The effect of fatty acid composition on emissions from biodiesel-fueled diesel engines

by

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TABLE OF CONTENTS

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1. INTRODUCTION

Rudolf Diesel, a German engineer, introduced the compression ignition engine over 100 years ago in 1892. In the last 20 years engine research and development has exploded in order to address the issues of air pollution, fuel supplies, and international competition. Based on the diesel engine's superiority in fuel economy and low emissions of hydrocarbons and carbon monoxide, the diesel engine is a popular choice for medium and heavy duty applications. However, due to dwindling petroleum supplies and increasing air pollution concerns, interest in renewable fuels has become increasingly important.

A number of studies have shown that organic seed oils, such as soybean, safflower, rapeseed, and their esters, are viable alternative fuels for diesel engines. One benefit of these alternative diesel fuels is that they are nontoxic and biodegradable. Two areas where vegetable oils and biodiesel have significant advantages over diesel are its low particulate emissions and high cetane number.

A number of diesel emissions studies have been conducted with blends of esters of vegetable oils with diesel fuel. Specifically, extensive research has been conducted with methyl soyate, the methyl ester of soybean oil. However, no study has investigated why methyl soyate reduces emissions. Also, no research has been conducted to determine which ester in methyl soyate provides the lowest emissions. Knowing which ester produces the lowest emissions could lead to breeding of soybeans to produce more of the low emission fatty acid. Also, the soybean oil could be processed differently in order to produce more of low emission esters. The objective of this study is to test the various esters in methyl soyate to determine which ester produces the lowest emissions. This should provide a basis for understanding methyl soyate's emission reduction effect. Also, the cetane improving effect of methyl soyate is evaluated.

The major tasks for this project were:

1. Evaluate the impact of the oxygen content in the methyl soyate on the exhaust emissions from a diesel engine and compare the emissions of blends of methyl soyate with diesel fuel, octadecane with diesel, and a cetane improver with No. 2 diesel fuel.
2. Compare the emission levels of the various fatty esters which make up methyl soyate.

2. LITERATURE REVIEW

In this chapter vegetable oils and their esters are discussed and their emissions characteristics are evaluated.

2.1 Vegetable Oils

Interest in vegetable oils as alternative diesel engine fuels resulted from the oil shortages of the 1970's. In the late 1970's and early 1980's extensive research on vegetable oils as a possible diesel fuel substitute was conducted. Many researchers concluded that vegetable oils can be safely burned for short periods of time in diesel engines. However, using raw vegetable oils in diesel engines for extended periods of time may result in undesirable effects on the engine. For instance, heavier ring groove deposits and ring sticking have been observed [1,2,3]. Also, injector deposits increase dramatically and spray patterns are adversely affected with use of vegetable oils. Schlautman et al. [2] observed that after 159 hours of use the fuel injectors no longer atomized the fuel, instead, the fuel injector only produced four streams of fuel.

Another problem with vegetable oils relates to their physical properties. Table 2.1 lists a few properties of some common vegetable oils compared with diesel fuel. One can see that the viscosity of the vegetable oils is between 10 and 15 times larger than the viscosity of No. 2 diesel fuel. Higher viscosity reduces fuel atomization and increases fuel injection spray penetration. Deeper spray penetration increases the likelihood of fuel impinging on the cylinder wall, which is believed to increase piston ring sticking and lubrication oil dilution [2,3]. Also, the cloud and pour points of the vegetable oils are considerably higher than for

Table 2.1. Fuel properties of vegetable oil [5].

Fuel	HHV, MJ/kg	Cetane No.	Cloud Point, °C	Pour Point, °C	Viscosity, cSt @40°C
Peanut Oil	39.5	41.8	12.8	-6.7	39.60
Soybean Oil	39.6	37.9	-3.9	-12.2	32.60
Sunflower Oil	39.6	37.1	7.2	-15.0	33.90
No. 2 Diesel	45.3	47.0	-15.0	-33.0	2.70

diesel fuel. The cloud point of a fuel is the temperature at which the fuel begins to crystallize and become cloudy. The pour point is the temperature where the fuel will no longer flow from an overturned container. A high cloud and pour point restricts the usage of the fuel to warm climates and summer use.

If vegetable oils are to compete with diesel fuel, the oil must meet today's exhaust emissions standards with only minor modifications to the engine or exhaust system. Barsic and Humke [1] fueled a single cylinder, direct injection, naturally-aspirated diesel engine with peanut oil, sunflower oil, and 50/50 blends of these oils with No. 2 diesel fuel. The results indicated that the oxides of nitrogen (NO_x) emissions for the vegetable oils were not significantly different than for diesel fuel. Increases in unburned hydrocarbon (HC), carbon monoxide (CO), and particulate emissions at maximum fuel delivery were due primarily to operation at higher equivalence ratios. Based on an equal energy input, NO_x emissions were similar for the vegetable oils and their blends with diesel fuel. Hydrocarbon emissions for peanut oil, sunflower oil and their blends were 50% higher than for neat diesel fuel. Carbon monoxide emissions for vegetable oils were about twice that of diesel fuel for some operating conditions and lower for others. The increase in CO emissions as greater amounts of vegetable oil were blended with diesel fuel may be due to fuel property effects. Also, particulate emissions increased as the concentration of vegetable oil was increased. There were generally higher emissions as the concentration of vegetable oil was increased.

Hemmerlein et al. [6] used six diesel engines to evaluate the engine performance and emissions characteristics when fueled with rapeseed oil. The results were that CO emissions were up to 100% higher with rapeseed oil compared to diesel fuel. An increase in HC emission was also measured. The increase depended on the operating range of the engines and could increase by as much as 290% compared to diesel fuel, but the NO_x emissions were up to 25% lower with rapeseed oil. Particulate emissions were reduced by 30 to 50% with rapeseed oil in engines with indirect injection combustion chambers. Direct injection engines showed higher particulate emissions (90 to 140%) with rapeseed oil compared to diesel fuel.

The results discussed above indicate mixed results when using vegetable oils in diesel engines. A large amount of research has also been conducted with vegetable oil esters, commonly referred to as biodiesel. Biodiesel consists of alkyl esters of fats and oils from renewable sources, such as plants and animals. Nearly every study performed to date has shown that alcohol esters of vegetable oils or their blends with No. 2 diesel fuel can be used as a substitute for diesel in short term tests. The presence of oxygen atoms in the biodiesel fuels assures more complete combustion of the fuel. This reduces CO, HC, and particulate matter in the exhaust gas when compared to No. 2 diesel fuel. In order to better understand esters, the esterfication process, called transesterfication, is explored next.

2.2 Transesterfication

In order to solve some of the problems associated with burning vegetable oils in diesel engines, the vegetable oils may be reacted with an alcohol to create an ester. Figure 2.1 shows the chemical reaction for producing esters of vegetable oils. The vegetable oils consist of a 3-carbon glycerin molecule with three attached fatty acid chains, represented by R_1, R_2, and R_3. This molecule is called a triglyceride. The transesterfication process involves reacting the vegetable oil with an excess of the stoichiometric amount of alcohol in the presence of a base catalyst [4]. Figure 2.1 illustrates the reaction using methyl alcohol and potassium hydroxide. Other alcohols, such as ethyl, isopropyl, and butyl alcohol, may be used instead of methyl alcohol. Also, many bases may be used in the place of potassium hydroxide.

2.3 Properties of Vegetable Oil Esters

Table 2.2 lists some of the properties of alcohol esters of vegetable oils. The viscosities of the esters are reduced substantially from the viscosities measured for the

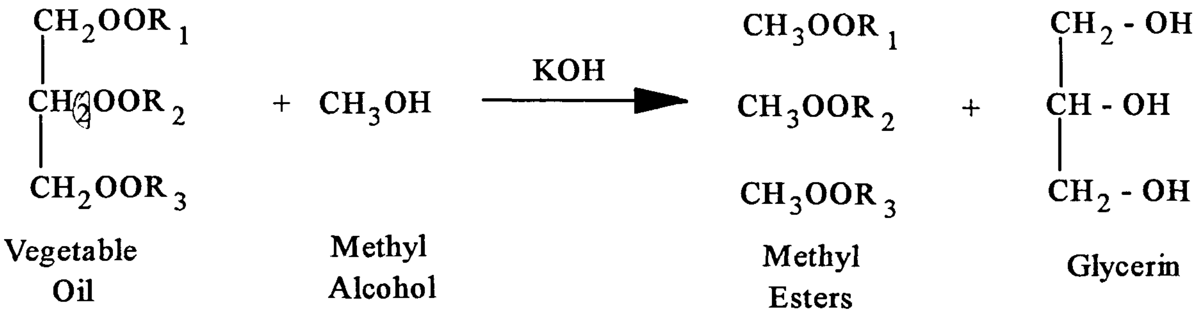

Figure 2.1. Transesterfication of vegetable oil using methyl alcohol and potassium hydroxide catalyst [4].

vegetable oils, although they are still slightly higher than No. 2 diesel fuel. Reducing the viscosity will improve fuel atomization and improve air-fuel mixing in the combustion chamber. The heating values of the esters are slightly increased from their vegetable oil derivatives. However, the heating values for the esters are still lower than the heating value of diesel fuel. A lower heating value will result in slightly higher fuel consumption.

Freedman et al. [7] investigated possible methods for predicting the heat of combustion for fatty esters and triglycerides. First, the heat of combustion was measured using a Parr adiabatic calorimeter according to a modification of ASTM D240 and D2015. A linear regression analysis yielded equations that related the heat of combustion to carbon number (CN) or chain length, electron number (EN) or number of valence electrons, or molecular weight (MW). The calculated heats of combustion for the fuels were nearly

Table 2.2. Fuel properties of vegetable oil esters [5].

Fuel	HHV, MJ/kg	Cetane No.	Cloud Point, °C	Pour Point, °C	Viscosity, cSt @40°C
Methyl Soybean	39.8	46.2	2.0	-1.0	4.08
Ethyl Soybean	40.0	48.2	1.0	-4.0	4.41
Butyl Soybean	40.7	51.7	-3.0	-7.0	5.21
Methyl Sunflower	39.8	47.0	0.0	-	-
Methyl Peanut	-	54.0	5.0	-	4.90
Methyl Rapeseed	40.1	-	-3.3	-14.7	6.10
Ethyl Rapeseed	41.4	-	-4.7	-18.7	6.75
No. 2 Diesel	45.2	46.0	-19.0	-33.0	2.70

identical for all three regression equations, based on either CN, EN, or MW.

One of the most important properties of a fuel used in a compression ignition engine is the cetane number. The cetane number is a measure of the ignition quality of a fuel. Ignition quality is dependent on a number of factors such as molecular weight, structure, and volatility. Goering et al. [8] reported that the cetane number of fatty esters increases with increasing carbon chain lengths and decreasing number of double bonds. Callahan et al. [9] investigated the cetane numbers of several fatty esters, fatty alcohols, and triglycerides using a constant volume bomb. He established a relationship which calculated an estimated cetane number (ECN) from the measured ignition delay time as determined in the bomb. Callahan also reported that the ECN increased with carbon length from C_{12} to C_{20} with saturated esters, and from C_{14} to C_{18} for saturated alcohols. For saturated triglycerides the ECN decreased with increasing carbon numbers from C_{12} to C_{18}. For all classes of fatty materials, the ECN decreased as unsaturation increased.

Freedman et al. [10] correlated the cetane number of methyl esters with various other properties. The measured cetane number and physical properties of the esters were analyzed to obtain regression equations and to rank the physical properties' ability to correctly estimate cetane number according to the R-squared values. The descending order of precision for predicting cetane number from the physical properties is as follows: boiling point, viscosity, heat of vaporization, heat of combustion, carbon number, surface tension, melting point, refractive index (n^{20}_{d}), and density.

A common method of increasing the cetane number of a diesel fuel is to add a small amount of what is called a cetane improver. One of the most common cetane improvers available today is ethylhexyl nitrate. Sobotowski et al. [11] studied the cetane response of several low sulfur diesel fuels with ethylhexyl nitrate used as a cetane improver. Seven fuels from East Coast, Gulf Coast and Midwest refineries, an emissions certification fuel and a low aromatic California fuel were evaluated. The test results demonstrated a lower cetane response of the non-California diesel fuels than would have been considered typical in the past. However, the low aromatic California fuels were exceptionally responsive to the addition of ethylhexyl nitrate. For example, for a 0.1% ethylhexyl nitrate concentration, the non-California fuels produced a 2.9-3.9 cetane increase, but the low aromatic California fuel produced a 7.6 increase in cetane number. Also, relatively small differences in cetane response of the non-California fuels were observed.

2.4 Effect of Fuel Composition on Engine Emissions

Using biodiesel or blends of biodiesel with diesel fuel has several desirable effects on the fuel properties. First, biodiesels have higher cetane numbers than No. 2 diesel. This higher cetane number is believed to help reduce particulate emissions. Another desirable effect biodiesel produces is the reduction of aromatic compounds in the fuel. The presence of aromatic compounds in the fuel is believed to increase particulate formation in diesel engines [32]. The final desirable effect of biodiesel is the presence of oxygen in the fuel. The additional oxygen leans out the mixture and helps reduce particulate, HC, and CO. Unfortunately, it also tends to increase NO_x concentrations.

Spreen et al. [23] fueled a 1994 7.6 liter Navistar DTA-466, direct injection, turbocharged and aftercooled heavy-duty diesel engine with a set of ten fuels having specific variations in cetane number, aromatics, and oxygen to study the effects of those fuel properties on emissions. The emissions were measured during the EPA transient FTP operation of the Navistar engine tuned for a nominal 5 g/hp-hr NO_x, then repeated using a 4 g/hp-hr NO_x calibration.

For the Navistar engine the cetane number was determined to be the most important fuel variable associated with HC, CO, and NO_x emissions. The emissions data indicated that the engine was more sensitive to cetane number changes when it was calibrated for 4 g/hp-hr NO_x emissions than 5 g/hp-hr NO_x emissions. For the 4 gram calibration, increasing cetane number by 10, while keeping all other fuel variables constant, resulted in a HC decrease 13 times as great as the corresponding HC decrease for the 5 gram calibration. For a cetane number increase of 10, the CO and NO_x emissions for the 4 gram calibration decreased by 4.5 and 1.5 times the amount of the corresponding decreases for the 5 gram calibration. Increasing only cetane number decreased particulate emissions for the 4 gram calibration but did not change the particulate emissions for the 5 gram calibration.

Spreen reduced the aromatic content of the fuel by using fuels with a naturally low aromatic content (10%). The aromatic content of the fuel significantly affected particulate matter emissions for both engine calibrations. Aromatic content was a significant factor for the emissions of HC and NO_x for the 5 gram calibration, but not for the 4 gram calibration.

The oxygen level of the fuel was increased by adding two forms of glycol diether materials, ethylene glycol dimethyl ether (monoglyme) and diethylene glycol dimethyl ether (diglyme). The oxygen content of the fuel was a significant variable in particulate matter emissions. A 2 percent oxygen content of the fuel produced an equal particulate matter decrease for both engine calibrations. For the 5 gram calibration, addition of monoglyme increased HC emissions, but addition of diglyme did not. Also, for the 5 gram calibration, addition of diglyme increased NO_x, but monoglyme did not.

