duration and could be loaded on to an DAQ computer using the facilities at EERL [25].

Figure 4-5 Engine Speed and Torque versus Time for the ISM HH4 Route Cycle

5. RESULTS AND DISCUSSION

5.1. Test Fuels

Eight fuels were examined for this study which included seven commercially available No.2 diesel fuels and a biodiesel blend (B20) fuel. The diesel fuels used in previous studies on effect of fuel properties on emissions have tested reformulated diesel fuels and only some of the studies have used commercially available fuels. The fuels were drawn out of stations from two different states, West Virginia and California, which have differences in fuel properties.

Three diesel fuels were drawn from local gas stations in Morgantown, West Virginia. Two fuels were drawn from Sheetz and Kroger gas stations in Sabraton. The third fuel was a British Petroleum (BP) drawn from the station on the Mileground. Two other fuels used for testing were from California State, of which one of them was from Shell branded fuel from Bakersfield and the other CECD. Guttman-1 and Guttman-2 diesel fuels are the No.1 diesel fuels used for engine dynamometer cycle testing in WVU EERL. A B20 blend was prepared by blending 80% of Guttman-2 diesel fuel along with 20% of biodiesel.

Fuels samples were collected at the end of testing and stored in one gallon containers designated with a WVU Number (for example WVU F0302) for identification. For consistency in analysis results of the fuels, all the samples were sent to Southwest Research Institute (SwRI) in San Antonio, Texas.

The California fuels had lower sulfur content in them when compared to fuels from the state of West Virginia. The Shell Bakersfield had very high nitrogen content when compared to the other fuels. The total aromatics varied between 10 (% wt) to 30 (%wt) over all the fuels. The cetane numbers for the Guttman-1 and Guttman-2 were high when compared to other fuels ranged between 60 and 65.

The fuel analysis obtained for all fuels from SwRI is displayed in Table 5-1, along with standards by which they were analyzed. The average values of all the fuel properties analyzed, along with variation is attached in Appendix B. The correlation between the fuel properties is shown in the results and discussion chapter.

Table 5-1 Fuel Analysis Results

ASTM Method	Fuel Property	WVF0304	WVF0303	WVF0302	WVF0301	WVF0305	WVF0306	WVF0307	WVF0439
		Sabraton Kroger	Guttman-1	Shell Bakersfield	CECD1	Sabraton Sheetz	Mileground BP	Guttman-2	Biodiesel
ASTM D2622	Sulfur (ppm)	293.0	455.0	166.0	207.0	418.0	397.0	384.0	306.0
ASTM D1298	Specific Gravity	0.856	0.810	0.843	0.837	0.859	0.851	0.814	0.828
ASTM D287	API Gravity	33.9	43.2	36.4	37.6	33.2	34.8	42.4	39.6
ASTM D445	Kinematic viscosity @ 40°C(cST)	2.663	2.264	2.639	2.325	2.844	2.613	2.183	2.476
ASTM D5291	Elemental Analysis (wt%)								
	Carbon	86.90	85.73	86.19	86.46	86.94	86.86	85.66	83.8
	Hydrogen	12.83	14.13	13.19	13.19	12.77	13.01	13.97	13.9
ASTM D4629	Nitrogen (ppm)	83.6	10.3	474.4	143.0	176.5	116.2	32.0	22.2
ASTM D5186	Diesel Aromatics by SFC, wt%								
	Total Aromatics (%wt)	34.6	12.9	10.2	30.5	32.7	29.3	14.7	14.8
	Mono Aromatics (%wt)	25.4	10.8	8.0	25.6	21.0	19.4	12.0	12.1
	Polynuclear Aromatics (%wt)	9.2	2.0	2.2	5.0	11.7	9.9	2.7	2.7
ASTM D613	Cetane Number	46.0	63.6	44.1	49.0	46.6	48.1	61.7	57.1
ASTM D93	Flash point (°F)	127.0	148.0	152.0	152.0	156.0	154.0	154.0	156.0
ASTM D86	Distillation, °F								
	IBP	323.1	345.1	363.2	335.4	328.6	343.4	346.5	350.3
	5%	400.9	371.7	374.8	368.7	400.7	385.0	369.6	371.7
	10%	423.1	381.4	385.7	382.2	424.8	409.9	380.4	386.8
	15%	438.5	394.0	397.7	395.4	440.8	424.6	389.2	399.9
	20%	451.5	405.0	408.8	408.1	454.3	438.5	398.8	414.4
	30%	473.1	428.5	432.1	436.1	479.2	463.0	422.0	446.5
	40%	492.6	454.8	457.5	462.4	500.0	486.7	449.6	484.7
	50%	509.5	482.7	484.9	488.5	519.0	507.0	478.3	522.6
	60%	527.7	512.0	513.9	515.4	537.3	526.8	507.2	556.6
	70%	547.3	543.0	545.8	544.6	556.4	547.7	536.1	583.7
	80%	568.9	571.8	579.7	578.6	579.9	572.1	562.7	605.1
	90%	601.4	600.0	620.4	621.8	611.0	603.7	589.0	623.1
	95%	627.4	618.1	648.8	655.4	635.9	630.4	607.5	635.1
	FBP	649.1	630.4	666.3	680.8	656.0	652.5	621.7	650.1
	Recovered	98.0	97.4	97.3	97.9	98.3	98.3	97.2	98.5
	Loss	1.2	1.4	1.1	1.2	1.3	1.1	1.3	0.5
	Residue	0.8	1.2	1.6	0.9	0.4	0.6	1.5	1.0

5.2. Fuel Properties

Most of the important fuel properties that have an influence on engine emissions have been discussed earlier in the literature review chapter. The following section discusses about the differences in the fuel properties and their effect on emissions.

5.2.1. Cetane Number

Cetane number is an important property of fuels which influences combustion process and NO_x emissions. Figure 5-1 shows a comparison of the cetane numbers for the tested fuels with Guttman-1 having highest cetane number of 63.6 and the Shell Bakersfield having lowest cetane number of 44.1. The No.2 diesel fuels cetane number ranged from 44.1 to 49.0 and for the B20 it was 57.1. The average was 52.0 and variation of all fuels was 14.65%. A plot of cetane number versus total aromatic content is attached in Appendix C which represent the correlation between them.

Figure 5-1 Cetane Number of Tested Fuels

5.2.2. Aromatics

A comparison of the total aromatic content along with polyaromatics and monoaromatics of fuels tested is displayed in Figure 5-2. The total aromatic content was as high as 34.6 (% wt) for the Sabraton Kroger and lowest for the Shell Bakersfield fuel of 10.6 (%wt) with the over all variation of 45.28%. The No.1 diesel fuels had lower total aromatic content when compared to the other fuels. The polynuclear aromatic content ranged between 2 (%wt) to 12 (%wt) with No.1 diesel having the lowest polynuclear aromatic content. The ratio of polynuclear aromatics to total aromatics varied between 0.15 to 0.35.

Figure 5-2 Aromatic Contents of Tested Fuels

5.2.3. Specific Gravity

Generally, lower specific gravity fuel results in high paraffin content, leading to increase in cetane number [26]. This observation can be made from graphical presentations seen in Figure 5-1 and Figure 5-3. The Guttman-1 fuel had the lowest specific gravity of 0.81 and correspondingly high cetane number of 63.3 and the Sabraton Sheetz fuel had a highest

specific gravity of 0.856 with a low cetane number of 46.6. The average specific gravity of all the fuels was 0.837 with an over all variation of 2.2%.

Figure 5-3 Specific Gravity of Tested Fuels

5.2.4. Sulfur Content

The sulfur content for the fuels was less than 500ppm which falls under the low sulfur diesel fuels group which can be observed from Figure 5-4. The Shell Bakersfield fuel contained the lowest sulfur content of 166 ppm and Guttman-1 having the highest of 455 ppm. The average sulfur content was 328.3 ppm with an over all variation of 31.55%. This shows that the sulfur content has a wide range in the fuels tested within regulation limits.

5.2.5. Volatility

The distillation temperatures of individual fuels from 5% to 95% recovery along with initial and final boiling point temperatures are displayed in Figure 5-5. The minimum and maximum distillation temperature at 90% recovery for No.2 diesel fuels is 539.6 °F and 640.4 °F. The fuels tested ranged between 589 °F and 623.1 °F at the 90% recovery temperature. The fuels from California had low temperatures at low distillation rate but had highest 95%

distillation recovery temperatures. The Guttman-1 and Guttman-2 fuels showed a different trend with low temperatures at low distillation rate with lower 95% recovery temperatures where as the remaining fuels showed similar trends to each other.

Figure 5-4 Sulfur Content of Tested Fuels

Figure 5-5 Distillation Temperatures of Test Fuels

5.3. Fuel Specific Emissions

Diesel combustion involves physical and chemical processes which are complex in nature including atomization, vaporization, ignition and combustion. The engines response to the changes in fuel property varies with design, control strategy and operating conditions. High NO_x formation is associated with high in-cylinder temperatures as a result of high premix burn fraction. HC are normally formed due to over or under mixing of fuel and air, and large size droplets at end of fuel injection. PM originates from organic and inorganic substances accompanied with fuel and air. It mainly consists of carbonaceous matter as a result of heterogeneous combustion process and CO is a product of incomplete combustion.

The two cycles, FTP and ESC, chosen for discussion emit out different levels of emissions and therefore absolute comparison of emissions and fuel sensitivity cannot be made. However, the data comparison shows the general effect of fuel property on emissions from the two cycles.

The results for the test displaying the regulated emissions (HC, CO, CO₂, NO_x and PM), actual work done, brake specific fuel consumption (bsfc) and fuel consumption for both the engines along with variation analysis are shown in Table 5-2 through Table 5-9.

Table 5-2 FTP Results for DDC S60

FTP								
	Sabraton Kroger	Guttman-1	Shell Bakersfield	CEDC1	Sabraton Sheetz	Mileground BP	Guttman-2	Biodiesel B20
HC (g/bhp-hr)	0.114	0.104	0.124	0.112	0.099	0.113	0.096	0.088
Standard Deviation	0.009	0.005	0.003	0.002	0.002	0.001	0.002	0.004
CO (g/bhp-hr)	2.680	2.493	3.086	2.717	2.826	2.848	2.612	2.300
Standard Deviation	0.301	0.008	0.037	0.046	0.091	0.039	0.034	0.023
CO ₂ (g/bhp-hr)	520.7	517.0	521.9	527.0	532.8	527.3	531.3	530.6
Standard Deviation	7.472	0.311	2.022	1.142	0.650	1.060	6.834	1.182
NO _x (g/bhp-hr)	4.745	4.469	4.896	4.798	5.203	5.125	4.590	4.789
Standard Deviation	0.485	0.006	0.027	0.020	0.036	0.015	0.008	0.019
PM (g/bhp-hr)	0.219	0.208	0.235	0.226	0.236	0.225	0.226	0.172
Standard Deviation	0.008	0.005	0.004	0.003	0.008	0.005	0.002	0.002
Actual work (bhp-hr)	23.73	23.20	24.51	24.28	24.90	24.57	23.41	23.59
Standard Deviation	0.950	0.029	0.136	0.240	0.025	0.010	0.021	0.055
BSFC (lb/bhp-hr)	0.383	0.379	0.387	0.420	0.389	0.389	0.380	0.390
Standard Deviation	0.007	0.000	0.001	0.035	0.001	0.002	0.001	0.001
Fuel consumption (lb)	9.083	8.786	9.477	10.184	9.678	9.566	8.895	9.191
Standard Deviation	0.531	0.014	0.046	0.745	0.026	0.035	0.011	0.002

Table 5-2 displays the FTP data obtained from the older engine (1992, DDC S60) which shows the average values of three hot starts on each fuel. Table 5-3 displays the variation analysis showing the average emissions for all the fuels, one standard deviation, coefficient of variation (COV) and min-max percentage difference. The individual run data for the FTP cycles is attached in Appendix C.