2.5 Durability

Zhang et al. [12] used three Yanmar 3TN75E-S direct injected, naturally aspirated diesel engines fueled with the methyl ester of rapeseed oil, a 50/50 blend of methyl ester of rapeseed oil with No. 2 diesel, and No. 2 diesel to evaluate engine durability and performance. The three engines were tested with their respective fuels for 200 hours. It was determined that the methyl ester of rapeseed oil and diesel fuel did not show significant differences when compared on a basis of performance and durability. Factors investigated include engine brake power, thermal efficiency, carbon deposits, injector tip coking, lubrication oil deterioration, and wear of engine components. The only noticeable undesirable effect of the ester fuel was an increase in lubricating oil dilution. The engine fueled with the 50/50 blend showed possible durability problems including carbon deposits in the combustion chamber, injector coking, and an increase in metal concentration in the lubricating oil.

Perkins et al. [13] also used three Yanmar 3TN75E-S direct injected, naturally aspirated diesel engines fueled with methyl ester of rapeseed oil, a 50/50 blend of methyl ester of rapeseed oil with No. 2 diesel, and No. 2 diesel. Each engine was operated for 1000 hours to evaluate the engine's durability. The primary factors which were investigated were engine brake power, injector coking, and engine component wear. It was found that the methyl ester of winter rapeseed oil was equivalent to No. 2 diesel when compared on the basis of long term performance and wear. The only noticeable adverse effect due to the ester fuel was a slight decrease in the engine oil viscosity.

2.6 Diesel Engine Emissions Fueled with Vegetable Oil Esters

One of the most important areas of research of biodiesel is the engine emissions produced by engines fueled with biodiesel. Geyer et al. [14] reported that methyl esters of cottonseed and sunflower oil have displayed significant reductions in particulate, but have contributed to higher exhaust temperatures as well as higher NO_x emissions. Kaufman and Ziejewski et al. [15] found that methyl and ethyl esters of sunflower oil have reduced smoke emissions. Contrary to Geyer's results, Kaufman and Ziejewski found that the methyl and ethyl esters of sunflower oil reduced exhaust temperature. Furthermore, Kaufman and Ziejewski found that the methyl esters of winter rapeseed oil, when evaluated as a supplement to diesel fuel, have demonstrated smoke and exhaust temperature reduction in blends containing as little as 10% ester.

Schumacher et al. [16] used a Caterpillar 3408 and four International Harvester 574 tractors fueled with diesel fuel and soybean-based biodiesel blends to test the engine's emissions and performance. The results indicated that engines fueled with 100% soybean-based biodiesel did not lose a significant amount of maximum torque capacity, but developed approximately 5 to 7% less power at peak power conditions than engines fueled with No. 2 diesel fuel. The engine's exhaust opacity readings declined as the concentration of soybean-based biodiesel in the biodiesel/No. 2 diesel fuel blend increased. Carbon monoxide emissions tended to decrease when engines were operated at peak torque as the percent of soybean-based biodiesel in the fuel mixture increased, but remained relatively constant at peak power conditions. NO_x exhaust emissions tended to be lower when engines were fueled with 10-40% biodiesel/diesel blends compared to 100% diesel or 100% soybean-based biodiesel, with 100% soybean-based biodiesel having the highest NO_x emissions. Kusy [17] found similar results when he fueled a direct injection John Deere 4640 tractor with the ethyl ester of soybean oil.

Schumacher et al. [18] also used a 5.9 liter direct injection turbocharged Cummins diesel engine in a Dodge pickup to compare engine efficiency, wear, performance, and emissions of 100% soybean-based biodiesel with 100% diesel fuel. He found that the fuel efficiency was nearly identical to that obtained when the engine was fueled with diesel fuel. The engine did not appear to be wearing at an accelerated rate and no abnormal coking was observed on the fuel injectors, on top of the piston, or on the valves. The power of the engine fueled with 100% soybean-based biodiesel was 5% less than when fueled with No. 2 diesel. Carbon monoxide emissions stayed about the same, HC was reduced by 48%, particulate matter by 20%, but NO_x emissions were increased by 13% when the engine was fueled with 100% soybean-based biodiesel. Based on performance tests with 100% soybean-based biodiesel in a 1.6 liter Volkswagon indirect injection diesel engine, Pischinger et al. [19] reported that the difference in power and torque between diesel fuel and soybean-based biodiesel were insignificant while smoke levels were significantly lower for biodiesel compared with diesel fuel.

The effects of methyl, ethyl, and butyl esters of soybean oil on the performance and emissions of a John Deere 4239TF, direct injection, turbocharged diesel engine were investigated by Wagner et al. [20]. The performance of soybean-based biodiesel did not differ greatly from those of diesel fuel. The HC, CO, and particulate matter emissions were similar to diesel fuel. NO_x emissions were higher for all the ester fuels. Smoke was definitely less visible under full rack conditions for the methyl and ethyl esters compared to diesel fuel, but was greater for the butyl ester.

Alfuso et al.[21] found that methyl ester of rapeseed oil caused a rise in NO_x emissions, a decrease in HC and CO emissions, and a strong reduction in smoke levels in direct injected diesel engines. However, particulate matter produced by the methyl ester in transient cycles was higher than that given by diesel fuel. Mittelbach et al. [22] noted that two different methyl ester fuels derived from rapeseed oil gave significantly lower total particulate matter and polynuclear HC emissions than No. 2 diesel. However, the methyl ester fuels produced higher levels of NO_x emissions and aldehyde emissions than did No. 2 diesel fuel. Geyer et al. [14] reported that methyl esters of cottonseed and sunflower oil displayed significant reductions in particulates, but also had higher exhaust gas temperatures as well as higher NO_x levels.

Zhang et al. [25] used a John Deere 4276T, four cylinder, turbocharged, direct injected diesel engine to investigate the emission characteristics of blends of methyl and isopropyl esters of soybean oil with No. 2 diesel fuel during a steady state test. All of the esters were observed to reduced CO emissions, with the greatest reduction of 25.3% produced by a 50% blend of methyl ester with diesel. Also, all of the esters produced lower HC emissions with the maximum reduction of 29.0% from the 50% isopropyl ester blended with diesel. Particulates and solid carbon emissions were significantly reduced when the engine was fueled with blends of methyl and isopropyl esters. The 50% isopropyl ester blended with diesel fuel gave the largest reduction of particulates and solid carbon emissions, at 28.0% and 55.3%, respectively. However, the soluble organic fraction of the particulates for the methyl and isopropyl blends increased with increasing concentrations of esters in the fuel blends. The NO_x emissions for all ester blends were slightly higher than for diesel fuel.

McDonald et al. [24] used a Caterpillar 3304 PCNA, 7 liter, indirect injection, naturally aspirated diesel engine equipped with a diesel oxidation catalyst. The engine was fueled with soybean-based biodiesel and blends with diesel to test the engine's emission and performance characteristics. The results showed that when the engine was fueled with 100% soybean-based biodiesel the engine had 9% less peak power and 13.7% higher brake specific fuel consumption than when fueled with No. 2 diesel fuel. When the engine was fueled with a 30/70 blend of soybean-based biodiesel with No. 2 diesel, the blend produced 4% less peak power and had 3.8% greater brake specific fuel consumption.

The tests performed by McDonald included a steady state and a transient engine test. The steady state test was the ISO 8178-C1 steady state test procedure. The 30/70 blend decreased total particulate matter without the oxidation catalyst, but the decrease was not statistically significant. The neat soybean-based biodiesel reduced total particulate by 31%

without the oxidation catalyst. When the oxidation catalyst was used, the blend reduced particulate matter by 35% and the neat soybean-based biodiesel reduced particulate matter by 59% when compared to No. 2 diesel fuel. The particulate matter results for the transient test were similar to the steady-state ISO tests, with the neat soybean-based biodiesel providing total particulate matter reductions of 23% for the light-duty transient cycle and 30% for the heavy-duty transient cycle.

McDonald reported that gaseous emissions showed a decrease of several species for the neat soybean-based biodiesel. The neat-soybean based biodiesel showed a 12% reduction in NO_x when compared to diesel, but the 30/70 blend did not show a statistically significant change. Using neat soybean-based biodiesel reduced HC by 24% and HC was reduced 18% for the 30/70 blend. The CO did not decrease when using the neat soybean-based biodiesel, but decreased 6% when the 30/70 blend was used.

In general, vegetable oils, their esters, and their blends with diesel fuel, lower carbon monoxide, unburned hydrocarbon, smoke and particulate emissions, but usually increase NO_x emissions slightly relative to No. 2 diesel fuel. The engine performance and durability of these fuels is also similar to diesel fuel. Vegetable oil esters have proven that they have the potential to replace diesel fuel. They also show potential for being useful as diesel fuel additives to reduce emissions and improve cetane numbers.

3. EQUIPMENT AND PROCEDURES

This chapter will dicuss the equipment used for this study and descibe how the equipment was used. First, a brief description of the engine setup is presented. The second section discusses the emissions equipment used in the study. The third section describes the data acquisition system used to collect the data. The last section discusses methods and equations used for data analysis.

3.1 Engine Test Setup

The engine used to conduct the engine tests was a John Deere 4276T four cylinder, turbocharged, direct injected diesel engine. The engine specifications are given in Table 3.1. The engine was connected to a General Electric model TLC2544 DC electric dynamometer. The dynamometer was controlled with a GE Siltron dynamometer controller. The dynamometer was used to control the speed of the engine. The output torque from the engine was controlled by changing the rack position of the fuel injection pump. The engine torque

Table 3.1. Specifications of John Deere 4276T.

Bore	106.5 mm
Stroke	127.0 mm
Connecting Rod Length	202.9 mm
Compression Ratio	16.8
Maximum Power	57.1 kW @ 2100 rpm
Peak Torque	305.0 N-m
Firing Order	1-3-4-2

was measured with a Lebow load cell mounted on the dynamometer torque arm.

Fuel consumption was determined by placing a six gallon fuel tank on a Toledo model 8140 Weight Plate electronic scale with a 0.01 kg resolution. The mass of the fuel was recorded at the beginning and end of each test. The time between fuel measurements was measured with a stopwatch. Fuel temperature was measured by a thermocouple at the inlet to the fuel injection pump and held constant at 40 °C ± 2 °C. The fuel was cooled by a shell and tube heat exchanger after leaving the tank and was reheated with a 250 Watt Chromalox model CIR-2101 cartridge heater. The heater was controlled by an Omega model CN76022 electronic temperature controller and model SSR240AC25 solid-state relay.

The atmospheric pressure was measured with a Datametrics Barocel pressure sensor. Boost pressure, exhaust pressure, and engine lubricating oil pressure were measured with bourdon pressure gauges. A Kistler model 6061A pressure transducer was installed in the engine cylinder head and was used to measure the cylinder pressure at every 0.25 degree of crankshaft rotation. The pressure signal was amplified with a PCB charge amplifier and recorded with a Zenith Z-386 computer through an Analog Devices RTI-860 data acquisition board. A computer program collected pressure data for 24 engine cycles, calculated an average cycle, and the result was saved to a floppy disk.

Thermocouples were used to measure temperatures at various locations on the engine and the emissions sampling system. The thermocouples used for this study are listed in Appendix A.

The volume flow rate of air into the engine was measured with a Meriam model

50MC2-4 laminar flow element. The pressure drop across the laminar flow element was measured with a water manometer.

3.2 Emission Measurement Equipment

3.2.1 Gaseous Emissions Equipment

The sampling system used for all the gaseous emission analyzers except the hydrocarbon analyzer is illustrated in Figure 3.1. The sample was drawn from the exhaust pipe after the turbocharger with a vacuum pump. Two filters were used to remove particulates and other solid material from the sample stream. The first filter was a 12 inch long, 1 inch diameter stainless steel tube loosely packed with glass wool. The second filter was a Balston model 38/25 filter. After the sample stream was filtered, it was passed through a condenser. The condenser is a coil of 0.375 inch diameter stainless steel tubing in a 10 gallon container filled with ice water. The water in the sample stream condensed on the interior surface of the tubing. The water ran down the tube into a reservoir constructed of PVC plastic. The dried sample exited the ice bath and was introduced into a manifold, where the sample was distributed to the analyzers. The concentrations of carbon monoxide and carbon dioxide in the engine exhaust were measured with two Beckman model 864 infrared analyzers. The concentrations of nitric oxide and total oxides of nitrogen were determined with a Beckman model 955 chemiluminescent NO/NO_x analyzer and a Thermo Electron model 10A chemiluminescent NO/NO_x analyzer.

The sample for the hydrocarbon analyzer was drawn from the exhaust pipe after the turbocharger. The sample was drawn to the analyzer through a line heated to 190 °C by a

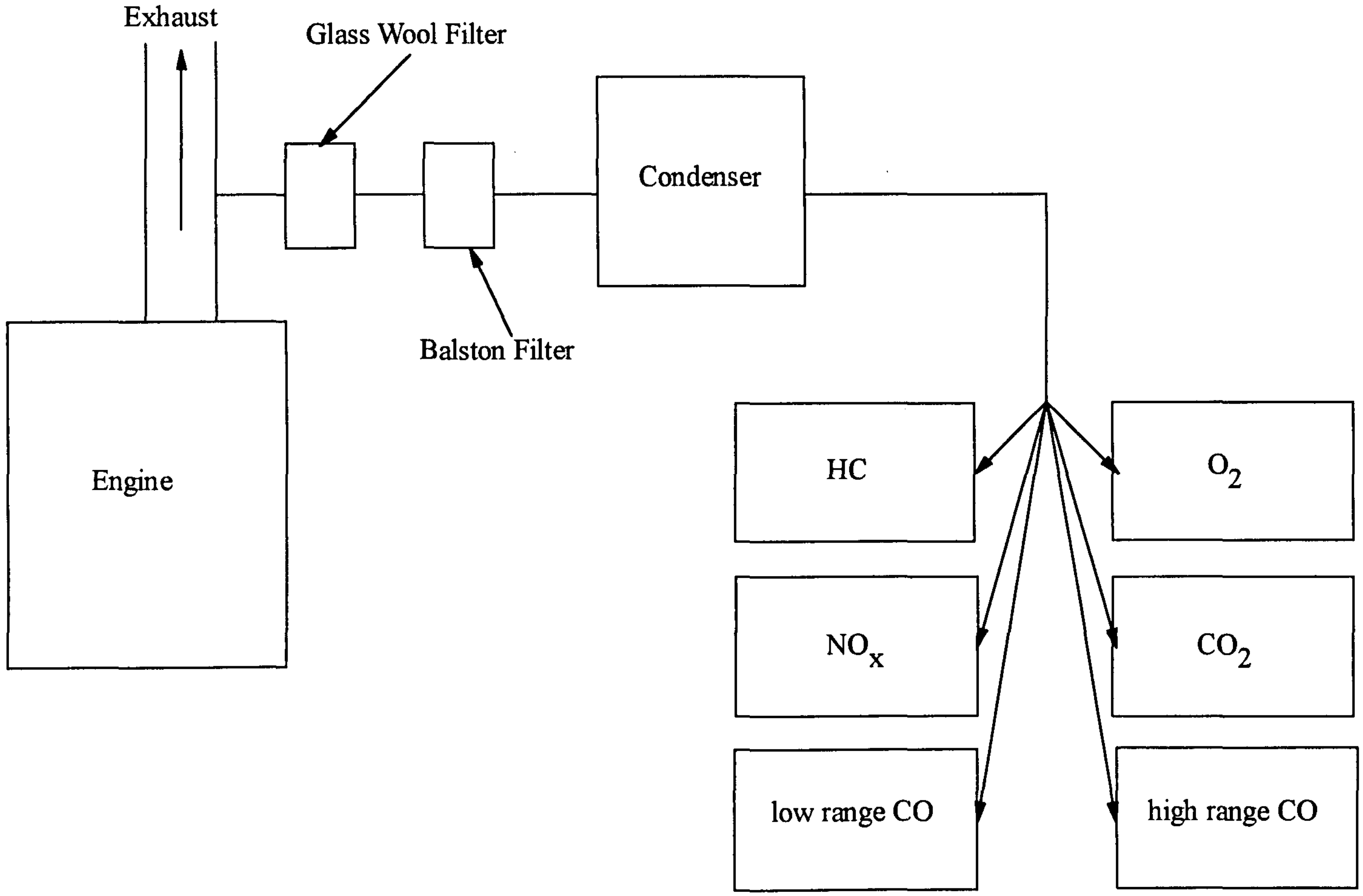

Figure 3.1. Gaseous emissions sampling system.

vacuum pump internal to the analyzer. Since the sample for the hydrocarbon analyzer was not passed through the ice bath condenser, the unburned hydrocarbon was measured on a wet basis. The unburned hydrocarbon in the exhaust gas was measured with a Beckman model 402 heated flame ionization detector hydrocarbon analyzer. Finally, the oxygen concentration was measured with a Beckman model 7003 polarigraphic oxygen monitor.