Table 5-3 Variation Analysis of FTP Results for DDC S60

FTP				
	Average	Standard Deviation	Coefficient of Variation (%)	Min - Max % difference
HC (g/bhp-hr)	0.106	0.01	10.82	40.0
CO (g/bhp-hr)	2.695	0.24	8.85	34.2
CO2 (g/bhp-hr)	526.1	5.66	1.1	3.1
NOx (g/bhp-hr)	4.827	0.25	5.12	16.4
PM (g/bhp-hr)	0.218	0.02	9.47	37.2
Actual work (bhp-hr)	24.02	0.62	2.58	7.3
BSFC (lb/bhp-hr)	0.389	0.01	3.33	10.9
Fuel consumption (lb)	9.36	0.46	4.93	15.9

Table 5-4 displays the weighted emissions, work done and brake specific fuel consumption (bsfc) for the ESC on the older engine and the variation analysis is shown in Table 5-4.

Table 5-4 ESC Results for DDC S60

ESC												
Weighted Emissions	Sabraton Kroger	Guttman-1	Shell Bakersfield	CEDC1	Sabraton Sheetz	Mileground BP	Guttman-2	Biodiesel B20	Average	Standard Deviation	Coefficeint of Variation (%)	Min-Max % difference
HC (g/bhp-hr)	0.048	0.046	0.053	0.049	0.043	0.048	0.050	0.048	0.05	0.003	5.93	22.7
CO (g/bhp-hr)	3.207	3.070	3.415	3.043	3.142	3.175	3.008	2.742	3.10	0.192	6.20	24.6
CO2 (g/bhp-hr)	472.3	461.2	465.5	467.3	473.2	469.7	469.3	471.8	468.78	4.029	0.86	2.6
NOx (g/bhp-hr)	8.308	7.306	7.643	7.694	8.220	8.000	7.350	7.746	7.78	0.370	4.75	13.7
PM (g/bhp-hr)	0.106	0.107	0.102	0.105	0.094	0.111	0.053	0.041	0.09	0.027	30.36	173.2
Weighted BhpHr (g/bhp-hr)	4.196	3.855	4.144	4.102	4.231	4.170	3.846	3.875	4.05	0.165	4.07	10.0
Weighted BSFC (g/bhp-hr)	164.0	257.3	164.3	161.5	163.2	162.2	244.3	243.4	195.0	44.3	22.7	59.3

Table 5-5 displays the regulated emissions, work done, bsfc and fuel consumption for the on-road cycle data for the older engine. The results obtained from the on-roads cycles are additional data so as to represent influence of fuel properties on emissions. This data is not used for comparison between engines due to different on-road cycles used for testing.

Table 5-5 On-Road Cycle Results for DDC S60

On-Road cycle												
	Sabraton Kroger	Guttman-1	Shell Bakersfield	CEDC1	Sabraton Sheetz	Mileground BP	Guttman-2	Biodiesel B20	Average	Standard Deviation	Coefficient of Variation (%)	Min-Max % difference
HC (g/bhp-hr)	0.066	0.063	0.059	0.063	0.059	0.057	0.057	0.053	0.059	0.004	6.76	23.1
CO (g/bhp-hr)	2.158	2.000	2.102	2.311	2.035	1.923	2.173	1.762	2.058	0.169	8.19	31.2
CO2 (g/bhp-hr)	474.1	457.0	471.1	467.0	468.9	474.4	467.7	468.6	468.6	5.5	1.2	3.8
NOx (g/bhp-hr)	6.193	5.581	6.033	5.744	5.900	6.233	5.561	5.835	5.885	0.256	4.35	12.1
PM (g/bhp-hr)	0.137	0.134	0.139	0.149	0.131	0.136	0.148	0.104	0.135	0.014	10.51	43.9
Actual work (bhp-hr)	114.9	110.6	114.5	114.2	113.7	115.5	111.3	111.8	113.3	1.839	1.62	4.4
BSFC (lb/bhp-hr)	0.352	0.358	0.352	0.350	0.351	0.351	0.341	0.348	0.350	0.005	1.35	5.0
Fuel consumptionn (lbs)	40.44	39.59	40.32	39.93	39.85	40.60	37.94	38.92	39.70	0.89	2.24	7.0

Table 5-6 through Table 5-9 displays the results of regulated emissions similar to the DDC, for the FTP, ESC and on-road cycles for the 2004, Cummins ISM 370 engine (modern engine).

Table 5-6 FTP Results for Cummins ISM 370

FTP								
	Sabraton Kroger	Guttman-1	Shell Bakersfield	CEDC1	Sabraton Sheetz	Mileground BP	Guttman-2	Biodiesel B20
HC (g/bhp-hr)	0.184	0.199	0.201	0.188	0.181	0.190	0.199	0.166
Standard Deviation	0.002	0.004	0.002	0.005	0.002	0.001	0.003	0.001
CO (g/bhp-hr)	0.606	0.540	0.621	0.548	0.574	0.571	0.551	0.524
Standard Deviation	0.011	0.008	0.004	0.006	0.012	0.006	0.006	0.001
CO2 (g/bhp-hr)	582.8	571.3	572.2	574.3	582.4	578.3	577.8	575.0
Standard Deviation	0.562	0.574	1.144	1.195	0.653	0.749	7.293	1.079
NOx (g/bhp-hr)	2.296	2.101	2.161	2.149	2.290	2.259	2.102	2.223
Standard Deviation	0.002	0.008	0.003	0.008	0.004	0.004	0.008	0.006
PM (g/bhp-hr)	0.070	0.061	0.060	0.060	0.074	0.072	0.062	0.045
Standard Deviation	0.001	0.000	0.002	0.002	0.000	0.001	0.000	0.002
Actual work (bhp-hr)	25.92	24.55	25.53	25.25	25.98	25.72	24.51	24.38
Standard Deviation	0.000	0.015	0.015	0.012	0.010	0.012	0.006	0.029
BSFC (lb/bhp-hr)	0.413	0.412	0.411	0.416	0.415	0.414	0.413	0.426
Standard Deviation	0.000	0.000	0.000	0.001	0.001	0.002	0.000	0.001
Fuel consumption (lb)	10.71	10.11	10.50	10.50	10.77	10.64	10.12	10.39
Standard Deviation	0.009	0.009	0.004	0.025	0.020	0.041	0.001	0.043

Table 5-7 Variation Analysis of FTP Results for Cummins ISM 370

FTP				
	Average	Standard Deviation	Coefficient of Variation (%)	Min - Max % difference
HC (g/bhp-hr)	0.188	0.01	6.27	21.2
CO (g/bhp-hr)	0.567	0.03	5.84	18.6
CO2 (g/bhp-hr)	576.8	4.35	0.75	2.0
NOx (g/bhp-hr)	2.198	0.08	3.63	9.2
PM (g/bhp-hr)	0.063	0.01	14.58	63.2
Actual work (bhp-hr)	25.23	0.66	2.63	6.6
BSFC (lb/bhp-hr)	0.415	0.00	1.14	3.6
Fuel consumption (lb)	10.47	0.25	2.39	6.5

Table 5-8 ESC Results for Cummins ISM 370

ESC											
Weighted Emissions	Sabraton Kroger	Guttman-1	CEDC1	Sabraton Sheetz	Mileground BP	Guttman-2	Biodiesel B20	Average	Standard Deviation	Coefficient of Variation (%)	Min-Max % difference
HC (g/bhp-hr)	0.102	0.107	0.107	0.106	0.106	0.109	0.090	0.104	0.006	6.01	20.60
CO (g/bhp-hr)	0.311	0.312	0.305	0.343	0.311	0.308	0.286	0.311	0.017	5.40	19.92
CO2 (g/bhp-hr)	520.1	506.7	610.9	513.4	520.8	510.7	512.1	527.833	36.984	7.01	20.56
NOx (g/bhp-hr)	1.979	1.894	1.919	2.043	1.993	1.866	1.961	1.951	0.062	3.16	9.51
PM (g/bhp-hr)	0.018	0.016	0.017	0.021	0.019	0.018	0.013	0.017	0.002	13.61	54.79
Weighted BhpHr (g/bhp-hr)	4.256	4.039	4.146	4.281	4.218	4.055	4.036	4.147	0.106	2.56	6.08
Weighted BSFC (g/bhp-hr)	163.3	168.1	168.1	164.9	163.2	168.6	169.6	166.5	2.671	1.60	3.90

Table 5-9 On-Road Cycle Results for Cummins ISM 370

On-Road cycle											
	Sabraton Kroger	Guttman-1	CEDC1	Sabraton Sheetz	Mileground BP	Guttman-2	Biodiesel B20	Average	Standard Deviation	Coefficient of Variation (%)	Min-Max % difference
HC (g/bhp-hr)	0.121	0.115	0.119	0.111	0.118	0.117	0.098	0.114	0.008	6.71	22.7
CO (g/bhp-hr)	0.325	0.315	0.316	0.313	0.319	0.314	0.282	0.312	0.014	4.43	15.2
CO2 (g/bhp-hr)	522.9	507.7	514.2	523.5	520.9	508.5	509.7	515.338	6.996	1.36	3.1
NOx (g/bhp-hr)	2.146	1.955	2.023	2.140	2.112	1.967	2.245	2.084	0.106	5.10	14.8
PM (g/bhp-hr)	0.052	0.042	0.041	0.051	0.051	0.044	0.029	0.044	0.008	18.22	78.7
Actual work (bhp-hr)	49.250	49.220	49.250	49.230	49.330	49.240	49.210	49.247	0.039	0.08	0.2
BSFC (lb/bhp-hr)	0.371	0.365	0.371	0.373	0.371	0.366	0.377	0.371	0.004	1.09	3.2
Fuel consumption (lb)	18.29	17.97	18.26	18.38	18.29	18.02	18.54	18.25	0.197	1.08	3.2

5.3.1. Fuel Specific HC emissions

The fuel specific HC emissions of the two engine emissions are displayed in the same graph to observe the trend for all the fuels as shown in Figure 5-6. The graph displays the data obtained from FTP cycle (along with one standard deviation represented by the bars) and ESC data. The older engine showed a greater minimum to maximum variation of 40% between fuels when compared to the modern engine which was only 20%. For the FTP data obtained, the lowest HC emissions of 0.88 g/bhp-hr for the biodiesel was observed with 0.124 g/bhp-hr being the highest for the shell Bakersfield fuel for the older engine. A similar pattern in the graph was seen in the case of modern engine except for No.1 diesel fuels which showed lower HC emissions when compared to the older engine. The emissions ranged between 0.166 g/bhp-hr to 0.201 g/bhp-hr for the same fuels respectively. An interesting observation was the HC emissions were higher in the modern engine when compared to the older engine [27]. The HC emissions were within the regulatory standards of 1.3 g/bhp-hr.

Figure 5-6 Fuel Specific HC Emissions for FTP and ESC Cycles

For the ESC data in the older engine, the variation between fuels was 23% with the weighted fuel specific HC emissions varying from 0.043 g/bhp-hr for Sabraton Sheetz to 0.053 g/bhp-hr for Shell Bakersfield fuel. A variation of 21% was seen in the modern engine with HC emissions ranging between 0.090 g/bhp-hr for the B20 to 0.109 for the Guttman-2 fuel. The ESC data for Shell Bakersfield fuel was not taken. The results from ESC cycle showed a similar trend to that seen in FTP cycle.

5.3.2. Fuel Specific NO_x Emissions

When compared to HC emissions, the NO_x variations were lesser but significant. A variation of 16% between the fuels was observed with emissions varying from 4.429 g/bhp-hr for Guttman-1 to 5.203g/bhp-hr for Sabraton Sheetz for the older engine, as seen in Figure 5-7. A lesser variation of 9% was seen in the modern engine with NO_x emissions varying between 2.101 g/bhp-hr for Guttman-1 and 2.296 for g/bhp-hr Sabraton Kroger as seen in Figure 5-7. The emissions were generally within the regulatory standards for both the engines.

Figure 5-7 Fuel Specific NO_x Emissions for FTP and ESC Cycles

The variations for the ESC data were even smaller when compared to the FTP. The older engine showed a variation of 14% between fuels ranging between 7.306 g/bhp-hr for the Guttman-1 to 8.308 g/bhp-hr for the Sabraton Kroger fuel. The modern engine showed a similar variation of 9% when compared to the older engine with emissions ranging between 1.866 g/bhp-hr for the Guttman-2 to 2.043 g/bhp-hr for the Sabraton Sheetz fuel. It is noted that the older engine technology exhibited significantly higher NO_x emissions value (approximately 1.8 times the certification limit) compared to the newer technology. This higher NO_x for the old engine was the motivation of the Consent Decrees.

5.3.3. Fuel Specific PM Emissions

When compared to NO_x variations, PM variations were far more significant with 37% between fuels on the older engine and PM emissions ranged between 0.172 g/bhp-hr for the B20 to 0.236 g/bhp-hr for Sabraton Sheetz as seen in Figure 5-8. The modern engine showed a better response to the fuel property changes with a variation of 63% between fuels. The PM emissions ranged between 0.045 g/bhp-hr for the B20 to 0.074 g/bhp-hr for and Sabraton Sheetz as seen in Figure 5-8.

Figure 5-8 Fuel Specific PM Emissions for FTP and ESC Cycles

Data obtained for the ESC on the older engine did not show the same variation seen in the FTP data. A variation of 14% was seen with emissions ranging between 0.041 g/bhp-hr for Sabraton Sheetz to 0.111 g/bhp-hr for Guttman-2 fuel. However the variation was a similar to that of the FTP which was of 55% and emissions ranging between 0.013 g/bhp-hr for Sabraton Kroger to 0.021 for Guttman-1 fuel in the modern engine.

5.3.4. Fuel Specific CO and CO₂ Emissions

The variations for CO emissions were 34% for the FTP data ranging between 2.3 g/bhp-hr for the B20 and 3.086 g/bhp-hr for Shell Bakersfield. A lower variation of 24% for the ESC data was seen in the older engine with emissions ranging between 2.742 g/bhp-hr and 3.415 g/bhp-hr. The CO₂ variations were the lowest when compared to other emissions with 3% for the FTP data ranging from 461.1 g/bhp-hr to 473.2 g/bhp-hr. The ESC data showed a similar variation of 4%. The modern engine showed a lower CO variation of 19% for the FTP and ranging between 0.524 and 0.621 and 19% for the ESC with a maximum of 0.343. For the CO₂ emissions, the variation was 2% for FTP cycle and ranging between 582.8 g/bhp-hr and 571.3 g/bhp-hr. The ESC data showed a greater variation of 20% with maximum emissions of 610.9 g/bhp-hr. The figures for the CO and CO₂ data are attached in Appendix D.

5.3.5. Work and Fuel Economy

Figure 5-9 displays the actual work done and bsfc for all the fuels tested on the FTP cycle for both the engines. The variation in work done for both engines seemed to be the same of 7% for both the engines however the older engine showed more variation in bsfc of 10%, and lower in that of the modern engine which was only of 3%. For the ESC, variation of work done was 10% a little more than seen in the FTP for the older engine where as the modern engine showed a closer response to that of the FTP which had a variation of 6%.

Figure 5-9 Fuel Specific Work Done and BSFC over FTP

5.4. NO_x-PM Trade off

One of the prominent problems being faced by the engine manufacturers in reducing the emissions is the trade off between NO_x and PM. The engine manufacturers design control strategies to reduce NO_x but see an increase in the PM. This was not observed in this study as seen from the plot of PM versus NO_x in Figure 5-10. The plot illustrates the effect of fuel properties on NO_x and PM.

Figure 5-10 NO_x PM Trade off for FTP

5.5. Influence of Fuel Properties on Emissions

Studies in the past tried to isolate individual fuel properties that affected emissions in HDDE and have found some important properties, which include specific gravity, cetane number, sulfur, aromatics and volatility. The difficulties in identifying properties having an influence on emissions, involve in mainly decoupling the intercorrelation between fuel properties so as to finding out the controlling variable and another aspect is the different control strategies involved in the engines. Some of the previous studies have had success in doing so and some failed. This study focuses on decoupling the intercorrelation between properties and looking into properties that have an influence on emissions of HDDE to correlate with the studies made earlier on effect of fuel properties on emissions.

5.5.1. Effect of Cetane Number

Cetane number influences the ignition delay of a fuel. Higher cetane number influences the premixed combustion by reducing the ignition delay thus resulting in lower NO_x production [7]. HC emissions have seen beneficial effect in some studies which tend to reduce HC emissions but some studies have not shown any influence on HC emissions which is largely to do with the engine design [28].

Figure 5-11 displays the effect of cetane on HC, NO_x and PM emissions tested on older engine over the FTP. The graph shows a linearly fitted line to express the correlation between fuel property and emissions. The NO_x emissions decreased with an increase in cetane number which correlated to the previous studies made and had a R^2 value of 0.5518. HC emissions also reduced with increase in cetane number and had a R^2 value of 0.4542. Some of the studies made earlier were biased with regards to the effect of cetane on PM. This engine showed little effect of cetane on PM emissions having a R^2 value of 0.264. The modern engine showed a lower response to changes in cetane number on emissions as seen in Figure 5-12.

Figure 5-11 Effect of Cetane on DDC S60 over FTP

Effect of cetane on NOx emissions in modern engine showed a lower R^2 of 0.4347 which was lower than the older engine. There was a little effect on PM emission, having an R^2 of 0.2066 where as the HC emissions showed a negligible effect with an R^2 of 0.0155. The modern engine showed smaller variations in emissions when compared to the older engine.

Figure 5-12 Effect of Cetane on Cummins ISMover FTP

5.5.2. Effect of Density on Emissions

Density, another important fuel property is related to volumetric fuel efficiency and power. Effect of density is also seen in the case of injection period which increases with decrease in density due to lower instantaneous mass flow rate of fuel [29]. Some studies have expressed the correlation with aromatics [30]. In regulatory emissions, PM reduces with reduction in density and has a negative effect on HC emissions leading to higher production of hydrocarbons. Also a reduction in NO_x is seen as density reduces [31].

Figure 5-13 displays the effect of specific gravity on emissions obtained from the old engine. The NO_x emissions reduced as the specific gravity reduced and had a good R² value of 0.702 showing good correlation between the two. However, the specific gravity had insignificant effect on PM and HC emissions having a R² value of 0.1741 and 0.1931, respectively.

Figure 5-13 Effect of Specific gravity on DDC S60 over FTP

On the modern engine, the NO_x emissions had the same effect as seen in the older engine having an R² value of 0.7713 showing a better response to density changes as seen in Figure 5-13. Density changes were less in the case of HC emission, where as the PM showed a better response to specific gravity change when compared to the older engine. Previous

studies have shown that PM reduction was seen in older engine but in this study the modern engine was more sensitive to changes in specific gravity.

Figure 5-14 Effect of Specific gravity on Cummins ISM over FTP

5.5.3. Effect of Sulfur on Emissions

Sulfur content in fuels was considered to influence PM in HHDE, studied at large by many researches [32]. However, the effect of sulfur has no significant effect on engine emissions in this study [33]. Previous studies have discussed about the conversion rate and have approximately calculated the conversion of sulfur to sulfates through SO_2 to be between 1-2% irrespective of sulfur level or engine design [34]. Reducing sulfur levels is not straight answer to reduce PM, since PM consists of carbonaceous soot, un-burnt or partially burnt fuel or lubricant and from fuel derived sulfates.

In one of the studies made earlier on effect of fuel properties on PM, sulfur, T90 and aromatic content seem to play a role in effecting PM [35]. They observed reduction in these properties reduced the PM. Another study found density to have an effect on PM which increased with increase in density [36].

Figure 5-15 displays the effect of sulfur on emission resulted from a DDC S60 engine. The engine showed negligible emissions changes with respect to NO_x or PM. The only noticeable effect was that HC reduced with increase in sulfur content. However, this may be attributed to other fuel properties.

Figure 5-15 Effect of Sulfur on DDC over FTP

The modern engines response to the changes in sulfur level of the fuel is presented in Figure 5-16. When compared to the older engine, the effects were lower than the older engine. Due to lower levels of sulfur content in fuels their effect on PM is negligible as seen from the plots.

Figure 5-16 Effect of Sulfur on Cummins ISM over FTP

5.5.4. Effect of Total Aromatics on Emissions

One of the concerns linked with finding the effects of total aromatics on emissions faced by prior studies was trying to decouple the intercorrelation that existed with other properties like density, cetane number and T90 [37]. However recent studies have focused on that aspect and have made efforts to decouple the correlation with other properties [38]. The influence of total aromatics has not shown any significant effect on PM, HC or CO emissions. Figure 5-17 displays the effect of total aromatics on emissions out of the DDC S60 engine. NO_x emissions were affected by the changes in total aromatic content which had a R^2 value of 0.2829 which indicates the increase in NO_x emissions with increase in total aromatic content. HC emissions were not affected by the changes to aromatic content but PM showed a lower effect having an R^2 value of 0.1131, when compared to the NO_x emissions.