3.2.2 Dilution System

Diesel engine particulate matter is measured in a different manner than the gaseous emissions. Figure 3.2 illustrates the particulate sampling system specified by the Environmental Protection Agency in the Code of Federal Regulations [27]. The system consists of a primary dilution tunnel, a heat exchanger, a positive displacement pump (PDP), and a constant volume sampler (CVS). The dilution tunnel is intended to simulate the mixing process which occurs in the atmosphere, where some of the unburned hydrocarbons will be adsorbed and condensed onto the particulate surface.

In the particulate sampling system the PDP will draw a constant volumetric flow rate of diluted exhaust gas through the dilution tunnel. During a transient test the temperature and flow rate of the exhaust gas will vary considerably. Therefore, the heat exchanger is used to maintain a constant temperature of the diluted gas entering the PDP. Since the pressure in the dilution tunnel does not vary significantly during a transient test, the PDP will draw a constant mass flow rate of diluted exhaust gas.

The particulate measurement system as specified by the Code of Federal Regulations is very expensive. Many researchers have developed less expensive dilution tunnel systems.

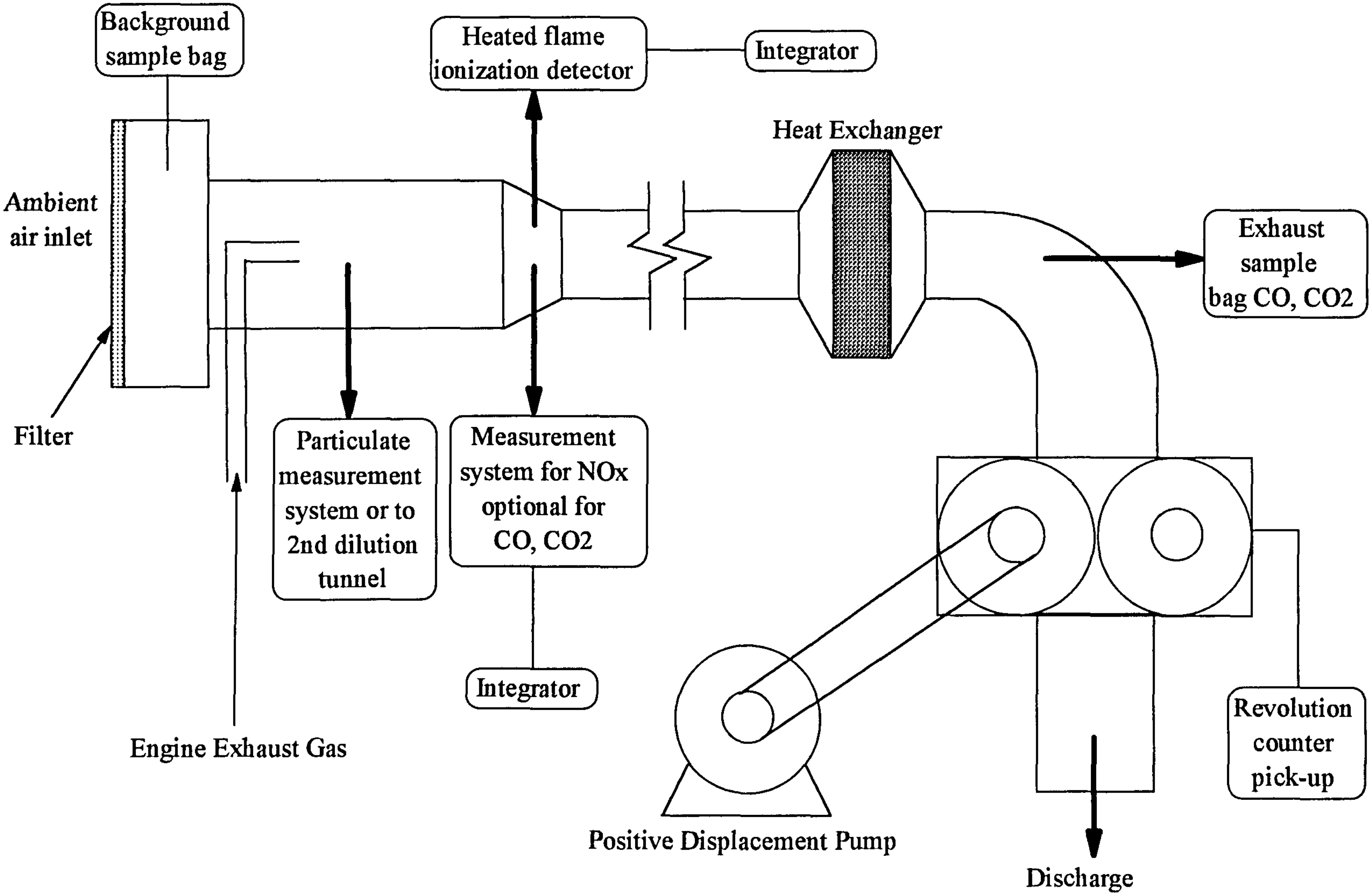

Figure 3.2. EPA specified particulate sampling system.

The dilution tunnel used in this study is a simplified full flow dilution tunnel. Since the objective of this study was not to determine if the engine met EPA emission levels, the system illustrated in Figure 3.2 was not necessary. The dilution tunnel system used for this study was designed and built by B.C. Murray and the details of the design and validation tests can be found in his M.S. thesis [33].

The particulate sampling system used in this study contained a double dilution tunnel. Figure 3.3 is a schematic of the primary and secondary dilution systems. The primary dilution system was used to dilute the exhaust gas with compressed air and the secondary dilution system allows the diluted exhaust gas to be further diluted. For the tests performed during this study, the secondary dilution system was not used because sufficient dilution was acheived with the primary dilution system.

The primary dilution tunnel was built in 1989 of standard galvanized spiral ventilation duct. The tunnel has a diameter of 0.305 meters. The distance between the introduction of the engine exhaust and the sample probe is 3.05 meters, corresponding to ten tunnel diameters. This distance was selected to provide sufficient distance and time for proper mixing of the engine exhaust with the dilution air. Yu Zhang conducted tests to verify that proper mixing occurred and the details are included in his 1994 M.S. thesis [25].

Dilution air was supplied to the primary dilution tunnel by an Ingersoll-Rand Centac II two stage air compressor. The compressed air was supplied to the primary dilution tunnel through a 5 cm diameter pipe at 620 kPa and the flow rate was controlled with a ball valve. An in-line air filter and a smooth edged orifice were installed after the ball valve. A Viatron

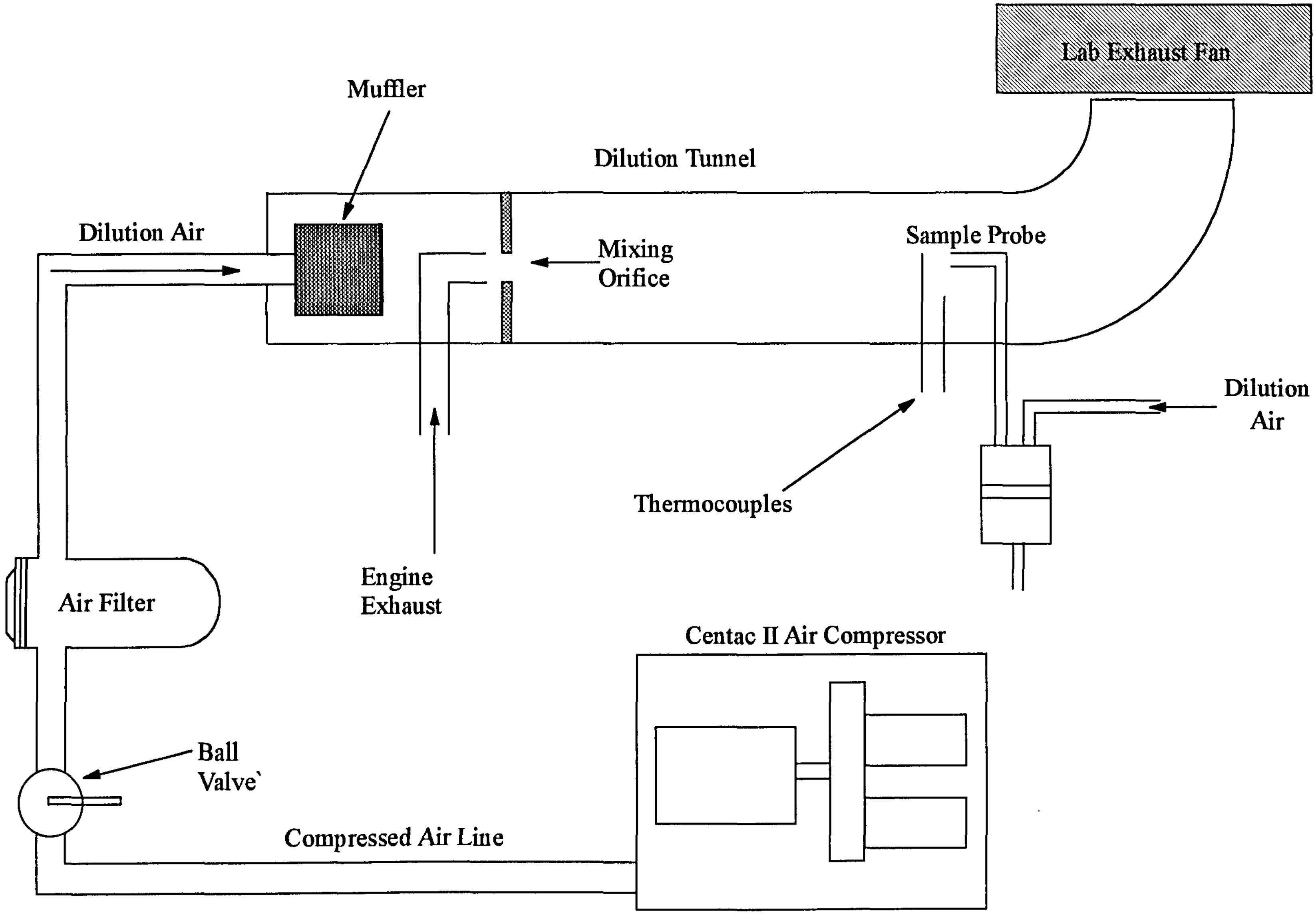

Figure 3.3. Dilution system for particulate measurement.

model 141 pressure transducer and a thermocouple were located between the compressed air filter and the orifice plate. The dilution air flow rate was calculated using the measured pressure and temperature of the compressed air on the upstream side of the orifice plate. The orifice plate calibration was extracted from B.C. Murray's thesis [33]. The in-line filter was used to prevent particles from entering the dilution tunnel from the compressed air line. An air-exhaust muffler was fitted to the end of the compressed air line to reduce noise associated with the uncontrolled expansion of the dilution air as it entered the dilution tunnel.

3.2.3 Particulate Sampling System

Figure 3.4 shows the particulate sampling system used in this study. The sampling system consists of valves, a vacuum pump, a flow meter, a by-pass valve, a vacuum gauge, and a filter holder apparatus. The ball valve immediately after the dilution tunnel was opened at the beginning of the test and closed at the end so the filters could be changed. The secondary dilution system, which was located upstream of the filter chamber, could increase the dilution ratio. However, for the tests run during this study, a higher dilution ratio was not necessary. The filter chamber was used to support a primary and a secondary filter. The distance between these filters was 8.9 cm, and a thermocouple was positioned between them to measure the temperature in the filter holder during sampling. A second thermocouple was located at the inlet to the gas meter so the density of the sample flow could be computed.

The electric counter attached to the ROOTS sample flow meter was capable of displaying the total amount of gas that had passed through the sampling system during the test as well as the instantaneous flow rate. The sampling pump had a by-pass line with a valve that

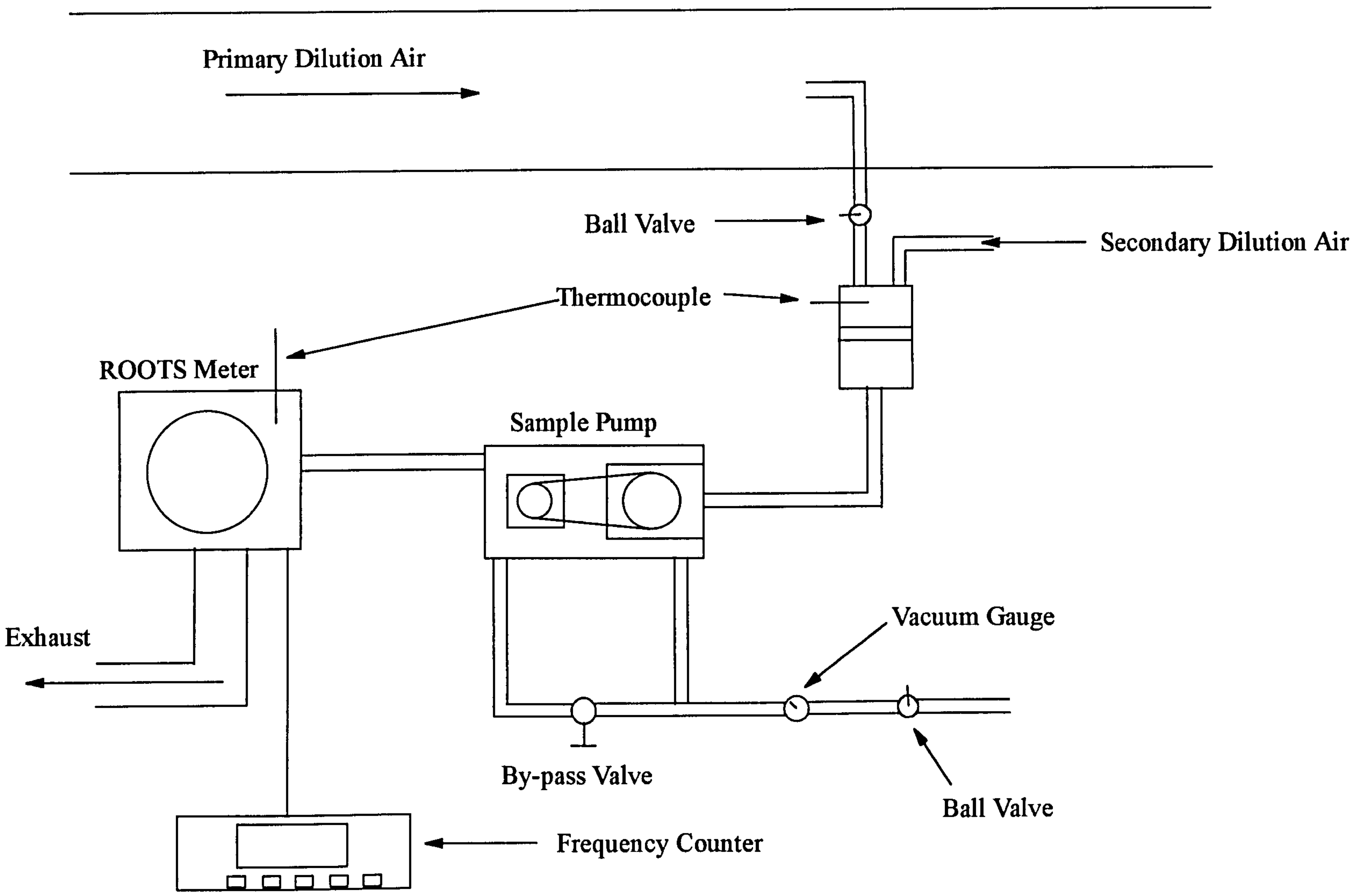

Figure 3.4. Particulate Sampling System.

was adjusted manually to keep the flow rate of particulate sample constant during the test. This was necessary because the sample flow rate would drop as the filters became loaded with particulate.