Figure 5-18 displays the effect of total aromatic content for fuels tested on Cummins ISM 370. This engine showed a better response towards NO_x emissions which increased with increased in aromatic content having a R^2 value of 0.5168. The HC emissions also responded to the changes in aromatic content of fuels having an R^2 value of 0.4507. The PM was also influenced by aromatic content but was not of much significance. Overall, the sensitivity of modern emissions towards changes in aromatic content was larger when compared to the older engine.

Polyaromatics have been a focus of recent studies, which is similar to total aromatics but have higher flame temperatures and C/H ratios. Thus, reducing polyaromatics has had a beneficial effect on NO_x emissions along with HC and PM [28]. Figure 5-19 display the effect of polyaromatics on emissions for the DDC S60 engine. The only observable effect of emissions was seen in NO_x which increased with increase in polyaromatics, which has an R^2 value of 0.561. PM emissions showed little response and HC seem to be not affected. Figure 5-20 shows the effects of polyaromatics on emissions for the Cummins ISM 370 engine. The modern engine showed better response to changes in polyaromatic content of the fuels, of which the NO_x was the most significant one with R^2 value of 0.7261 and PM having a slightly lower R^2 value of 0.6448 and polyaromatics had no impact on HC emissions.

Figure 5-17 Effects of Total Aromatics on DDC S60 over FTP

Figure 5-18 Effect of Total Aromatics on Cummins ISM over FTP

Figure 5-19 Effect of Polyaromatics on DDC S60 over FTP

Figure 5-20 Effect of Polyaromatics on Cummins ISM over FTP

5.5.5. Effect of Specific Gravity on Energy Content

Energy content is calculated by multiplying density by per mass of heating value (defined as the energy released when a unit quantity of fuel is burned), thus reflecting the influence of density on energy content. The general trend is energy content increases with increase in density which is also seen in this study in Figure 5-21.

Figure 5-21 Effect of Specific Gravity on Energy Content

The energy contents of No.1 diesel and bio-diesel blends are lower when compared to No.2 diesel fuel which is evident from the work done by these fuels. For this study energy content was not analyzed. The modern engine shows a good linear relation between energy content and specific gravity which had an R^2 value of 0.991 whereas the older engine shows scattered data thus not showing a good linear relation but had an R^2 value of 0.6369 which indicated that the energy content was influenced by changes in specific gravity of fuel.

Figure 5-22, displays the engine map data obtained where the plot indicates the differences in energy content (heating value) of fuels. The curves in Figure 5-22 show a low powered fuel and higher powered fuel for both engines. Sabraton Sheetz was the fuel which showed that it contained more heat energy when compared to other fuels. It is noted that energy content was not measured as part of the fuel analysis as illustrated in Table 5-1.

Figure 5-22 Difference in Engine Maps

5.5.6. Effect of Volatility on Emissions

The most important distillation points considered in diesel fuels are the back end volatility namely the T95 and T90 [29]. This study looks into the back end distillation (T90) and influence of T50 on emissions. The NO_x emissions had a negative impact with increase in T50 temperatures. The PM and HC emissions showed a positive effect with increase in T50 temperatures but of little impact as seen in Figure 5-23 for the DDC S60. For the T95 temperature shown in Figure 5-24, all the emissions increased with increase in distillation temperatures with NO_x being the most influenced out of the three emissions.

The Cummins ISM 370 responded with greater sensitivity to the changes in T50 temperature. The most affected emissions were the HC emissions and NO_x as seen in Figure 5-25, where HC had a beneficial impact with increase in T50 temperatures and NO_x had a negative impact with increase in T50 temperatures. The R^2 value for HC and NO_x emissions was of the order of 0.7903 and 0.7638, respectively. In the case of T95 temperatures, the emissions were not affected which is evident from the graph presented in Figure 5-26.

Figure 5-23 Effect of T50 on DDC S60

Figure 5-24 Effects of T50 on Cummins ISM370

Figure 5-25 Effect of T95 on DDC S60

Figure 5-26 Effect of T95 on Cummins ISM 375

5.6. Decoupling Fuel Properties

Finding the correlation between fuel properties was an important aspect so as to determine individual fuel properties that influenced the emissions. This was one of the problems faced by prior researchers who were not able to do decouple the correlation between fuel properties and were ambiguous about the results obtained. So, correlations were used to determine fuel properties that were correlated to one another. This was achieved by recent studies using statistical analysis methods for correlation and were successful in identify fuel variables.

To determine the correlation between fuel properties, the common and efficient method used was the Pearson Correlation Coefficients method which is also being used in this study to correlate the results made by other studies. The coefficients obtained are shown in Table 5-10, which was calculated using built-in program called Correlation under data analysis tool in Microsoft Excel. A strong correlation existed between fuel properties if the Pearson correlation coefficient was equal to 1. The correlation coefficients greater than 0.9 were considered good to show that the two properties correlated well. The converse holds good for the values which were close to 0 indicating that there was no correlation existing between them. The coefficients with a positive sign signified that the two properties were positively correlated and the negative sign signified the inverse correlation.

The properties that showed correlations were identified as those having correlation coefficient greater than 0.90 for this study. Among the fuels tested and examining the results obtained as shown in Table 5-10, specific gravity showed correlation with viscosity and cetane number and hydrogen content. Specific gravity and viscosity had a positive relationship where as hydrogen and cetane had an inverse relationship.

Additionally, correlations between fuel properties and HC, NO_x, PM and CO emissions were also made so as to see which fuel property correlated with emissions.

Table 5-10 Pearson Correlation Coefficient

	Sulfur	Specific Gravity	API Gravity	Viscosity	Carbon	Hydrogen	Nitrogen (ppm)	Total Aromatics	Mono Aromatics	Polynuclear Aromatics	Cetane Number	50%	90%	95%
Sulfur	1.000	-0.236	0.244	-0.094	0.028	0.282	-0.650	0.068	-0.062	0.274	0.545	0.142	-0.661	-0.748
Specific Gravity	-0.236	1.000	-1.000	0.913	0.622	-0.974	0.434	0.740	0.612	0.837	-0.924	0.610	0.301	0.495
API Gravity	0.244	-1.000	1.000	-0.906	-0.633	0.978	-0.441	-0.742	-0.616	-0.835	0.930	-0.595	-0.298	-0.500
Viscosity	-0.094	0.913	-0.906	1.000	0.438	-0.825	0.475	0.496	0.311	0.732	-0.804	0.689	0.321	0.390
Carbon	0.028	0.622	-0.633	0.438	1.000	-0.754	0.329	0.667	0.589	0.687	-0.614	-0.104	-0.258	0.150
Hydrogen	0.282	-0.974	0.978	-0.825	-0.754	1.000	-0.468	-0.786	-0.686	-0.825	0.940	-0.442	-0.244	-0.519
Nitrogen (ppm)	-0.650	0.434	-0.441	0.475	0.329	-0.468	1.000	-0.146	-0.200	-0.023	-0.693	-0.175	0.472	0.628
Total Aromatics	0.068	0.740	-0.742	0.496	0.667	-0.786	-0.146	1.000	0.964	0.890	-0.566	0.492	-0.013	0.231
Mono Aromatics	-0.062	0.612	-0.616	0.311	0.589	-0.686	-0.200	0.964	1.000	0.737	-0.492	0.371	0.042	0.291
Polynuclear Aromatics	0.274	0.837	-0.835	0.732	0.687	-0.825	-0.023	0.890	0.737	1.000	-0.601	0.616	-0.102	0.096
Cetane Number	0.545	-0.924	0.930	-0.804	-0.614	0.940	-0.693	-0.566	-0.492	-0.601	1.000	-0.353	-0.456	-0.696
50%	0.142	0.610	-0.595	0.689	-0.104	-0.442	-0.175	0.492	0.371	0.616	-0.353	1.000	0.343	0.181
90%	-0.661	0.301	-0.298	0.321	-0.258	-0.244	0.472	-0.013	0.042	-0.102	-0.456	0.343	1.000	0.902
95%	-0.748	0.495	-0.500	0.390	0.150	-0.519	0.628	0.231	0.291	0.096	-0.696	0.181	0.902	1.000
Cummins	HC	0.014	-0.324	0.309	-0.352	0.412	0.170	0.341	-0.349	-0.338	-0.310	0.124	-0.889	-0.474
	NOx	0.048	0.878	-0.870	0.866	0.342	-0.774	0.045	0.719	0.571	0.849	-0.659	0.874	0.210
	PM	0.354	0.592	-0.598	0.485	0.926	-0.674	0.111	0.671	0.527	0.803	-0.455	0.065	-0.136
	CO	-0.432	0.633	-0.640	0.612	0.634	-0.675	0.754	0.196	0.106	0.318	-0.761	-0.059	0.266
DDC	HC	-0.531	0.439	-0.455	0.301	0.663	-0.549	0.710	0.173	0.176	0.139	-0.674	-0.333	0.145
	NOx	-0.046	0.838	-0.835	0.822	0.437	-0.781	0.424	0.532	0.355	0.749	-0.743	0.602	0.358
	PM	-0.100	0.417	-0.430	0.281	0.870	-0.572	0.551	0.336	0.267	0.401	-0.514	-0.380	-0.236
	CO	-0.375	0.579	-0.590	0.509	0.731	-0.668	0.853	0.188	0.090	0.328	-0.749	-0.219	0.107

5.7. Prediction of Emissions from Mathematical Models

A mathematical model was created to predict the transient FTP emissions using statistical analysis software (SAS). Fuel properties were selected which did not have any correlation with other fuel properties. The selected fuel properties included sulfur, specific gravity, cetane number, viscosity, hydrogen, carbon content, total aromatics and T95 distillation temperatures. The best model was selected based on the best correlation from the selected fuel properties. Few properties were selected as primary variables (total aromatic content, sulfur and carbon content) which were used in all equations to predict emissions. The secondary variables were those which differed for different emissions. Before using the variables to create models, the variable were divided into different groups which are shown in Table 5-11 and Table 5-12 and shows the designation used for fuel variables.

Table 5-11 Combination of Fuel Properties

Combinations					
Group-1	X1	X2	X5	X8	X14
Group-2	X1	X4	X5	X8	X14
Group-3	X1	X6	X5	X8	X14
Group-4	X1	X11	X5	X8	X14

Table 5-12 Fuel Variables

X1	X2	X4	X5	X6	X8	X11	X14
Sulfur	Specific gravity	Viscosity	Carbon	Hydrogen	Total Aromatics	Cetane Number	T50

Shown below are the best mathematical modeled equations obtained from the SAS program.

For Cummins ISM 370,

$$HC(p) = -0.884 - 7.98E-7 * (X1) - 0.020 * (X4) + 0.014 * (X5) - 1.09 * E-3 * (X8) - 6.90E-6 * (X14)$$

$$NOx(p) = 2.03 + 1.25E-4 * (X1) + 5.12(X2) - 4.03E-2 * (X5) + 1.70E-6 * (X8) - 1.16E-4 * (X14)$$

$$PM(p) = -0.615 + 1.23E-4 * (X1) + 0.150 * (X6) - 7.18E-4 * (X5) + 7.10E-6 * (X8) - 1.12E-4 * (X14)$$

For DDC S60,

$$HC(p) = -0.843 - 5.31E-6 * (X1) - 3.71E-2 * (X11) + 1.07E-2 * (X5) - 5.79E-4 * (X8) - 3.90E-6 * (X14)$$

$$NO(p) = -10.5 + 1.44E-4 * (X1) + 13.7 * (X6) - 0.017 * (X5) - 8.30E-4 * (X8) - 8.01E-4 * (X14)$$

$$PM(p) = -1.72 - 2.10E-5(X1) - 0.051 * (X4) + 0.023 * (X5) - 8.52E-5(X8) + 5.32-6 * (X14)$$

Where (p) is the predicted value.

The equation shown above predicts the emissions in g/bhp-hr, where the predicted emission equation is calculated using the intercept indicated by the first number in the equation along with the coefficients of the fuel properties. The positive sign against the coefficients signifies that emissions have a linear relation with the fuel property and negative signs signifies an inverse relation between emissions and fuel properties. The R^2 values obtained from each group for HC, NOx and PM are shown in Table 5-13. The best related model was used for predicting emissions as shown above. The comparison between predicted values and measured emissions for both engines are shown in Table 5-14 and Table 5-15. The SAS results obtained are attached in Appendix E.

Table 5-13 R^2 Values for All Models

Cummins FTP					DDC FTP				
Variables		HC	NOx	PM	Variables		HC	NOx	PM
Group-1	R^2 Value	0.9919	0.9846	0.9968	Group-1	R^2 Value	0.854	0.8487	0.8767
Group-2	R^2 Value	0.9992	0.979	0.9943	Group-2	R^2 Value	0.8532	0.7681	0.8774
Group-3	R^2 Value	0.992	0.9638	0.9984	Group-3	R^2 Value	0.853	0.8747	0.8763
Group-4	R^2 Value	0.9881	0.9806	0.9969	Group-4	R^2 Value	0.8547	0.8656	0.8768

Table 5-14 Comparison between Measured and Predicted Emissions for Cummins

Cummins ISM 370						
Fuel	Measured Emissions			Predicted Emissions		
	HC (g/bhp-hr)	NOx (g/bhp-hr)	PM (g/bhp-hr)	HC(p) (g/bhp-hr)	NOx(p) (g/bhp-hr)	PM (p) (g/bhp-hr)
Sabraton Kroger	0.184	2.296	0.070	0.185	2.225	0.071
% Difference				-0.3	3.0	-0.8
Guttman-1	0.199	2.101	0.061	0.2	2.066	0.062
% Difference				-0.4	1.6	-1.0
Shell Bakersfield	0.201	2.161	0.060	0.201	2.145	0.06
% Difference				-0.1	1.0	0.0
CECD1	0.188	2.149	0.060	0.188	2.103	0.06
% Difference				-0.3	2.1	0.3
Sabraton Sheetz	0.181	2.290	0.074	0.182	2.249	0.0773
% Difference				-0.6	1.8	0.7
Mileground BP	0.190	2.259	0.072	0.188	2.212	0.072
% Difference				-0.1	2.1	0
Guttman-2	0.199	2.102	0.062	0.199	2.092	0.061
% Difference				-0.4	0.5	1.4
Biodiesel	0.166	2.223	0.045	0.165	2.201	0.045
% Difference				-0.1	1.0	0.2

Table 5-15 Comparison between Measured and Predicted Emissions for DDC

DDC S60						
Fuel	Measured Emissions			Predicted Emissions		
	HC (g/bhp-hr)	NOx (g/bhp-hr)	PM (g/bhp-hr)	HC(p) (g/bhp-hr)	NOx(p) (g/bhp-hr)	PM (p) (g/bhp-hr)
Sabraton Kroger	0.114	4.745	0.219	0.111	4.872	0.227
	% Difference			3.2	-2.7	-3.8
Guttman-1	0.104	4.469	0.208	0.1	4.607	0.217
	% Difference			4.0	-3.0	-4.5
Shell Bakersfield	0.124	4.896	0.235	0.124	4.896	0.235
	% Difference			-0.1	-0.1	0
CEED1	0.112	4.798	0.226	0.113	4.76	0.223
	% Difference			-1.0	1.0	1.0
Sabraton Sheetz	0.099	5.203	0.236	0.106	5.188	0.227
	% Difference			-6.9	0.3	3.8
Mileground BP	0.113	5.125	0.225	0.108	5.027	0.229
	% Difference			4.8	1.9	1.7
Guttman-2	0.096	4.590	0.226	0.102	4.458	0.215
	% Difference			-5.8	2.9	4.7
Biodiesel	0.088	4.789	0.172	0.087	4.798	0.173
	% Difference			1.0	-0.2	-0.3

5.8. Influence of Fuel Properties on Steady State Modes in ESC

To study the effect of fuel properties changes in steady state cycle, two modes from the 13 mode ESC were examined. The NOx emissions from all the 13 modes were plotted for both engines tested on Sabraton Kroger fuel and are displayed in Figure 5-28.

An interesting observation was made, where the peaks for NOx formation were in different modes for both the engines. For the Cummins ISM maximum NOx formation was in mode 8 where as for DDC in mode 10 evident from Figure 5-28

High NOx formation is normally associated at higher loads because of an increase in boost pressure and subsequent peak cylinder pressure. This is evident from mode 10 which was at 100% load and higher speed when compared to mode 8 which was at 100% load but at lower speed in the DDC S60 engine. The Cummins ISM doesn't show the same trend as seen in DDC S60 which can be seen in Figure 5-28.

Figure 5-27 Comparison of NO_x Emissions Over the 13 Mode ESC for the Two Engines

Figure 5-28 shows peak NO_x emissions at mode 8 for the modern engine in comparison with the older engine. This is due to the effect of EGR which is sensitive to the A/F ratio conditions. This observation was made by a study on effect of EGR on emission which confirms that deterioration in combustion is predominant at higher load and low speed and low boost pressure due to decrease in A/F ratio [39]. Figure 5-29 displays the NO_x emissions for modes 8 and 10 for all fuels.

Figure 5-28 NO_x emissions of 8 mode and 13 mode of ESC

5.9. Effect of Cetane on NOx Emissions in ESC

Figure 5-29 represents NOx emissions from three modes of the ESC for both the engines to compare the effects of cetane number on NOx emissions. Guttman-1 and Sabraton fuel was used which represented a clean and dirty fuel (based on NOx emissions). The older engine showed larger reductions in NOx emissions between 30% to 40% when compared to modern engine which showed less than 10% reduction as seen in Figure 5-29. However the observation made may not be general since ESC data collected was for one test on each fuel in this study.

Figure 5-29 Cetane Effects on NOx in Some ESC Modes

5.10. Comparison between Conventional and Biodiesel blend

Biodiesel is one of the alternative fuels being used which is become an important substitute to conventional diesels which are either plant or animal extract. The added advantage of using biodiesels include it is produced from renewable resources, is biodegradable and most important of all is its potential to reduce emissions.

A B20 blend was used for this study, as the name suggests it composed of 20% of Biodiesel and 80% conventional diesel. The biodiesel used for mixing was from a local supplier, which was a soybean extract. B20 has an edge over other alternative fuels due to its

compatibility with the diesel engines which doesn't need any modification for using it. This fuel was tested over the FTP and ESC to see the effect of B20. The average data obtained from three hot starts over the FTP cycle is displayed in Table 5-15 for the Cummins ISM and DDC S60. Reductions in emissions were observed where the percentage difference with a positive sign shows a reduction from conventional diesel fuel and negative sign signifies an increase. The most significant reduction was seen in PM which reduced by 27% for modern engine and 24% on the older engine, HC emissions reduced by 17% for the modern engine and 8% on older engine. However the NO_x went up by 5% or 6% which was one of the negative attributes of using B20. CO reduction was of 5% on the modern and 12% on the older and negligible difference was seen in CO₂.

Table 5-16 Comparison between conventional and Biodiesel over FTP

	Cummins FTP			DDC FTP		
	Guttman-2	Biodiesel B20	% Difference	Guttman-2	Biodiesel B20	% Difference
HC (g/bhp-hr)	0.199	0.166	-16.7	0.096	0.088	-7.7
CO (g/bhp-hr)	0.551	0.524	-4.8	2.612	2.300	-12.0
CO ₂ (g/bhp-hr)	577.8	575.0	-0.5	531.3	530.6	-0.1
NO _x (g/bhp-hr)	2.102	2.223	5.7	4.590	4.789	4.3
PM (g/bhp-hr)	0.062	0.045	-27.1	0.226	0.172	-23.7
Actual work (bhp-hr)	24.507	24.377	-0.5	23.407	23.593	0.8
BSFC (lb/bhp-hr)	0.413	0.426	3.2	0.380	0.390	2.5
Fuel consumption (lb)	10.118	10.388	2.7	8.895	9.191	3.3

A study was made by Colorado Institute for fuels and High-Altitude Engine Research, in 1996 which studied the effect of neat biodiesel (100%) and biodiesel blended with conventional diesel (B20, B35, B65). The observation made in this study was that NO_x increased with increased in the percentage of biodiesel in the fuel. HC, CO and PM decreased with increase in percentage of biodiesel [40].

The data obtained from ESC is displayed in Table 5-17, shows a significant reduction in HC, PM and CO. The NO_x increase was similar to that seen in FTP.

Table 5-17 Comparison between Conventional and Biodiesel over ESC

	Cummins ESC			DDC ESC		
	Guttman-2	Biodiesel B20	% Difference	Guttman-2	Biodiesel B20	% Difference
HC (g/bhp-hr)	0.109	0.090	-17.1	0.050	0.048	-5.0
CO (g/bhp-hr)	0.308	0.286	-7.2	3.008	2.742	-8.8
CO2 (g/bhp-hr)	510.7	512.1	0.3	469.3	471.8	0.6
NOx (g/bhp-hr)	1.866	1.961	5.1	7.350	7.746	5.4
PM (g/bhp-hr)	0.018	0.013	-23.7	0.053	0.041	-22.9
Actual work (bhp-hr)	4.055	4.036	-0.5	3.846	3.875	0.8
BSFC (lb/bhp-hr)	168.609	169.571	0.6	244.300	243.377	-0.4

6. CONCLUSIONS

The changes in emissions due to fuel property differences appear to be small when compared to the emission levels achieved by changes in technologies. But the changes are significant which help in achieving the lower emissions standards being set by the regulatory boards. It was imperative to assess fuel properties that affect emissions and to observe the sensitivity of engines to fuel changes. This was achieved in this study which tested fuels that had a wide range of fuel properties on two different engines, representing early and current production engine technologies. The observations on regulatory emissions measured from different fuels exercised over engine dynamometer cycles on both engines are as follows.