The filters used to collect the particulate sample in this study were 110 mm Pallflex T60A20 filters. The particulate sample volume flow rate was selected to be 7.0 cfm in order to collect at least 10 mg of particulate matter on the filters to reduce the impact of filter weighing errors.

3.2.4 Particulate Filter Weighing

The particulate filters were stored and weighed in a humidity controlled weighing chamber. Humidity was controlled with an Omega humidity controller. The temperature of the chamber was monitored and was 75 °F ± 1°F.

The particulate filters were stored in the weighing chamber for at least 48 hours before weighing, before and after the particulate sample was collected. This period allowed the filters to equilibrate to the environment in the weighing chamber. The filters were stored in 150 mm diameter plastic petri dishes. The petri dish was lined with aluminum foil to allow any electrostatic charge which may have accumulated during the particulate collection process to be removed. The dish was then placed on a grounded rack in the weighing chamber.

After 48 hours of equilibration on the grounded rack, the filters were weighed with a Mettler model AE240 analytical balance. The scale was tared before each weighing and the filter was left on the scale for 90 seconds. At the end of 90 seconds, the filter mass was recorded. The filter was then placed back into the filter chamber. After all filters had been weighed, each filter was then reweighed using the same procedure. The filter masses were then averaged to determine the mass of the particulate.

3.2.5 Soluble Organic Fraction Extraction

The particulate filters were Soxhlet extracted for four hours with methylene chloride using 125 ml flasks and Allihn type condensers. During extraction the particulate filter was contained in an 80x25 mm extraction thimble. Two Electromantle heaters heated the flasks and maintained a constant solvent temperature.

3.2.6 Emissions Data Collection Procedure

The engine test procedures were primarily dictated by the small amount of fuel available for each test. Table 3.3 identifies the test procedures used for each fuel test. The diesel fuel column in Table 3.3 indicates the diesel fuel used for each fuel test. Four low sulfur diesel fuels were used throughout this study, denoted by LSA, LSB, LSC, or LSD. The notation for the fuels also indicates sulfur content of the diesel fuel. For instance, LSA stands for Low Sulfur diesel fuel A. Fuel properties for all of the fuels used during this study are presented in Appendix D. Tables 3.4 through 3.6 list each test procedure used. At the beginning of each day the engine was operated at 2100 rpm and 100% of full load for one hour to condition the engine and dilution tunnel. Since the main purpose of the testing was to determine the particulate reducing potential of the esters, all the engine tests were steady state tests at 1400 rpm and 100% full load. This operating condition was selected because the engine used for this testing produced its highest particulate level at this condition. Therefore, any filter weighing errors would become less significant in the final results. At the end of each

Table 3.3. Test procedures used for fuel tests.

Test	Diesel Fuel	Procedure
Oxygen	LSA	A
Cetane Improver/Octadecane	LSC	B
Methyl Soyate	LSC	C
Methyl Palmitate	LSB	C
Isopropyl Palmitate	LSB	C
Methyl Stearate	LSC	C
Isopropyl Stearate	LSC	C
Methyl Oleate	LSC	C
Methyl Ester of Safflower Oil	LSD	C
Methyl Ester of Linseed Oil	LSD	C

into a waste fuel container. Doing this allowed the fuel from the previous test to be washed day, the engine was operated at 2100 rpm and 100% of full load for 30 minutes to purge the engine of the tested fuel and to clean the fuel injectors.

After the warm-up period was completed, the engine speed was reset to 1400 rpm and allowed to equilibrate for 30 minutes. Following the equilibration period, a warm-up set of particulate filters were taken for 15 minutes. This filter set was used to warm-up the filter chamber so the temperature effects would be minimized. After the warm-up filter a 15 minute test was performed. A 15 minute test involved collecting a particulate sample for 15 minutes while simultaneously recording two 6 minute sets of emission data and recording cylinder pressure data. After the test was completed, the fuel tank was switched and the fuel system

Table 3.4. Fuel test procedure A.

RPM	% full load	Fuel	Time	Comment
2100	100	No. 2 Diesel	60 min	warm-up
1400	100	No. 2 Diesel	30 min	equilibration
1400	100	No. 2 Diesel, 20.5 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 20.8 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 21.0 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 21.3 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 21.7 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 22.0% O_2	15 min	data collection
1400	100	No. 2 Diesel, 20.5 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 20.8 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 21.0 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 21.3 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 21.7 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 22.0% O_2	15 min	data collection
1400	100	No. 2 Diesel, 20.5 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 20.8 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 21.0 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 21.3 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 21.7 % O_2	15 min	data collection
1400	100	No. 2 Diesel, 22.0 % O_2	15 min	data collection
2100	100	No. 2 Diesel	30 min	engine purge

Table 3.5. Fuel test procedure B.

RPM	% full load	Fuel	Time	Comment
2100	100	No. 2 Diesel	60 min	warm-up
1400	100	No. 2 Diesel	30 min	equilibration
1400	100	No. 2 Diesel	15 min	filter warm-up
1400	100	No. 2 Diesel	15 min	test
1400	100	0.5 % C.I.	30 min	equilibration
1400	100	0.5 % C.I.	15 min	filter warm-up
1400	100	0.5 % C.I.	15 min	test
1400	100	50 % MS	30 min	equilibration
1400	100	50 % MS	15 min	filter warm-up
1400	100	50 % MS	15 min	test
1400	100	50 % $C_{18}H_{38}$	30 min	equilibration
1400	100	50 % $C_{18}H_{38}$	15 min	filter warm-up
1400	100	50 % $C_{18}H_{38}$	15 min	test
1400	100	No. 2 Diesel	30 min	equilibration
1400	100	No. 2 Diesel	15 min	filter warm-up
1400	100	No. 2 Diesel	15 min	test
1400	100	0.5 % C.I.	30 min	equilibration
1400	100	0.5 % C.I.	15 min	filter warm-up
1400	100	0.5 % C.I.	15 min	test
1400	100	50 % MS	30 min	equilibration
1400	100	50 % MS	15 min	filter warm-up
1400	100	50 % MS	15 min	test
1400	100	50 % $C_{18}H_{38}$	30 min	equilibration
1400	100	50 % $C_{18}H_{38}$	15 min	filter warm-up
1400	100	50 % $C_{18}H_{38}$	15 min	test
1400	100	No. 2 Diesel	30 min	equilibration

Table 3.5 (continued).

RPM	% full load	Fuel	Time	Comment
1400	100	No. 2 Diesel	15 min	filter warm-up
1400	100	No. 2 Diesel	15 min	test
1400	100	0.5 % C.I.	30 min	equilibration
1400	100	0.5 % C.I.	15 min	filter warm-up
1400	100	0.5 % C.I.	15 min	test
1400	100	50 % MS	30 min	equilibration

was allowed to purge for 5 minutes. The fuel system was purged by draining the return fuel out of the fuel system. As shown in Tables 3.4-3.6, each test was replicated three times.

3.3 Data Acquisition System

An Analog Devices RTI-820 board was used to collect the emission data from the gaseous emission analyzers. The RTI-820 board with a Zenith Z-386 computer scanned the emission signal channels every second and placed the data in a file. The cylinder pressure data were measured with a Kistler pressure transducer and collected with an Analog Devices RTI-860 board. The pressure data was then averaged for 24 engine cycles. The engine crankangle signal was produced by a BEI incremental shaft encoder. Cylinder pressure data was taken every 0.25 degree of crankangle with 12 bits of resolution and was stored on a floppy disk for later analysis.

3.4 Data Analysis

The methods and equations for data analysis are presented in this section. The first part of the section discusses how the data for the gaseous emissions was processed. The

Table 3.6. Fuel test procedure C.

RPM	% full load	Fuel	Time	Comment
2100	100	No. 2 Diesel	60 min	warm-up
1400	100	No. 2 Diesel	30 min	equilibration
1400	100	No. 2 Diesel	15 min	filter warm-up
1400	100	No. 2 Diesel	15 min	test
1400	100	20 % test fuel	30 min	equilibration
1400	100	20 % test fuel	15 min	filter warm-up
1400	100	20 % test fuel	15 min	test
1400	100	50 % test fuel	30 min	equilibration
1400	100	50 % test fuel	15 min	filter warm-up
1400	100	50 % test fuel	15 min	test
1400	100	No. 2 Diesel	30 min	equilibration
1400	100	No. 2 Diesel	15 min	filter warm-up
1400	100	No. 2 Diesel	15 min	test
1400	100	20 % test fuel	30 min	equilibration
1400	100	20 % test fuel	15 min	filter warm-up
1400	100	20 % test fuel	15 min	test
1400	100	50 % test fuel	30 min	equilibration
1400	100	50 % test fuel	15 min	filter warm-up
1400	100	50 % test fuel	15 min	test
1400	100	No. 2 Diesel	30 min	equilibration
1400	100	No. 2 Diesel	15 min	filter warm-up
1400	100	No. 2 Diesel	15 min	test
1400	100	20 % test fuel	30 min	equilibration
1400	100	20 % test fuel	15 min	filter warm-up
1400	100	20 % test fuel	15 min	test
1400	100	50 % test fuel	30 min	equilibration
1400	100	50 % test fuel	15 min	filter warm-up
1400	100	50 % test fuel	15 min	test
2100	100	No. 2 Diesel	30 min	engine purge

second part presents the equations necessary for applying the humidity correction for oxides of nitrogen. The equations for calculating particulate emissions are presented in the third part. The last part explains the statistical methods used on the emission data.

3.4.1 Gaseous Emissions

The gaseous emission data was collected for each test at one second intervals for six minutes. This procedure was done twice during each fuel test, once with the NO/NO$_x$ meter set to NO and once with the meter set to NO$_x$. The data was then averaged to obtain a representative value for the emission levels during the test.

The common way to represent emission data is to express it on a "brake specific" basis. Brake specific emissions are the mass flow rate of the pollutant divided by the engine power. Representing the data in this way allows the emissions of different sized engines to be compared to each other.

In order to calculate the brake specific emissions, a chemical equation for the combustion of the fuel must be set up. The equation below is the balanced chemical equation for diesel fuel, assuming complete combustion.

$$C_xH_yO_z + (\frac{A}{F})\ [0.21O_2 + 0.79N_2] \rightarrow B\ [y_{CO_{2,\ dry}}CO_2 + y_{O_{2,\ dry}}O_2 + y_{N_{2,\ dry}}N_2] + C\ H_2O$$

where x = number of carbon atoms in an average fuel molecule

y = number of hydrogen atoms in an average fuel molecule

z = number of oxygen atoms in an average fuel molecule

$y_{i,\ dry}$ = mole fraction of chemical species on a dry basis

A/F = molar air/fuel ratio

B = number of moles of dry products

C = number of moles of water

The above equation was then solved for B and C in terms of the other variables. The expressions for B and C are listed below.

$$B = \left(\frac{A}{F}\right) + \frac{z}{2} - \frac{y}{2}\ A$$

$$C = \frac{y}{2}$$

By combining the chemical equation for fuel combustion with the measured emission data, the following equations for brake specific (BS) emissions were derived.

$$BSCO = 197.29\ B\ \frac{y_{CO,\,dry} \times m_{fuel}}{MW_{fuel} \times Torque \times RPM}$$

$$BSNO = 211.31\ B\ \frac{y_{NO,\,dry} \times m_{fuel}}{MW_{fuel} \times Torque \times RPM}$$

$$BSNO_x = 324.00\ B\ \frac{y_{NO_x,\,dry} \times m_{fuel}}{MW_{fuel} \times Torque \times RPM}$$

$$BSHC = 606.99\ (B+C)\ \frac{y_{HC,\ wet} \times m_{fuel}}{MW_{fuel} \times Torque \times RPM}$$

where m_{fuel} = mass flow rate of fuel, kg/h

MW_{fuel} = average molecular weight of fuel

Torque = engine brake torque, ft-lb_f

RPM = engine speed, rev/min

$y_{I,\ dry}$ = molar fraction of chemical species on a dry basis

$y_{I,\ wet}$ = molar fraction of chemical species on a wet basis

The units in the above equations are not all S.I. units because some of the instruments measured the quantities in units other than the standard S.I. units. The constants in the equations account for all necessary unit conversions.

3.4.2 Humidity Correction for Oxides of Nitrogen

The Society of Automotive Engineers recommends that a correction factor be applied to the NO_x levels to adjust the value to a standardized humidity level [27]. The specific humidity of the engine intake air, h, is computed from the following equation.

$$h = \frac{621.10 \times P_v}{P_b - P_v}$$

where h = specific humidity, g H_2O/kg dry air

P_b = observed barometric pressure, kPa

P_v = partial pressure of water vapor, kPa

The partial pressure of water vapor, P_v, can be calculated using Ferrel's equation [28] listed below.

$$P_v = P_w - 1.80A \times P_b\,(T_d - T_w)$$

where P_w = saturation pressure of water vapor at wet bulb temperature, kPa

T_d = dry bulb temperature, °C

T_w = wet bulb temperature, °C

A = experimentally derived constant, $A = 3.67 \times 10^{-4}\,(1+0.001152T_w)$

The saturation pressure of water vapor at the wet bulb temperature is calculated with the following equation, which is a least squares fit to Keenan and Keyes' steam table [29].

$$P_w = 0.6048346 + 4.59058x10^{-2}T_w + 1.2444x10^{\overset{-5}{\boxed{-3}}}T^3{}_w + 9.32206x10^{-8}T^4{}_w + 4.18128x\ 10^{-9}T^5{}_w$$

where P_w = saturation pressure of water vapor, kPa

T_w = wet bulb temperature, °C

The corrected oxides of nitrogen concentration can be calculated with the following equation [27].

$$NO_{corr} = NO_{wet} \times \frac{1}{k}$$

where NO_{corr} = corrected NO concentration, ppm

NO_{wet} = measured NO concentration on a wet basis, ppm

$k = 1 + 7A\,(h - 10.714) + 1.8B(T - 29.444)$

A = 0.044(F/A) - 0.0038

B = -0.116(F/A) + 0.0053

T = intake air temperature, °C

F/A = mass fuel-air ratio (dry basis)

h = specific humidity, g H_2O/kg dry air

3.4.3 Particulate Emissions

The total mass of particulates emitted by the engine during the test period is determined from the following equation.

$$m_{particulate} = \Delta m_{filter} \times \frac{mdot_{dil\ exh}}{mdot_{ROOTS}}$$

where $m_{particulate}$ = mass of total particulate emitted during test period

Δm_{filter} = particulate mass collected on filters during test period

$mdot_{dil\ exh}$ = mass flow rate of diluted exhaust

$mdot_{ROOTS}$ = mass flow rate of diluted exhaust which passed through the particulate sampling system

During the engine tests the mass flow rate of the sample was held nearly constant and the sample temperature was measured at the inlet to the ROOTS flow meter. The sample flow rate was calculated using the following equation.

$$mdot_{ROOTS} = \frac{P_{ROOTS} \times V_{ROOTS}}{R_{ROOTS} \times T_{ROOTS}}$$

where P_{ROOTS} = sample pressure at ROOTS meter. Assumed to be atmospheric pressure.

V_{ROOTS} = volumetric flow rate of sample through ROOTS meter

R_{ROOTS} = Gas constant of sample

T_{ROOTS} = sample temperature at ROOTS meter

The mass flow rate of diluted exhaust gas in the dilution tunnel was calculated from the following equation.

$$mdot_{dil\ exh} = mdot_{dil\ air} + mdot_{LFE} + mdot_{fuel}$$

where $mdot_{dil\ exh}$ = mass flow rate of dilution air

$mdot_{LFE}$ = mass flow rate of engine intake air through laminar flow element

$mdot_{fuel}$ = mass flow rate of fuel

The brake specific particulate emission was calculated using the following formula.

$$BSPM = \frac{\Delta m_{filter} \left(\frac{mdot_{dil\ exh}}{mdot_{ROOTS}}\right)}{Torque \times RPM}$$

3.4.4 Statistical Analysis

Statistical techniques were used in two areas of the data analysis. First, a t-test was used on the data to determine if the emissions of two different fuels were statistically different. The computer software SIGMA STAT was used to conduct the t-tests using a 90% confidence interval. SIGMA STAT's output included the probability of the two data sets being statistically different. If the probability was greater than 90%, the two data sets were considered to be statistically different. Tables summarizing the probabilities are included in Appendix C.

The second area in the data analysis process where statistics was used involved determination of error propagation. As mentioned above, a t-statistic was used to determine the 90% confidence interval of the brake specific data. The following formula was used to compute the confidence intervals [30].

$$\bar{x} - t_{\alpha/2} \frac{s}{\sqrt{n}} < \mu < \bar{x} + t_{\alpha/2} \frac{s}{\sqrt{n}}$$

where $\bar{x}$ = sample mean

s = sample standard deviation

μ = population mean

$t_{\alpha/2}$ = t-statistic with $\nu = n - 1$ degrees of freedom

n = number of data points

A portion of the data to be presented in Chapter 4 is given on a normalized basis. This means the value of the emissions level for an ester fuel is divided by the value of diesel fuel at the same operating condition.

In order to obtain accurate error bars for the normalized data, a propagation of errors was required. The confidence limits calculated by this method are derived from an uncertainty estimate based on the three replications of the experimental measurements. Bias errors associated with equipment malfunction or from other sources would not be included in this estimate. The following formula was used to calculate the 90% confidence interval for the normalized data.

$$\omega_R^{\,2} = \left(\frac{1}{y}\right)^2 \omega_x^{\,2} + \left(-\frac{x}{y^2}\right)^2 \omega_y^{\,2}$$

where x = emission for ester

y = emission for diesel

R = x/y = normalized emission

ω_x = uncertainty in x

ω_y = uncertainty in y

The ω_x and ω_y values were determined by using the t-statistic to calculate the 90% confidence interval, as was done for the brake specific emissions.

4. RESULTS AND DISCUSSION

The performance and emissions characteristics of a diesel engine fueled with methyl and isopropyl esters of fatty acids are presented in this chapter. The effect the esters have on the fuel's cetane number is investigated in the first section. The second section explores the reasons for emission reductions associated with biodiesel use. Section three investigates the emission characteristics of the fatty esters contained in the methyl ester of soybean oil. In section four the individual esters are evaluated and the optimum ester is identified. All of the raw data collected for this study is included in Appendix E.

4.1 Cetane Effect of Esters

One important property of diesel fuel is the cetane number. The cetane number of a diesel fuel is a measure of its ability to autoignite. A high cetane fuel will autoignite more easily than a low cetane fuel. Esters of fatty acids have shown that they tend to increase a fuel's cetane number when blended with No. 2 diesel. However, different fatty esters affect the fuel's cetane number differently.

In order to study how each ester affects the cetane number, cetane tests were conducted on blends of the esters. Cetane number data was collected for the esters for blends from 0% to 50% mixtures. A linear regression was then performed on the cetane number data for each ester. Table 4.1 contains the linear regression coefficients for all of the esters. The diesel fuel used for blending with the esters is listed in parenthesis in Table 4.1. The coefficients listed in Table 4.1 are the regression coefficients for following equation:

Cetane Number = a + b[% ester].

Table 4.1. Linear regression coefficients for cetane numbers of fatty ester blends.

Fuel	a	b	R^2
Methyl Soyate (LSA)	46.151	0.1013	0.4889
Methyl Soyate (LSC)	44.040	0.1293	0.8083
Methyl Soyate (HSA)	47.586	0.1245	0.9536
Methyl Palmitate (LSB)	45.954	0.2790	0.9450
Isopropyl Palmitate (LSB)	45.723	0.2394	0.9114
Methyl Stearate (LSC)	43.125	0.3550	0.8905
Isopropyl Stearate (LSC)	43.452	0.2488	0.9034
Methyl Oleate (LSC)	43.194	0.1930	0.7399
Octadecane (LSC)	43.090	0.5978	0.9965

The cetane response, which is the slope of the regression line, appears to change for each ester. The methyl soyate blends have a slope between 0.10 and 0.13. However, an interesting trend exits with the individual esters. The stearate esters have a higher cetane response than the palmitates. Also, the isopropyl esters show a lower cetane response than the methyl esters. Methyl oleate, the only unsaturated ester, has a lower cetane response than the saturated esters, but it is higher than methyl soyate. The highest cetane response of all of the fuels is the octadecane. Octadecane has a much higher cetane response than the other esters. This suggests that longer chain length, saturated compounds have higher cetane response than shorter chain length, unsaturated compounds. Cetane response data for the methyl esters of safflower and linseed oils were not available for analysis at the time this thesis was written.

4.2 Investigation of the Mechanism for Biodiesel Emission Reduction

This section will investigate three possible reasons why using an ester of soybean oil reduces emissions from diesel engines. First, fatty acid esters contain oxygen atoms in the molecules, whereas a hydrocarbon fuel like diesel fuel does not. The addition of oxygen in the fuel means the fuel will burn leaner in the central core of the fuel spray, which decreases the formation of solid carbon and permits more of the particulate and unburned hydrocarbon to burn completely before it leaves the combustion chamber.

In order to investigate the impact of the additional oxygen content associated with the esters, the intake air oxygen content was controlled between 20.5% and 22.0%. The oxygen content of the intake air was increased and decreased by adding oxygen and nitrogen, respectively, to the intake system of the engine. The emission data for the oxygen test is included in Table B.1 in Appendix B.

The total particulate emissions can be separated into two parts, the soluble organic fraction and the solid fraction. The soluble organic fraction (SOF) is the portion of the particulate which is removed by the solvent extraction process and primarily includes unburned fuel and lubrication oil. The solid portion (SOL) of the particulate is the remaining particulate which is not removed by the solvent extraction process.

All of the emission data for the oxygen tests and cetane improver/octadecane test is presented on a brake specific basis. The brake specific emission is simply the mass flow rate of material emitted from the engine divided by the engine power. For instance, if 5.0 grams of particulate matter is collected over a period of 15 minutes and the engine brake power is 40 kW, the brake specific particulate matter (BSPM) emissions would be 0.5 g/(kW-h).

Figure 4.1 illustrates the reduction of particulate as the oxygen content of the intake air increases. The solid portion of the particulate decreases by 33% as the oxygen content of the intake air increases from 20.5% to 22.0%. However, the soluble portion of the particulate remains relatively constant as the intake oxygen increases. Therefore, the decrease in total particulate emissions is due to the reduction in the solid portion of the particulate.

Another effect of increasing the oxygen content of the intake air is an increase in the oxides of nitrogen (NO_x) emissions. Figure 4.2 shows that NO_x emissions increased by 25% as the intake air oxygen increases from 20.5% to 22.0%. An increase in NO_x is observed partly because the higher oxygen concentration in the combustion chamber provides the excess oxygen needed to form oxides of nitrogen. Also, NO_x emissions increase because the higher oxygen concentration increases the flame temperature, which increases the rate of formation of NO_x in the combustion chamber.

Carbon monoxide (CO) emissions demonstrated a slight decrease as the oxygen content of the intake air was increased, as illustrated in Figure 4.3. Carbon monoxide emissions decrease because more oxygen is available to allow the CO to react and form CO_2 in the combustion chamber.

Figure 4.4 shows that hydrocarbon (HC) emissions remain relatively constant for increasing intake air oxygen percentages. Hydrocarbon emissions do not change because most HC emissions come from overmixed fuel, which is not affected by increased oxygen. Also, HC emissions from diesel engines are very small because diesel engines always operate

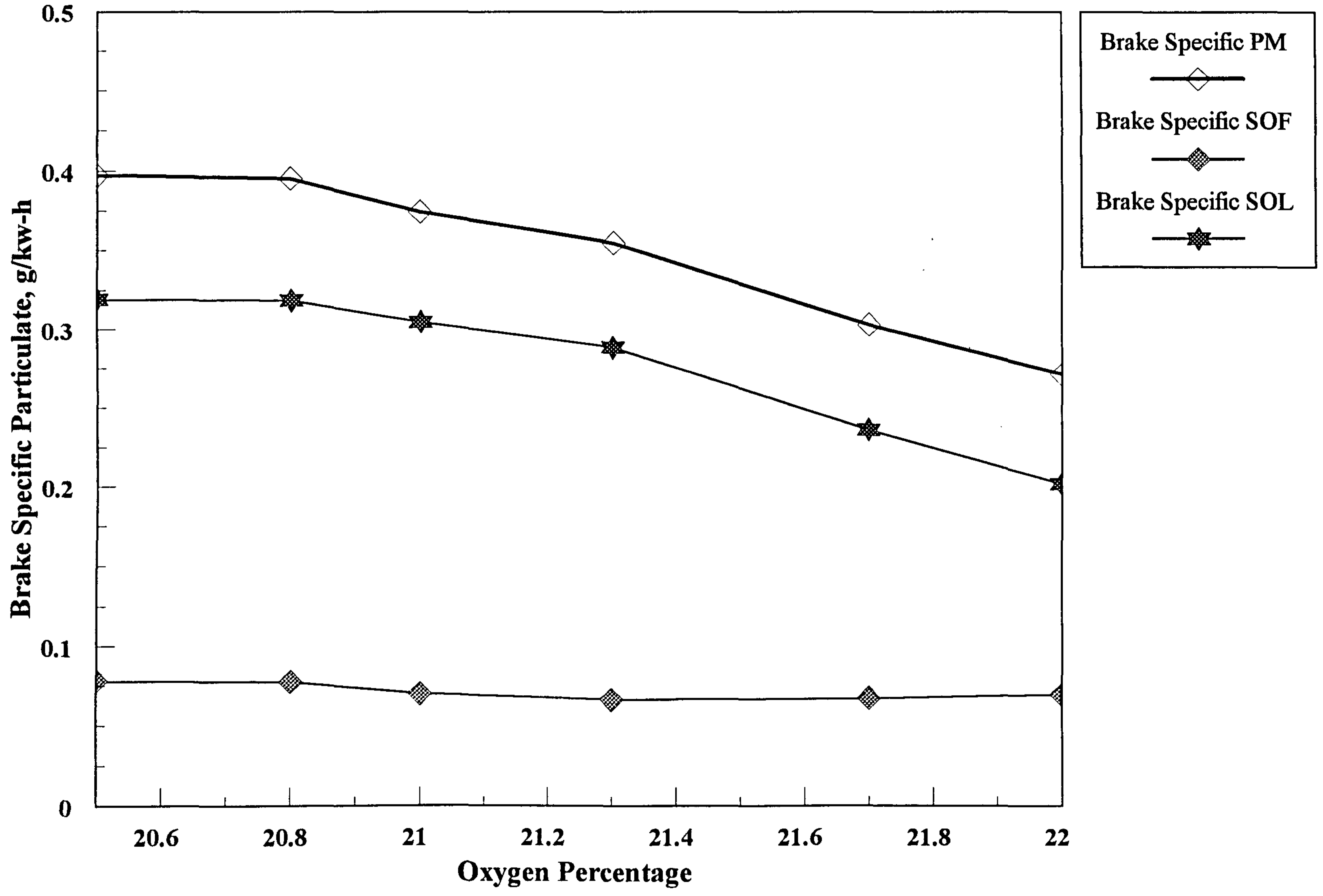

Figure 4.1. Brake specific particulate emissions for oxygen test.

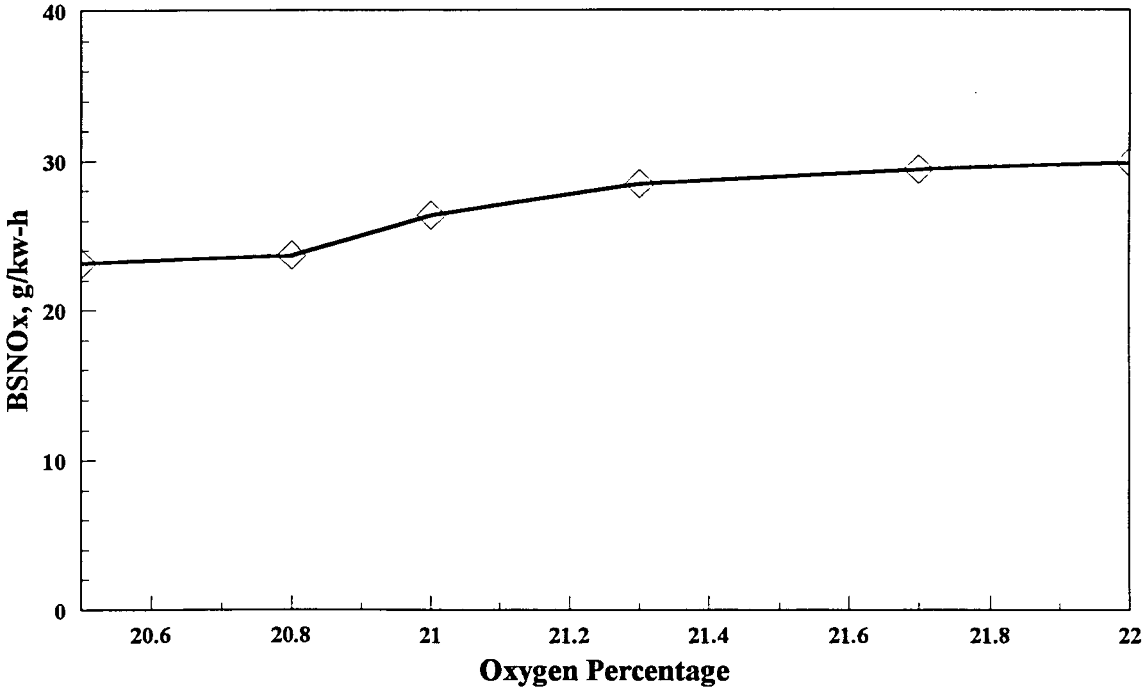

Figure 4.2. Brake specific NOx for oxygen test.