Correlation of NO_x emissions with fuel properties:

- NO_x showed good correlations with density, viscosity, polyaromatics and T50 which had a beneficial effect on NO_x emissions. From the emissions point of view a decrease in these fuel properties resulted in a decrease in NO_x emissions. This was observed in both engines but the modern engine showed better correlation when compared to the older engine. One of the fuel properties which is influential on NO_x and which was not studied in detail by previous studies is viscosity. The correlation coefficient values between fuel properties and NO_x emissions are shown in Table 6-1 along with the LR (R^2 value). The negative sign for Pearson Correlation Coefficient (PCC) indicate a inverse relation between fuel property and emissions.
- Cetane number, one of the influential properties on NO_x emissions, did show a correlation but was not as effective when compared to the other properties. The older engine showed more sensitivity to the changes in cetane number when compared to the modern engine as seen in Table 6-1.

Table 6-1 Correlation Coefficients between Fuel Properties and NO_x

Cummins		Specific Gravity	Polyaromatics	T50	Cetane Number
NO _x	PCC	0.8783	0.8495	0.8740	-0.6593
	LR	0.7713	0.7216	0.7638	0.4347
DDC		Specific Gravity	Polyaromatics	T50	Cetane Number
NO _x	PCC	0.8379	0.7490	0.6025	-0.743
	LR	0.7020	0.7216	0.7638	0.5518

Correlation of PM emissions with fuel properties:

- Sulfur did not show any significant changes on PM on both engines due to lower content in sulfur levels of fuels tested which is evident from correlation coefficients between sulfur and PM shown in Table 6-2. The modern engine was a little more sensitive to sulfur changes where as the older engine showed no effect at all. However it is noted that the sulfur level at the fuels tested were all less than 500 ppm.
- Polyaromatics proved to be an influential property on PM in the modern engine when compared to the older engine which can be seen from the correlation coefficients seen in Table 6-2.
- Carbon played a crucial role in influencing PM as seen from the correlation coefficients for both the engines in Table 6-2.

Table 6-2 Correlation Coefficients between Fuel Properties and PM

Cummins		Carbon	Polyaromatics	Sulfur
PM	PCC	0.9261	0.8030	0.354
	LR	0.8577	0.6448	0.1255
DDC		Carbon	Polyaromatics	Sulfur
PM	PCC	0.870	0.401	-0.100
	LR	0.7560	0.1605	0.0099

Correlation of HC emissions with fuel properties:

- HC was influenced by fuel properties of which the most effective fuel property was T50, which is evident from the correlation coefficients in Table 6-3. The modern engine showed a better sensitivity to T50 when compared to older engine.

Table 6-3 Correlation Coefficients between HC and T50

Cummins		T50
HC	PCC	-0.8890
	LR	0.7903
DDC		T50
HC	PCC	-0.333
	LR	0.1111

All of the fuel properties that affected emissions did not affect both engines equally as seen from the correlation and testing results obtained. However, three properties were effective on emissions for both the engines of which the NO_x emissions had three properties that were common and included density, viscosity and polyaromatics. Both the engines were sensitive to carbon content in the fuel that had an effect on PM.

The mathematical model equations were derived in this study that predict the HC, NO_x and PM emissions based on some fuel properties. Predicted emissions from the models were close to the measured emissions and are engine specific only and do not represent universal equations that can be used for all engines.

Alternative fuels like biodiesel blends, B20, have a beneficial impact on emissions like HC, CO and PM where as the NO_x emissions increased by 5% to 6%, which may be attributed due to oxygen content in the biodiesel. However, the B20 blend associated well with the No.2 diesel fuel seen from the comparisons made which showed lower emissions and with changes to its fuel properties may even become more commonly used commercial diesel fuel in the near future.

The recommendations made for this study are as follows

- Testing wider range of diesel fuels which include summer and winter blends (which differ in energy content) from various locations in the US
- Examining the effect of the engine map being used for setpoints in certification of fuels
- Testing different biodiesel sources like plant, animal extract and processing to examine engine emissions
- Effect of adding additives like natural (hexadecane) and cetane boosters (2EHN) on regulated emissions
- Engine manufacturers equipping engines with on-board diagnostics (OBD) to monitor fuel properties to enable in deciding control strategy being used
- Impact of fuel properties on aftertreatment devices (DPF, SCR, NO_x Absorber, etc.)

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APPENDIX A

OICA Setpoints File created on 09-24-2005 at 00:52:06

Mode	Engine Speed	Torque
1	idle	0
2	1200	1310
3	1423	619
4	1423	929
5	1200	655
6	1200	983
7	1200	328
8	1423	1238
9	1423	310
10	1645	1142
11	1645	286
12	1645	857
13	1645	571

MaxPower: 358 MaxPowerSpeed: 1605 (Point: 1204)

NLo: 978 Nhi: 1867

NA:	1200	NA100:	1310
NB:	1423	NB100:	1238
NC:	1645	NC100:	1142

APPENDIX B

Table B Variation Analysis of Fuels

Property	Average	Standard Deviation	Coefficient of Variance
Sulfur (ppm)	328.3	103.3	31.5
Specific Gravity	0.837	0.019	2.2
API Gravity	37.6	3.8	10.1
Kinematic viscosity @ 40°C(cST)	2.501	0.228	9.1
Carbon	86.07	1.05	1.2
Hydrogen	13.37	0.54	4.0
Nitrogen (ppm)	132.3	150.6	113.9
Total Aromatics	22.5	10.2	45.3
Mono Aromatics	16.8	6.9	41.2
Polyaromatics	5.7	4.0	70.0
Cetane Number	52.0	7.6	14.6
Flash point (°F)	149.9	9.6	6.4
Distillation, (°F) IBP	342.0	12.7	3.7
5%	380.4	13.6	3.6
10%	396.8	19.2	4.8
15%	410.0	21.1	5.2
20%	422.4	22.2	5.2
30%	447.6	21.6	4.8
40%	473.5	19.5	4.1
50%	499.1	17.5	3.5
60%	524.6	16.3	3.1
70%	550.6	14.5	2.6
80%	577.4	12.7	2.2
90%	608.8	12.3	2.0
95%	632.3	15.5	2.4
FBP	650.9	18.7	2.9
Recovered	97.9	0.5	0.5
Loss	1.1	0.3	24.4
Residue	1.0	0.4	41.7

APPENDIX C

Figure C Cetane Number Versus Total Aromatics

APPENDIX D

Table D-1 Cummins FTP Data

Fuel	Sabraton Kroger						Guttman-1						Shell Bakersfield					
StartType	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV
Actual work (bhp-hr)	25.92	25.92	25.92	25.92	0.00	0.00	24.54	24.57	24.55	24.55	0.02	0.06	25.54	25.53	25.51	25.53	0.02	0.06
BSFC (lb/bhp-hr)	0.413	0.413	0.413	0.413	0.000	0.078	0.412	0.412	0.412	0.412	0.000	0.070	0.411	0.411	0.412	0.411	0.000	0.028
Fuel consumption (lb)	10.70	10.70	10.72	10.71	0.01	0.08	10.11	10.12	10.10	10.11	0.01	0.09	10.50	10.50	10.50	10.50	0.00	0.03
Fuel recovered (lb)	10.461	10.474	10.455	10.463	0.010	0.093	9.844	9.874	9.864	9.861	0.015	0.155	10.226	10.223	10.181	10.210	0.025	0.246
HC (g/bhp-hr)	0.182	0.185	0.184	0.184	0.002	0.861	0.195	0.199	0.204	0.199	0.004	2.139	0.198	0.202	0.202	0.201	0.002	1.209
CO (g/bhp-hr)	0.613	0.611	0.593	0.606	0.011	1.819	0.531	0.545	0.545	0.540	0.008	1.496	0.621	0.625	0.618	0.621	0.004	0.565
CO2 (g/bhp-hr)	582.7	583.4	582.3	582.8	0.6	0.1	570.6	571.7	571.4	571.3	0.6	0.1	572.9	572.9	570.9	572.2	1.1	0.2
NOx (g/bhp-hr)	2.295	2.298	2.294	2.296	0.002	0.091	2.093	2.103	2.108	2.101	0.008	0.363	2.158	2.164	2.161	2.161	0.003	0.139
NOx2 (g/bhp-hr)	2.310	2.311	2.312	2.311	0.001	0.043	2.132	2.115	2.124	2.124	0.009	0.400	2.168	2.175	2.168	2.170	0.004	0.186
PM (g/bhp-hr)	0.072	0.070	0.069	0.070	0.001	1.957	0.061	0.061	0.062	0.061	0.000	0.348	0.058	0.061	0.061	0.060	0.002	2.958
TEOM	0.051	0.050	0.050	0.050	0.000	0.644	0.040	0.042	0.042	0.041	0.001	2.965	0.039	0.041	0.042	0.040	0.002	3.860
Average humidity factor	1.023	1.022	1.023	1.023	0.001	0.056	1.009	1.012	1.014	1.012	0.003	0.249	1.007	1.009	1.013	1.010	0.003	0.303
Average relative humidity (%)	53.52	53.81	54.17	53.83	0.33	0.60	53.44	53.05	52.52	53.00	0.46	0.87	50.45	51.08	51.40	50.98	0.48	0.95
Intake absolute humidity (grain/lb)	83.54	83.32	83.80	83.55	0.24	0.29	78.58	79.51	80.19	79.43	0.81	1.02	77.80	78.45	79.75	78.67	0.99	1.26

Table D-2 Cummins FTP Data

Fuel	CEDC1						Sabraton Sheetz						Mileground BP					
StartType	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV
Actual work (bhp-hr)	25.26	25.24	25.24	25.25	0.01	0.05	25.99	25.98	25.97	25.98	0.01	0.04	25.73	25.71	25.71	25.72	0.01	0.04
BSFC (lb/bhp-hr)	0.416	0.415	0.417	0.416	0.001	0.227	0.415	0.414	0.414	0.415	0.001	0.153	0.415	0.415	0.412	0.414	0.002	0.366
Fuel consumption (lb)	10.51	10.47	10.52	10.50	0.03	0.24	10.80	10.76	10.76	10.77	0.02	0.19	10.68	10.66	10.60	10.64	0.04	0.39
Fuel recovered (lb)	10.07	10.08	10.10	10.08	0.02	0.19	10.49	10.50	10.50	10.50	0.01	0.06	10.29	10.28	10.31	10.29	0.01	0.12
HC (g/bhp-hr)	0.185	0.185	0.193	0.188	0.005	2.437	0.179	0.181	0.183	0.181	0.002	0.899	0.189	0.190	0.191	0.190	0.001	0.583
CO (g/bhp-hr)	0.545	0.545	0.555	0.548	0.006	1.053	0.587	0.571	0.563	0.574	0.012	2.130	0.572	0.577	0.565	0.571	0.006	1.055
CO2 (g/bhp-hr)	573.2	573.9	575.6	574.3	1.2	0.2	581.7	582.5	583.0	582.4	0.7	0.1	577.9	577.9	579.2	578.3	0.7	0.1
NOx (g/bhp-hr)	2.145	2.159	2.144	2.149	0.008	0.390	2.294	2.287	2.288	2.290	0.004	0.165	2.259	2.255	2.263	2.259	0.004	0.177
NOx2 (g/bhp-hr)	2.154	2.168	2.160	2.161	0.007	0.325	2.284	2.295	2.309	2.296	0.013	0.546	2.290	2.291	2.297	2.293	0.004	0.165
PM (g/bhp-hr)	0.058	0.062	0.061	0.060	0.002	3.046	0.074	0.074	0.074	0.074	0.000	0.605	0.071	0.073	0.073	0.072	0.001	1.236
TEOM	0.039	0.041	0.041	0.040	0.001	3.272	0.051	0.051	0.052	0.052	0.001	1.346	0.046	0.048	0.047	0.047	0.001	1.996
Average humidity factor	1.008	1.021	1.035	1.021	0.014	1.322	1.014	1.015	1.007	1.012	0.004	0.431	1.006	1.006	1.008	1.007	0.001	0.115
Average relative humidity (%)	51.54	51.46	53.38	52.13	1.09	2.08	51.49	50.83	49.64	50.65	0.94	1.85	52.88	52.37	52.44	52.56	0.28	0.53
Intake absolute humidity (grain/lb)	78.13	83.06	88.08	83.09	4.97	5.98	80.19	80.76	77.49	79.48	1.75	2.20	77.27	77.30	78.18	77.58	0.52	0.67