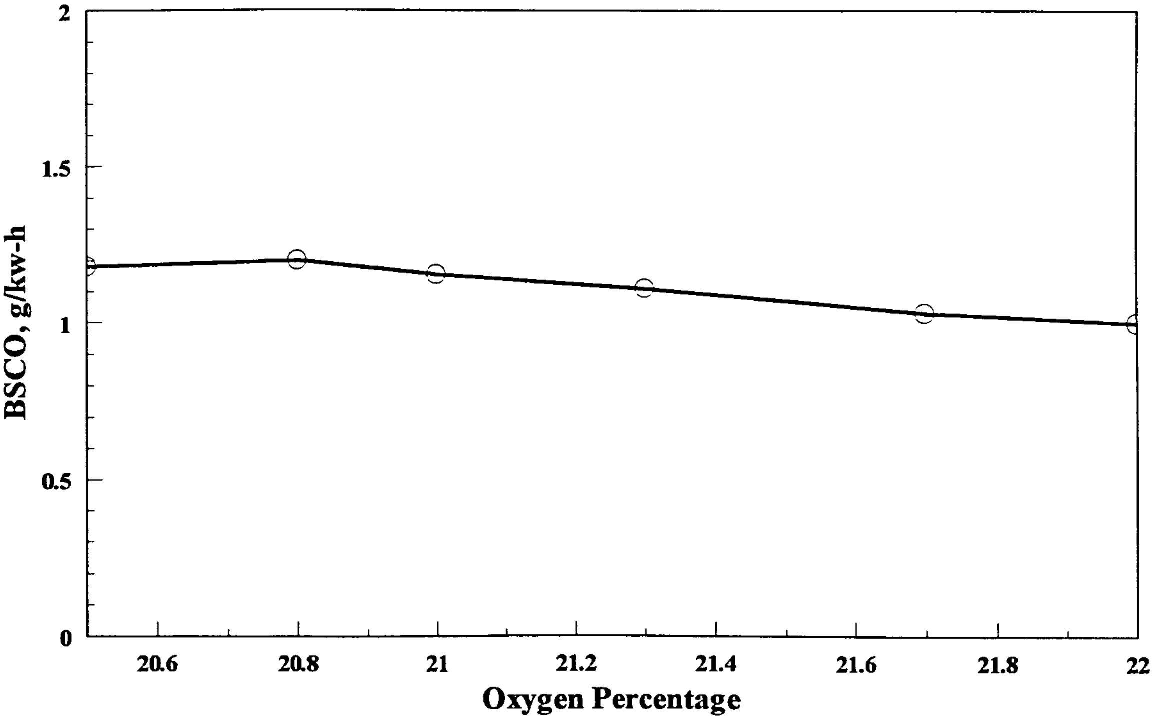

Figure 4.3. Brake specific CO emissions for oxygen test.

lean. By increasing the oxygen content of the air, the engine operates slightly leaner, which does not appear to reduce HC further.

Figure 4.5 illustrates that increasing the oxygen content of the intake air does not change fuel consumption. Fuel consumption does not change because no additional energy is added to the engine when the oxygen content is increased. Therefore, any variation in fuel consumption is due to experimental error. Figure 4.6 illustrates that the thermal efficiency of the engine also remains constant as the oxygen content of the intake air increases.

Another possible reason for emissions reductions when using biodiesel is the higher cetane number of biodiesel relative to No. 2 diesel fuel. A fuel with a high cetane number will autoignite more easily than a fuel with a low cetane number. Since the ignition process in a compression ignition engine relies solely on autoignition, a high cetane number fuel will begin combustion earlier in the injection process. Since combustion begins at an earlier time, the fuel will have more time to completely burn to water and carbon dioxide before the exhaust process begins. The more complete burning of the fuel will reduce hydrocarbon, particulate, and carbon monoxide emissions from the engine.

The third possible reason for emissions reductions associated with biodiesel is the addition of long chain hydrocarbons to the fuel. The esters in soybean-based biodiesel are long chain esters, usually between 16 and 18 carbons in length. Long chain hydrocarbons tend to have high cetane numbers, which leads to lower particulate emissions. Also, by adding the long chain hydrocarbons with the esters, the aromatic content of the fuel is reduced. It is widely known that the presence of aromatic compounds in the fuel facilitates

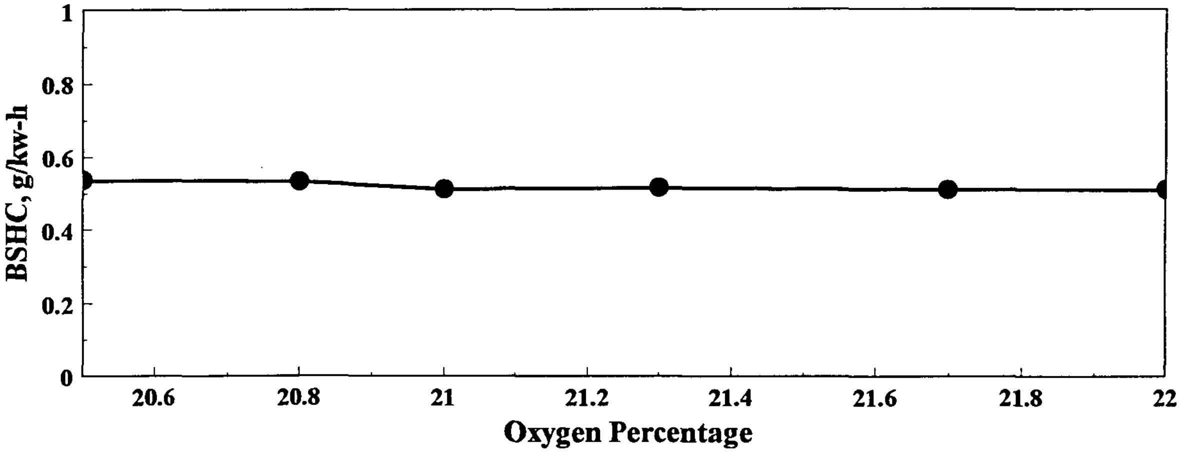

Figure 4.4. Brake specific HC emissions for oxygen test.

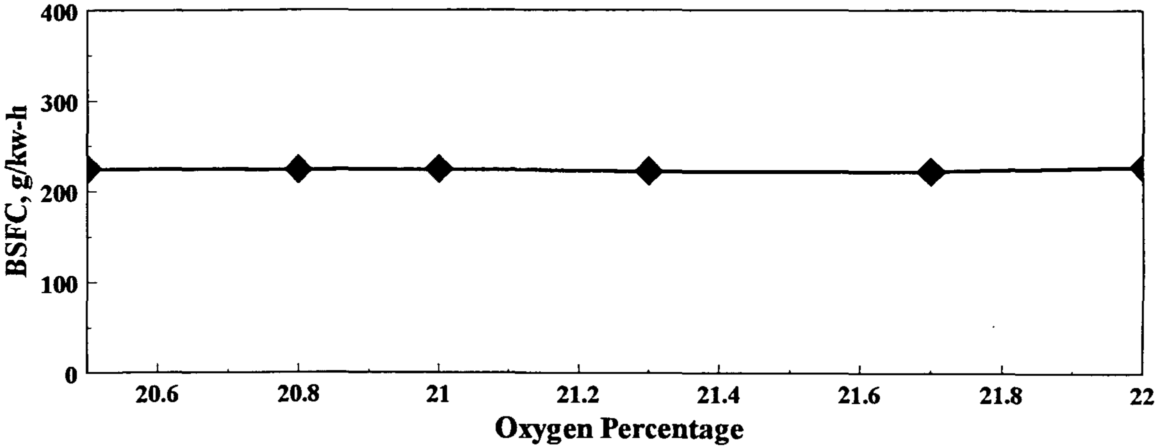

Figure 4.5. Brake specific fuel consumption for oxygen test.

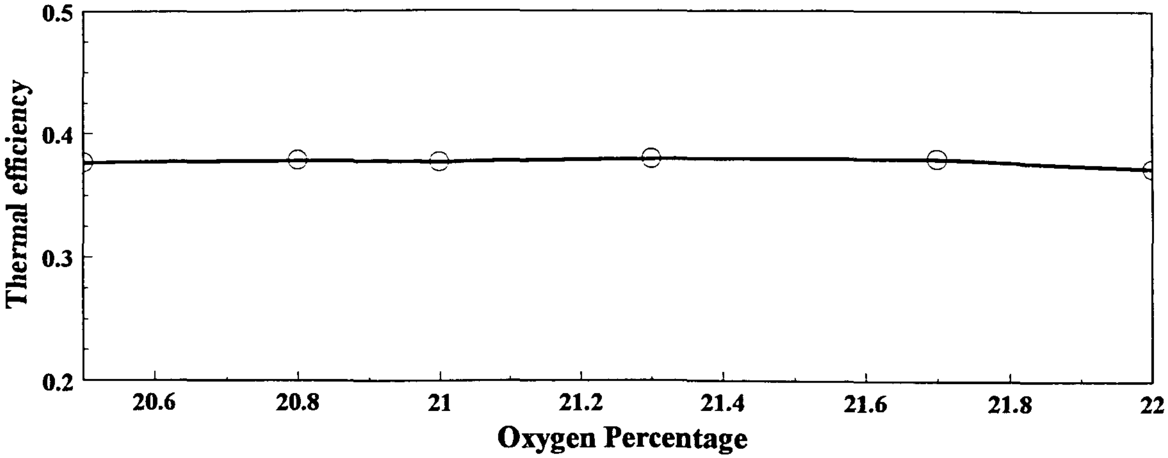

Figure 4.6. Thermal efficiency for oxygen test.

the particulate formation process in a diesel engine. Therefore, by reducing aromatics, particulate emissions should also be reduced.

In order to investigate the effect of cetane number and long chain hydrocarbons on emission levels, a test was conducted to compare three high cetane number fuels to a low sulfur diesel fuel. The three fuels used in this study were the following: diesel fuel with 0.5% ethylhexyl nitrate cetane improver additive, 50% octadecane with diesel fuel, and a 50% blend of methyl soyate with diesel fuel. The error bars on the figures refer to the 90% confidence interval for the data as determined with the t-statistic. Table B.3 in Appendix B contains the emission data for this test.

Figure 4.7 shows the total particulate emissions for the four fuels. The fuel with the cetane improver additive reduced the total particulate, but the reduction was not statistically significant. However, the 50% methyl soyate blend with diesel fuel reduced the total particulate by 27% and the 50% octadecane blend reduced the total particulate by 21%. Therefore, a small part of the particulate reduction may be attributable to the cetane increase, but the addition of the long chain hydrocarbons and the resulting aromatic reduction appears to be primarily responsible for the particulate reductions.

In order to better understand the particulate reduction, the particulates can be divided into the soluble component (SOF) and the solid carbon portion (SOL). Figure 4.7 indicates that while the cetane improver additive reduced the solid portion of the particulate, the reduction was not statistically significant. The 50% methyl soyate reduced the solid portion by 45% and the 50% octadecane reduced it 24%. This reduction suggests that the SOL reduction observed with the methyl soyate is due to more than the cetane increase and the long chain hydrocarbon addition. The lower SOL emissions also support the argument that the oxygen content of the ester reduces SOL, as indicated in Figure 4.1.

Figure 4.7 also illustrates that increasing cetane number and adding long chain hydrocarbons to the fuel increases SOF emissions, but the increase is not statistically significant. However, the 50% methyl soyate blend increased SOF by 64% above the level for No. 2 diesel fuel. One possible reason for this increase in SOF relates to the fuel volatility. Methyl soyate has a higher distillation curve and is much less volatile than No. 2 diesel fuel. Therefore, if unburned fuel molecules exit the exhaust of the engine, the methyl soyate will be more likely to condense on the particulate filters than the diesel fuel. This unburned fuel is measured as SOF.

Figure 4.8 shows the CO emissions for the four fuels. The cetane improver additive increased CO emissions, but the increase was not statistically significant. The 50% methyl soyate reduced CO emissions, but, again, the reduction was not statistically significant. However, the 50% octadecane blend did provide a statistically significant CO reduction.

Figure 4.9 illustrates the unburned hydrocarbon emissions for the cetane test. The cetane improver additive did not change the HC emissions. However, the 50% methyl soyate reduced HC by 28% and the 50% octadecane blend reduced HC by 21%. Although it may appear that the long chain hydrocarbons in these two fuels may be responsible for the HC reduction, the lower HC levels may actually be a result of an error caused by the method of measuring unburned hydrocarbon. Unburned hydrocarbon is measured by a heated flame

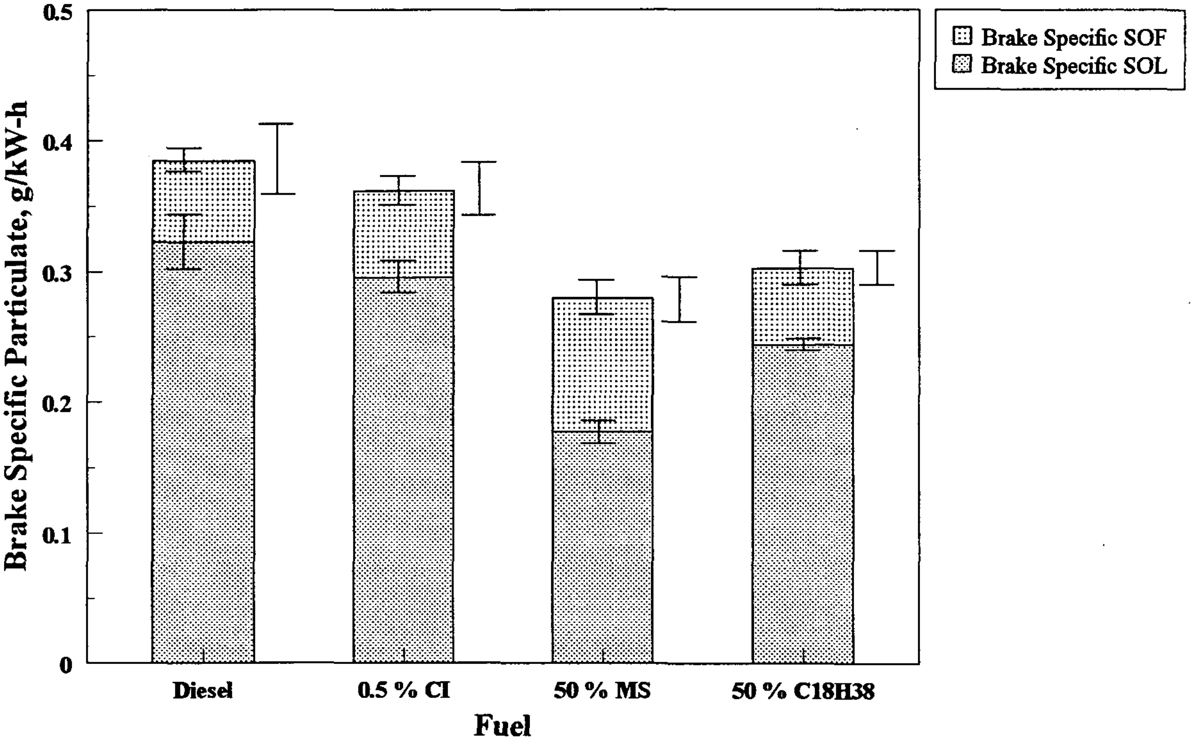

Figure 4.7. Brake specific PM emissions for cetane improver/octadecane test.