Table D-3 Cummins FTP Data

Fuel	Guttman-2						B20					
StartType	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV
Actual work (bhp-hr)	24.50	24.51	24.51	24.51	0.01	0.02	24.41	24.36	24.36	24.3767	0.02887	0.118
BSFC (lb/bhp-hr)	0.413	0.413	0.413	0.413	0.000	0.024	0.4274	0.4259	0.425	0.4261	0.00121	0.285
Fuel consumption (lb)	10.12	10.12	10.12	10.12	0.00	0.01	10.436	10.375	10.352	10.3877	0.04341	0.418
Fuel recovered (lb)	10.02	10.01	9.80	9.94	0.12	1.24	10.128	10.087	10.065	10.0933	0.03197	0.317
HC (g/bhp-hr)	0.197	0.202	0.197	0.199	0.003	1.437	0.1647	0.1672	0.1651	0.16567	0.00134	0.811
CO (g/bhp-hr)	0.554	0.554	0.544	0.551	0.006	1.048	0.525	0.524	0.523	0.524	0.001	0.191
CO2 (g/bhp-hr)	582.4	581.6	569.4	577.8	7.3	1.3	576.045	574.97	573.888	574.968	1.0785	0.188
NOx (g/bhp-hr)	2.102	2.095	2.110	2.102	0.008	0.357	2.222	2.217	2.229	2.22267	0.00603	0.271
NOx2 (g/bhp-hr)	2.113	2.108	2.140	2.120	0.017	0.812	2.25	2.25	2.25	2.25	0	0
PM (g/bhp-hr)	0.062	0.063	0.062	0.062	0.000	0.750	0.04303	0.04522	0.04798	0.04541	0.00248	5.462
TEOM	0.040	0.041	0.040	0.040	0.001	1.667	0.029	0.029	0.030	0.029	0.001	2.221
Average humidity factor	1.009	1.014	1.024	1.016	0.008	0.752	1.016	1.018	1.021	1.018	0.003	0.247
Average relative humidity (%)	50.03	49.91	52.81	50.92	1.64	3.22	51.36	50.37	50.69	50.81	0.51	0.99
Intake absolute humidity (grain/lb)	78.25	79.77	84.17	80.73	3.08	3.81	81.20	81.68	82.74	81.87	0.79	0.96

Table D-4 DDC FTP Data

Fuel	Guttman-1						Sabraton Kroger						Mileground BP					
StartType	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV
Actual work (bhp-hr)	23.22	23.22	23.17	23.20	0.03	0.1	24.83	23.17	23.20	23.73	0.95	4.0	24.58	24.57	24.56	24.57	0.01	0.0
BSFC (lb/bhp-hr)	0.38	0.38	0.38	0.38	0.00	0.1	0.39	0.38	0.38	0.38	0.01	1.8	0.39	0.39	0.39	0.39	0.00	0.4
Fuel consumption (lb)	8.794	8.794	8.77	8.786	0.013856	0.2	9.696	8.77	8.783	9.083	0.53091	5.8	9.529	9.571	9.598	9.566	0.03477	0.4
Fuel recovered (lb)	8.487	8.487	8.464	8.479	0.013	0.2	9.167	8.464	8.464	8.698	0.406	4.7	9.039	9.003	9.035	9.026	0.020	0.2
HC (g/bhp-hr)	0.1	0.1	0.1	0.1	0.0	4.5	0.1	0.1	0.1	0.1	0.0	8.2	0.1	0.1	0.1	0.1	0.0	0.7
CO (g/bhp-hr)	2.488	2.488	2.502	2.493	0.008	0.3	3.027	2.502	2.510	2.680	0.301	11.2	2.839	2.815	2.891	2.848	0.039	1.4
CO2 (g/bhp-hr)	517.2	517.2	516.6	517.0	0.3	0.1	529.3	516.6	516.1	520.7	7.5	1.4	527.9	526.1	527.9	527.3	1.1	0.2
NOx (g/bhp-hr)	4.466	4.466	4.476	4.469	0.006	0.1	5.304	4.476	4.454	4.745	0.485	10.2	5.139	5.109	5.127	5.125	0.015	0.3
NOx2 (g/bhp-hr)	4.477	4.477	4.494	4.48267	0.009815	0.2	5.3	4.494	4.468	4.754	0.47303	10.0	5.171	5.116	5.109	5.132	0.03396	0.7
PM (g/bhp-hr)	0.205	0.205	0.213	0.208	0.005	2.2	0.228	0.213	0.216	0.219	0.008	3.6	0.222	0.222	0.230	0.225	0.005	2.1
TEOM	0.157	0.157	0.163	0.159	0.004	2.4	0.169	0.163	0.167	0.166	0.003	1.7	0.164	0.160	0.167	0.163	0.004	2.2
Average humidity factor	1.00	1.00	1.00	1.00	0.00	0.1	0.99	1.00	1.00	1.00	0.01	0.7	0.98	0.98	0.98	0.98	0.00	0.3
Average relative humidity (%)	52.96	52.96	52.78	52.90	0.10	0.2	51.01	52.78	52.28	52.02	0.91	1.8	49.49	49.53	50.29	49.77	0.45	0.9
Intake absolute humidity (grain/lb)	75.127	75.127	75.534	75.263	0.235	0.3	71.050	75.534	75.961	74.182	2.720	3.7	66.782	66.025	68.036	66.948	1.016	1.5

Table D-5 DDC FTP Data

Fuel	Shell Bakersfield						CEDC1						Sabraton Sheetz					
StartType	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV
Actual work (bhp-hr)	24.46	24.40	24.66	24.51	0.14	0.6	24.29	24.03	24.51	24.28	0.24	1.0	24.87	24.90	24.92	24.90	0.03	0.1
BSFC (lb/bhp-hr)	0.39	0.39	0.39	0.39	0.00	0.2	0.41	0.46	0.39	0.42	0.03	8.3	0.39	0.39	0.39	0.39	0.00	0.4
Fuel consumption (lb)	9.45	9.45	9.53	9.48	0.05	0.5	10.00	11.01	9.55	10.18	0.75	7.3	9.71	9.66	9.66	9.68	0.03	0.3
Fuel recovered (lb)	9.03	8.95	9.04	9.01	0.05	0.5	8.95	8.88	9.02	8.95	0.07	0.8	9.24	9.27	9.28	9.26	0.02	0.2
HC (g/bhp-hr)	0.1	0.1	0.1	0.1	0.0	2.1	0.1	0.1	0.1	0.1	0.0	2.1	0.1	0.1	0.1	0.1	0.0	1.8
CO (g/bhp-hr)	3.128	3.056	3.075	3.086	0.037	1.2	2.760	2.722	2.669	2.717	0.046	1.7	2.913	2.835	2.731	2.826	0.091	3.2
CO2 (g/bhp-hr)	524.241	521.189	520.417	521.949	2.022	0.4	526.671	528.250	526.032	526.984	1.142	0.2	532.103	533.090	533.330	532.841	0.650	0.1
NOx (g/bhp-hr)	4.890	4.925	4.872	4.896	0.027	0.6	4.790	4.821	4.784	4.798	0.020	0.4	5.164	5.209	5.235	5.203	0.036	0.7
NOx2 (g/bhp-hr)	4.876	4.9	4.82	4.86533	0.041053	0.8	4.761	4.797	4.763	4.77367	0.02023	0.4	5.189	5.194	5.257	5.21333	0.0379	0.7
PM (g/bhp-hr)	0.238	0.231	0.236	0.235	0.004	1.6	0.230	0.225	0.224	0.226	0.003	1.4	0.245	0.234	0.230	0.236	0.008	3.4
TEOM	0.178	0.172	0.176	0.175	0.003	1.7	0.184	0.176	0.176	0.179	0.005	2.5	0.196	0.184	0.179	0.186	0.009	4.6
Average humidity factor	1.00	1.00	1.00	1.00	0.00	0.1	1.01	1.01	1.01	1.01	0.00	0.2	1.01	1.00	0.99	1.00	0.01	0.8
Average relative humidity (%)	50.38	51.42	51.65	51.15	0.68	1.3	51.88	51.19	50.97	51.35	0.47	0.9	52.64	52.75	53.25	52.88	0.33	0.6
Intake absolute humidity (grain/lb)	74.004	74.076	74.345	74.142	0.180	0.2	79.306	78.088	77.217	78.204	1.049	1.3	79.174	75.707	72.853	75.911	3.165	4.2

Table D-6 DDC FTP data

Fuel	Guttman-2						B20					
StartType	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV	Hot Start	Hot Start	Hot Start	Average	Standard Deviation	COV
Actual work (bhp-hr)	23.4	23.4	23.4	23.4	0.0	0.1	23.5	23.6	23.7	23.6	0.1	0.2
BSFC (lb/bhp-hr)	0.380	0.381	0.380	0.380	0.001	0.2	0.391	0.390	0.389	0.390	0.001	0.2
Fuel consumption (lb)	8.896	8.905	8.883	8.895	0.011	0.1	9.190	9.194	9.190	9.191	0.002	0.0
Fuel recovered (lb)	8.718	8.709	8.904	8.777	0.110	1.3	9.055	9.065	9.059	9.060	0.005	0.1
HC (g/bhp-hr)	0.096	0.093	0.098	0.096	0.002	2.6	0.084	0.091	0.089	0.088	0.004	4.1
CO (g/bhp-hr)	2.613	2.578	2.646	2.612	0.034	1.3	2.320	2.304	2.275	2.300	0.023	1.0
CO2 (g/bhp-hr)	527.1	527.6	539.2	531.3	6.8	1.3	531.6	530.9	529.3	530.6	1.2	0.2
NOx (g/bhp-hr)	4.599	4.586	4.585	4.590	0.008	0.2	4.767	4.799	4.801	4.789	0.019	0.4
NOx2 (g/bhp-hr)	4.649	4.675	4.645	4.656	0.016	0.3	4.815	4.857	4.837	4.836	0.021	0.4
PM (g/bhp-hr)	0.224	0.227	0.227	0.226	0.002	0.9	0.173	0.174	0.170	0.172	0.002	1.2
TEOM	0.169	0.172	0.178	0.173	0.005	2.7	0.139	0.140	0.141	0.140	0.001	0.6
Average humidity factor	1.02	1.02	1.01	1.01	0.01	0.7	1.00	1.00	1.00	1.00	0.00	0.1
Average relative humidity (%)	56.38	57.17	55.09	56.21	1.05	1.9	51.31	51.90	51.85	51.69	0.33	0.6
Intake absolute humidity (grain/lb)	81.49	82.339	82.752	82.1937	0.643	0.8	73.634	73.587	72.957	73.3927	0.378	0.5