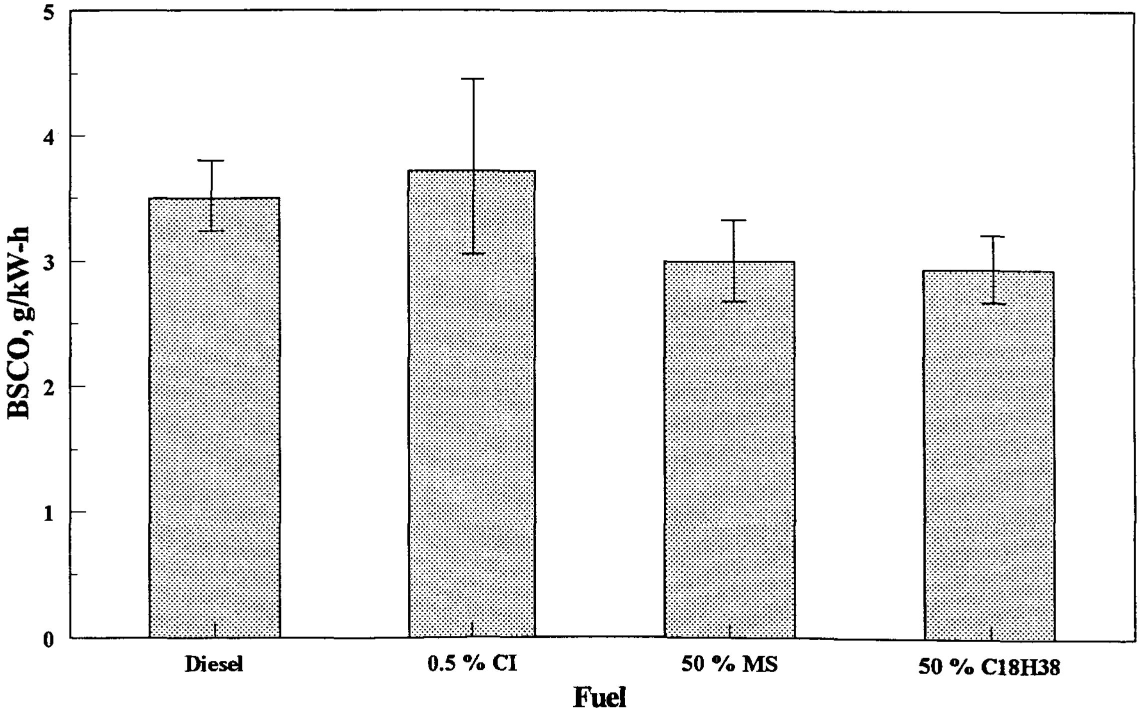

Figure 4.8. Brake specific CO emissions for cetane improver/octadecane test.

ionization detector (HFID). The sample line for the HFID is heated to 190 °C to prevent the typical hydrocarbons present in diesel exhaust from condensing and adsorbing to the particulate material in the sample line. However, the boiling points of methyl soyate and octadecane are much higher than diesel fuel. Therefore, the unburned methyl soyate and octadecane may condense in the sample line before they reach the hydrocarbon meter. This would lead to a low hydrocarbon measurement for fuels containing these compounds. At the same time, this less volatile material should be collected as SOF on the particulate filter.

The NO_x emissions shown in Figure 4.10 indicate that there was not a statistically significant change in NO_x emissions except for the 50% methyl soyate and this was probably due to the oxygen in the fuel.

Figure 4.11 illustrates that the brake specific fuel consumption (BSFC) remains constant for the cetane improver additive and the 50% octadecane fuels. However, the 50% methyl soyate has a 6.7% increase in BSFC. This increase is due to the lower heating value of the methyl soyate. Figure 4.12 shows that the thermal efficiency of the engine remains constant for all of the fuels.

4.3 Fatty Ester Comparison

The second part of this study involved evaluating the emission and performance characteristics of the fatty esters found in soybean-based biodiesel. Methyl esters of all of the fatty acids and isopropyl esters of two fatty acids were evaluated at 20% and 50% blends. All data was collected while operating the engine at 1400 rpm and 100% load. The measurements were repeated at least three times for all of the tests. The emissions expressed

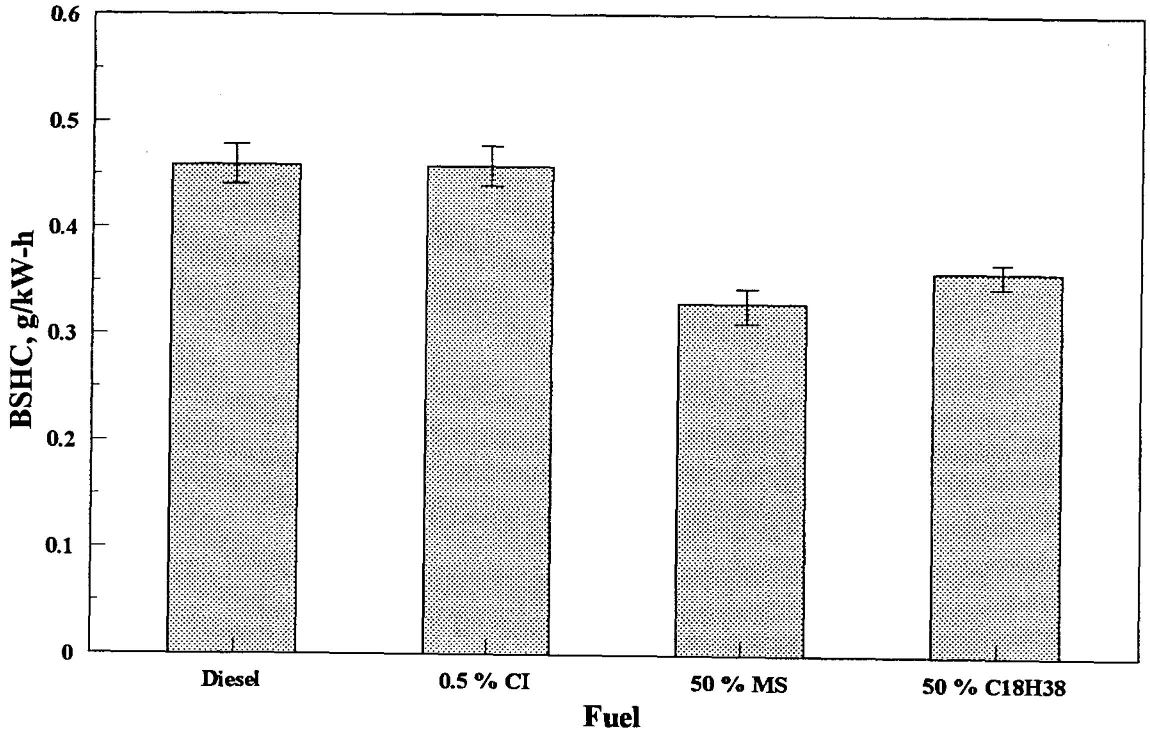

Figure 4.9. Brake specific HC emissions for cetane improver/octadecane test.

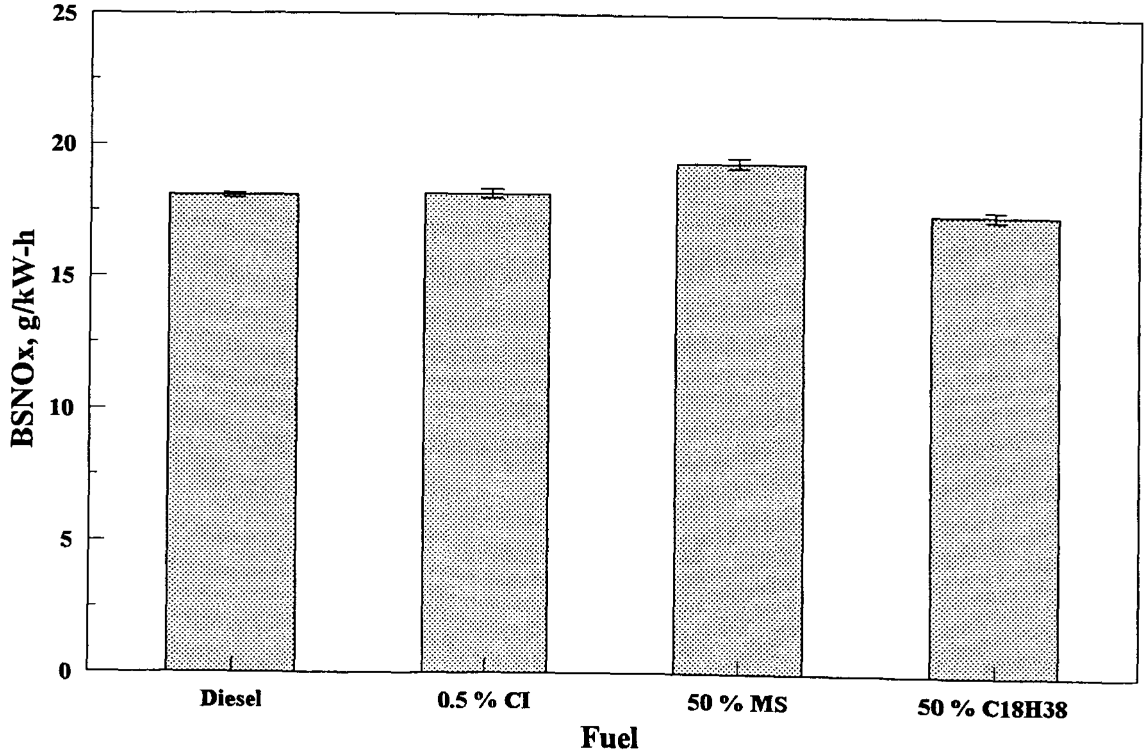

Figure 4.10. Brake specific NOx for cetane improver/octadecane test.

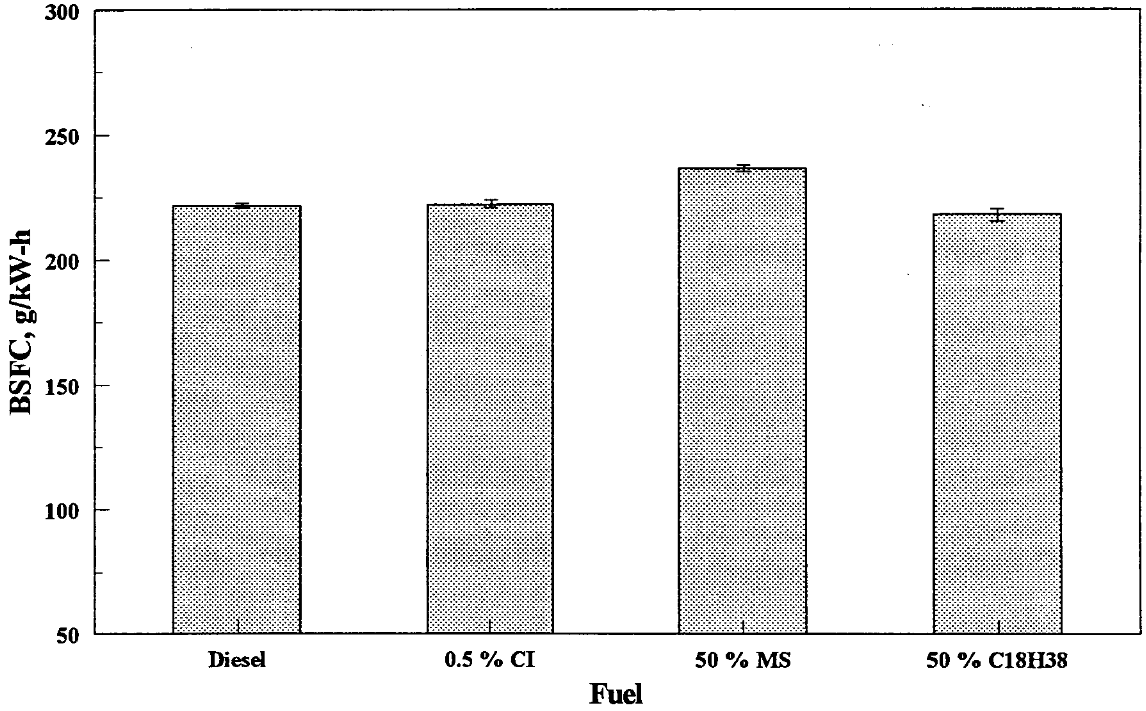

Figure 4.11. Brake specific fuel consumption for cetane improver/octadecane.

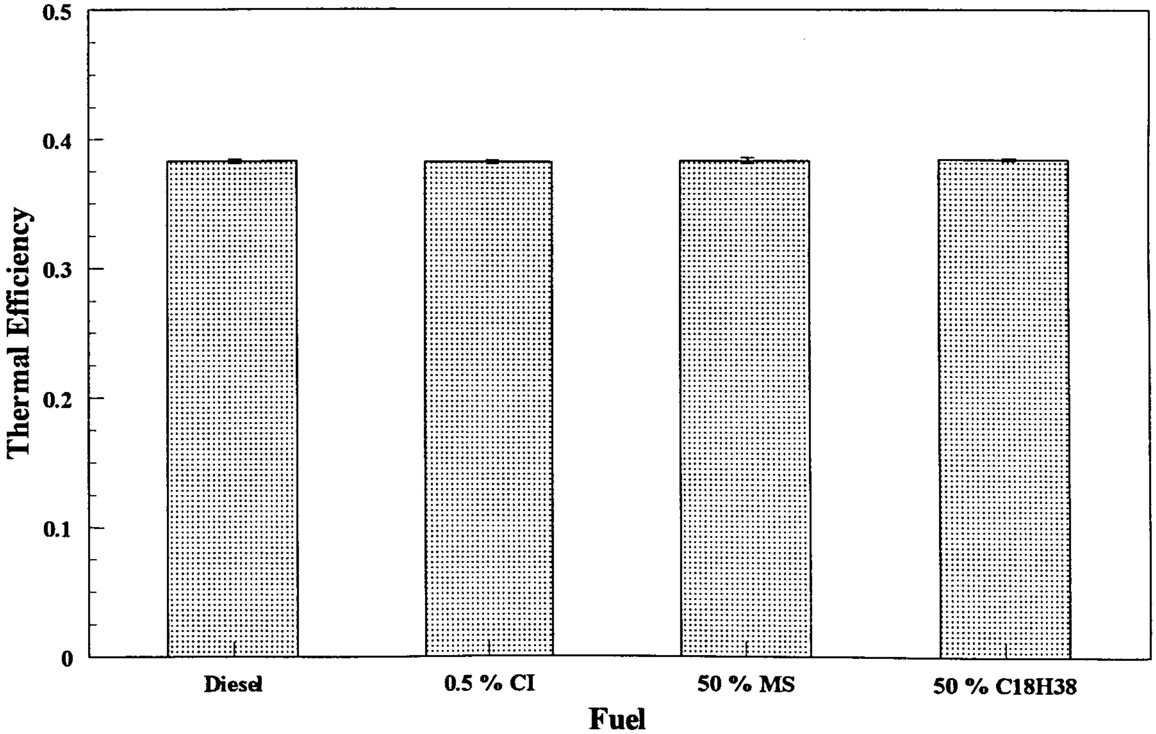

Figure 4.12. Thermal Efficiency for cetane improver/octadecane test.

as "normalized" are the emissions divided by those of diesel fuel. The emission data was normalized to correct for daily variations in lab conditions, day-to-day instrument variations, and fuel variations throughout the study. The error bars on the figures in this section refer to the propagated uncertainty in the normalized quantity. Table B.2 in Appendix B contains the emission data for all of the esters.