APPENDIX E

Figure E-1 Fuel Specific CO Emissions

Figure D-1 Fuel Specific CO₂ Emissions

APPENDIX F

The GLM Procedure

Number of Observations Read   8
Number of Observations Used   8
Test1 analysis   23:17 Sunday, June 11, 2006   4

The GLM Procedure

Dependent Variable: Y1

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	0.00096129	0.00019226	540.97	0.0018
Error	2	0.00000071	0.00000036		
Corrected Total	7	0.00096200			

R-Square	Coeff Var	Root MSE	Y1 Mean
0.999261	0.316259	0.000596	0.188500

Source	DF	Type I SS	Mean Square	F Value	Pr > F
X1	1	0.00000002	0.00000002	0.05	0.8373
X4	1	0.00011979	0.00011979	337.07	0.0030
X5	1	0.00038943	0.00038943	1095.76	0.0009
X8	1	0.00044953	0.00044953	1264.89	0.0008
X14	1	0.00000252	0.00000252	7.08	0.1170

Source	DF	Type III SS	Mean Square	F Value	Pr > F
X1	1	0.00000173	0.00000173	4.87	0.1580
X4	1	0.00009496	0.00009496	267.20	0.0037
X5	1	0.00078513	0.00078513	2209.18	0.0005
X8	1	0.00040403	0.00040403	1136.85	0.0009
X14	1	0.00000252	0.00000252	7.08	0.1170

Standard				
Parameter	Estimate	Error	t Value	Pr > t
Intercept	-.8841417927	0.03085978	-28.65	0.0012
X1	-.0000079835	0.00000362	-2.21	0.1580
X4	-.0203968593	0.00124779	-16.35	0.0037
X5	0.0138803602	0.00029531	47.00	0.0005
X8	-.0010964726	0.00003252	-33.72	0.0009
X14	-.0000691828	0.00002600	-2.66	0.1170

Test1 analysis 23:27 Sunday, June 11, 2006 1

The GLM Procedure

Number of Observations Read 8

Number of Observations Used 8

Test1 analysis 23:27 Sunday, June 11, 2006 2

The GLM Procedure

Dependent Variable: Y2

Sum of					
Source	DF	Squares	Mean Square	F Value	Pr > F
Model	5	0.04412042	0.00882408	25.67	0.0379

Error	2	0.00068745	0.00034373

Corrected Total	7	0.04480787

R-Square	Coeff Var	Root MSE	Y2 Mean

0.984658	0.843631	0.018540	2.197625

Source	DF	Type I SS	Mean Square	F Value	Pr > F

X1	1	0.00010031	0.00010031	0.29	0.6432
X2	1	0.03747343	0.03747343	109.02	0.0090
X5	1	0.00518655	0.00518655	15.09	0.0603
X8	1	0.00061435	0.00061435	1.79	0.3130
X14	1	0.00074578	0.00074578	2.17	0.2786

Source	DF	Type III SS	Mean Square	F Value	Pr > F

X1	1	0.00044415	0.00044415	1.29	0.3735
X2	1	0.01932905	0.01932905	56.23	0.0173
X5	1	0.00623221	0.00623221	18.13	0.0510
X8	1	0.00077899	0.00077899	2.27	0.2712
X14	1	0.00074578	0.00074578	2.17	0.2786

Standard

Parameter	Estimate	Error	t Value	Pr > t
Intercept	2.033926387	0.94198485	2.16	0.1635
X1	0.000125755	0.00011063	1.14	0.3735
X2	5.120755409	0.68286543	7.50	0.0173
X5	-0.040307116	0.00946601	-4.26	0.0510
X8	0.001789106	0.00118844	1.51	0.2712

X14	-0.001163939	0.00079019	-1.47	0.2786

The GLM Procedure

Number of Observations Read	8

Number of Observations Used	8

Test1 analysis	23:27 Sunday, June 11, 2006	6

The GLM Procedure

Dependent Variable: Y3

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	0.00059614	0.00011923	127.96	0.0078
Error	2	0.00000186	0.00000093		
Corrected Total	7	0.00059800			

R-Square	Coeff Var	Root MSE	Y3 Mean
0.996884	1.532206	0.000965	0.063000

Source	DF	Type I SS	Mean Square	F Value	Pr > F
X1	1	0.00007086	0.00007086	76.05	0.0129
X2	1	0.00029585	0.00029585	317.51	0.0031
X5	1	0.00022040	0.00022040	236.54	0.0042
X8	1	0.00000210	0.00000210	2.25	0.2721
X14	1	0.00000692	0.00000692	7.42	0.1124

Source	DF	Type III SS	Mean Square	F Value	Pr > F
X1	1	0.00001508	0.00001508	16.18	0.0566
X2	1	0.00001658	0.00001658	17.80	0.0519
X5	1	0.00019763	0.00019763	212.10	0.0047
X8	1	0.00000125	0.00000125	1.35	0.3657
X14	1	0.00000692	0.00000692	7.42	0.1124

Standard				
Parameter	Estimate	Error	t Value	Pr > t
Intercept	-.6154553332	0.04904506	-12.55	0.0063
X1	0.0000231724	0.00000576	4.02	0.0566
X2	0.1499857509	0.03555384	4.22	0.0519
X5	0.0071777200	0.00049285	14.56	0.0047
X8	-.0000718036	0.00006188	-1.16	0.3657
X14	-.0001120976	0.00004114	-2.72	0.1124

The GLM Procedure

Number of Observations Read 8
Number of Observations Used 8
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The GLM Procedure

Dependent Variable: Y4

Sum of					
Source	DF	Squares	Mean Square	F Value	Pr > F
Model	5	0.00081094	0.00016219	2.34	0.3259
Error	2	0.00013856	0.00006928		

Corrected Total   7   0.00094950

R-Square   Coeff Var   Root MSE   Y4 Mean

0.854757   7.833838   0.008323   0.106250

Source	DF	Type I SS	Mean Square	F Value	Pr > F
X1	1	0.00026951	0.00026951	3.89	0.1873
X11	1	0.00009157	0.00009157	1.32	0.3692
X5	1	0.00036803	0.00036803	5.31	0.1477
X8	1	0.00008098	0.00008098	1.17	0.3927
X14	1	0.00000085	0.00000085	0.01	0.9218

Source	DF	Type III SS	Mean Square	F Value	Pr > F
X1	1	0.00007942	0.00007942	1.15	0.3964
X11	1	0.00000101	0.00000101	0.01	0.9148
X5	1	0.00044238	0.00044238	6.39	0.1274
X8	1	0.00008180	0.00008180	1.18	0.3907
X14	1	0.00000085	0.00000085	0.01	0.9218

	Standard			
Parameter	Estimate	Error	t Value	Pr > t
Intercept	-.8434674946	0.42290335	-1.99	0.1843
X1	-.0000531768	0.00004967	-1.07	0.3964
X11	0.0370595655	0.30657189	0.12	0.9148
X5	0.0107388956	0.00424976	2.53	0.1274
X8	-.0005797707	0.00053355	-1.09	0.3907
X14	0.0000393751	0.00035476	0.11	0.9218

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The GLM Procedure

Number of Observations Read 8

Number of Observations Used 8

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The GLM Procedure

Dependent Variable: Y5

Source	Sum of		Mean Square	F Value	Pr > F
	DF	Squares			
Model	5	0.36352297	0.07270459	2.25	0.3363
Error	2	0.06475991	0.03237995		
Corrected Total	7	0.42828288			

R-Square	Coeff Var	Root MSE	Y5 Mean
0.874745	3.727967	0.179944	4.826875

Source	DF	Type I SS	Mean Square	F Value	Pr > F
X1	1	0.00092170	0.00092170	0.03	0.8815
X6	1	0.30607461	0.30607461	9.45	0.0915
X5	1	0.00965001	0.00965001	0.30	0.6399
X8	1	0.01157446	0.01157446	0.36	0.6106
X14	1	0.03530219	0.03530219	1.09	0.4060

Source	DF	Type III SS	Mean Square	F Value	Pr > F
X1	1	0.05775478	0.05775478	1.78	0.3134
X6	1	0.13841507	0.13841507	4.27	0.1746
X5	1	0.00113191	0.00113191	0.03	0.8689
X8	1	0.01678144	0.01678144	0.52	0.5463
X14	1	0.03530219	0.03530219	1.09	0.4060

Standard				
Parameter	Estimate	Error	t Value	Pr > t
Intercept	-10.51551490	9.14272646	-1.15	0.3690
X1	0.00143402	0.00107374	1.34	0.3134
X6	13.70315324	6.62776249	2.07	0.1746
X5	-0.01717778	0.09187533	-0.19	0.8689
X8	-0.00830396	0.01153477	-0.72	0.5463
X14	0.00800804	0.00766944	1.04	0.4060
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The GLM Procedure

Number of Observations Read 8
Number of Observations Used 8
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The GLM Procedure

Dependent Variable: Y6

Sum of					
Source	DF	Squares	Mean Square	F Value	Pr > F
Model	5	0.00263552	0.00052710	2.85	0.2802
Error	2	0.00037036	0.00018518		

Corrected Total   7   0.00300588

R-Square   Coeff Var   Root MSE   Y6 Mean

0.877465   6.231500   0.013608   0.218375

Source	DF	Type I SS	Mean Square	F Value	Pr > F
X1	1	0.00002871	0.00002871	0.16	0.7318
X4	1	0.00048528	0.00048528	2.62	0.2469
X5	1	0.00194233	0.00194233	10.49	0.0836
X8	1	0.00017917	0.00017917	0.97	0.4290
X14	1	0.00000002	0.00000002	0.00	0.9935

Source	DF	Type III SS	Mean Square	F Value	Pr > F
X1	1	0.00001359	0.00001359	0.07	0.8119
X4	1	0.00000190	0.00000190	0.01	0.9285
X5	1	0.00208717	0.00208717	11.27	0.0784
X8	1	0.00017695	0.00017695	0.96	0.4314
X14	1	0.00000002	0.00000002	0.00	0.9935

	Parameter	Estimate	Standard Error	t Value	Pr > t
	Intercept	-1.723709296	0.69140594	-2.49	0.1302
	X1	-0.000021996	0.00008120	-0.27	0.8119
	X4	-0.050809363	0.50121529	-0.10	0.9285
	X5	0.023325969	0.00694794	3.36	0.0784
	X8	-0.000852703	0.00087230	-0.98	0.4314
	X14	0.000005362	0.00057999	0.01	0.9935