4.3.1 Particulate Emissions

The normalized brake specific particulate emissions for the eight esters are illustrated in Figure 4.13. Some of the esters show little or no reduction of total particulate emissions, such as the methyl ester of safflower oil and methyl and isopropyl stearate. Several esters show a particulate reduction of approximately 10% for a 20% blend. Methyl soyate, isopropyl stearate, and the methyl ester of safflower oil did not statistically change the total particulate emissions relative to diesel fuel. However, methyl palmitate reduces the particulate more than all of the other fatty esters. A 50/50 mixture of methyl palmitate with diesel fuel reduces the total particulate emissions by approximately 30 percent. Figure 4.13 shows that the methyl and isopropyl palmitate esters have a lower BSPM than the methyl and isopropyl stearate esters. In general, the palmitate esters and methyl oleate tend to reduce BSPM more than methyl soyate.

Figure 4.14 shows the solid portion of the particulate emissions for the esters. The solid particulate emissions for all of the fuels decreased as the fraction of ester increased. One possible reason for this is due to the oxygen present in the esters. The additional oxygen makes the fuel-air mixture leaner and allows more of the solid carbon to burn completely.

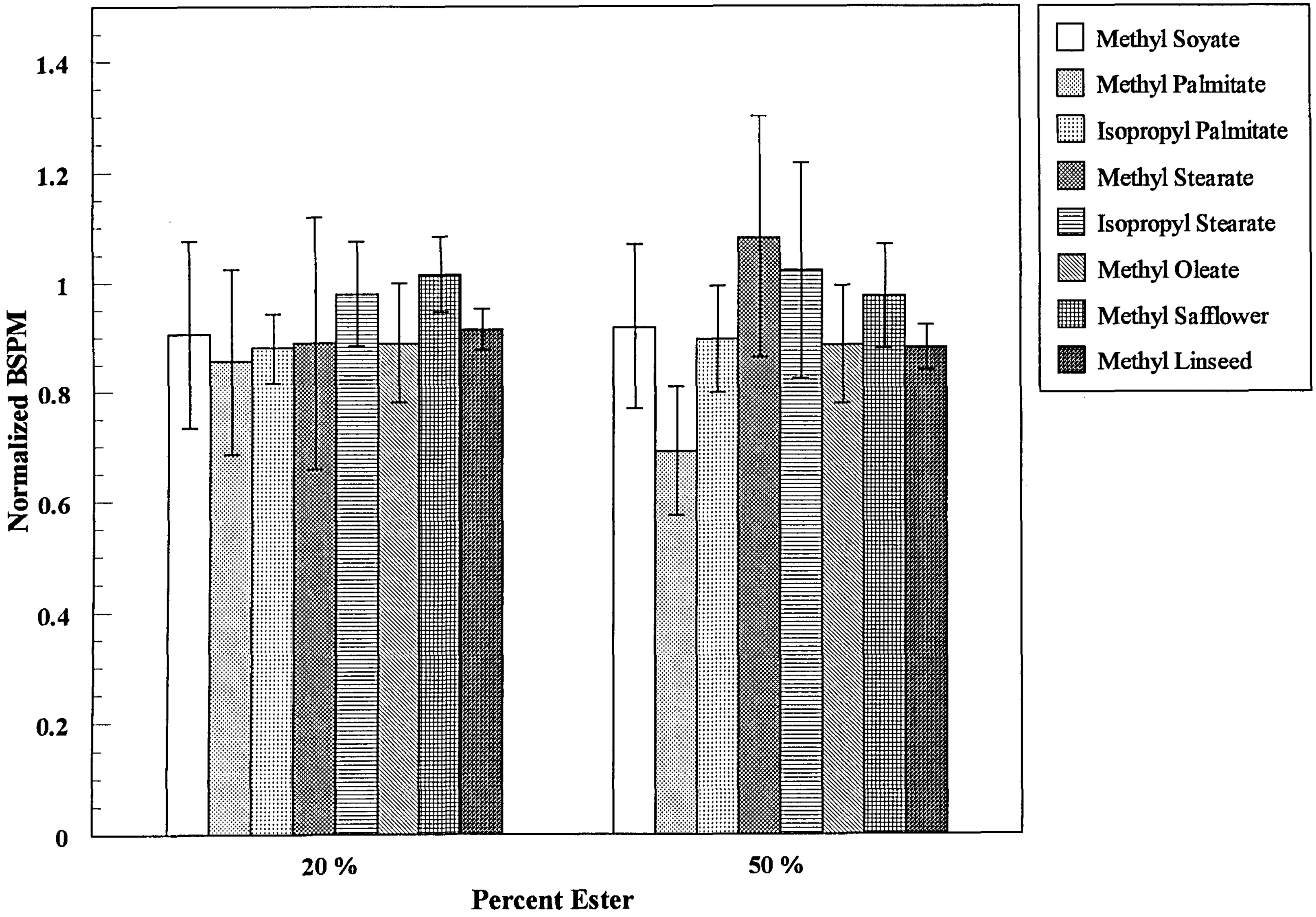

Figure 4.13. Normalized BSPM for fatty esters.

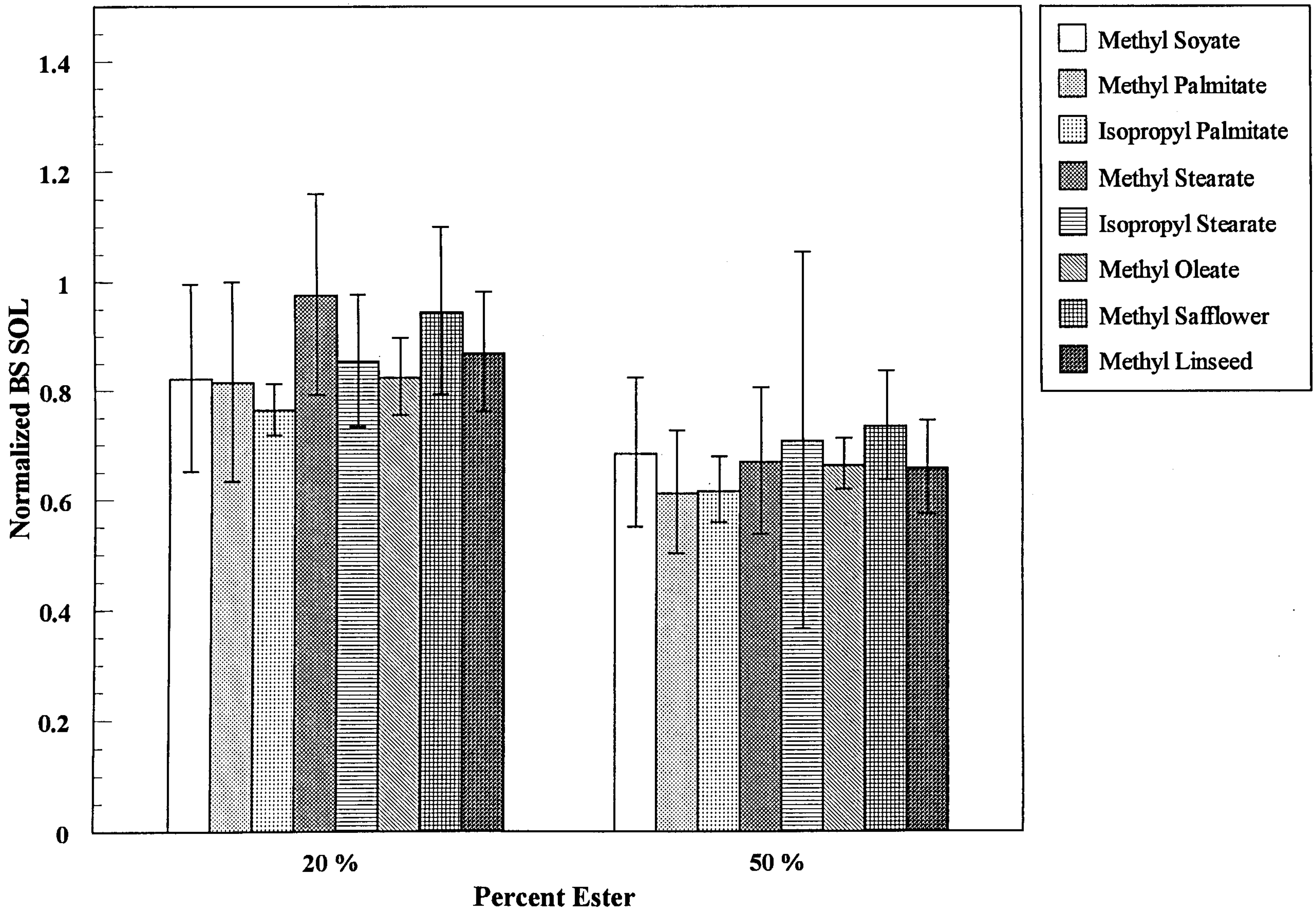

Figure 4.14. Normalized BS SOL for fatty esters.

Also, the increase in cetane number and aromatic reduction for the ester blends reduces the solid carbon emissions. Figure 4.14 also shows that the stearate esters had higher solid carbon emissions than the palmitate esters.

The soluble organic fraction of the total particulate emissions is illustrated in Figure 4.15. For all of the esters, the SOF increases with increasing ester concentration. Also, the saturated esters appear to have higher SOF emissions than the unsaturated esters, except for the methyl palmitate. The 50/50 methyl palmitate blend had the lowest SOF of all the esters. Figure 4.16 shows the SOF emissions for the 18 carbon length esters used in this study. As the degree of unsaturation increases, the SOF decreases. Bailey et al. [26] reports that unsaturated fatty acids have lower boiling points than saturated fatty acids. Boiling point data for esters was unavailable, but it is suspected that the boiling points of the fatty esters will follow the same trends as the fatty acids. Therefore, the lower SOF for the unsaturated esters shown in Figure 4.16 may be due to the lower boiling point unsaturated esters. An ester with a lower boiling point is more volatile and may not condense on the particulate filters as easily as a saturated ester.

4.3.2 Carbon Monoxide

Carbon monoxide is an intermediate product of normal hydrocarbon combustion, even under fuel-lean conditions. The normalized brake specific CO emissions are shown in Figure 4.17. The reduction in CO emissions for some of the esters is not significant. However, methyl stearate and methyl palmitate appear to reduce CO the most when blended with diesel fuel. The esters may reduce CO by reducing the amount of CO formed in rich zones due to

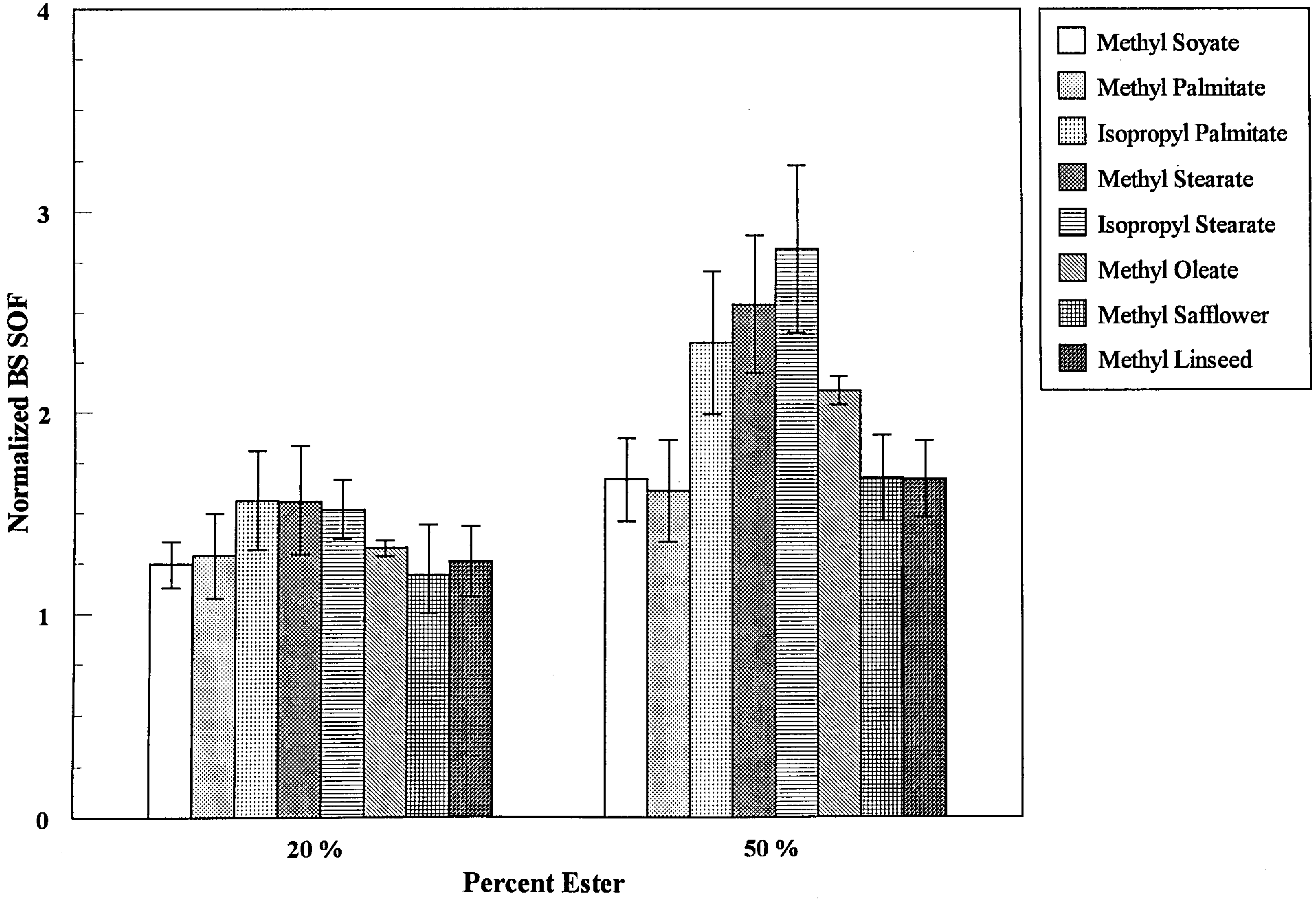

Figure 4.15. Normalized BS SOF for Fatty Esters

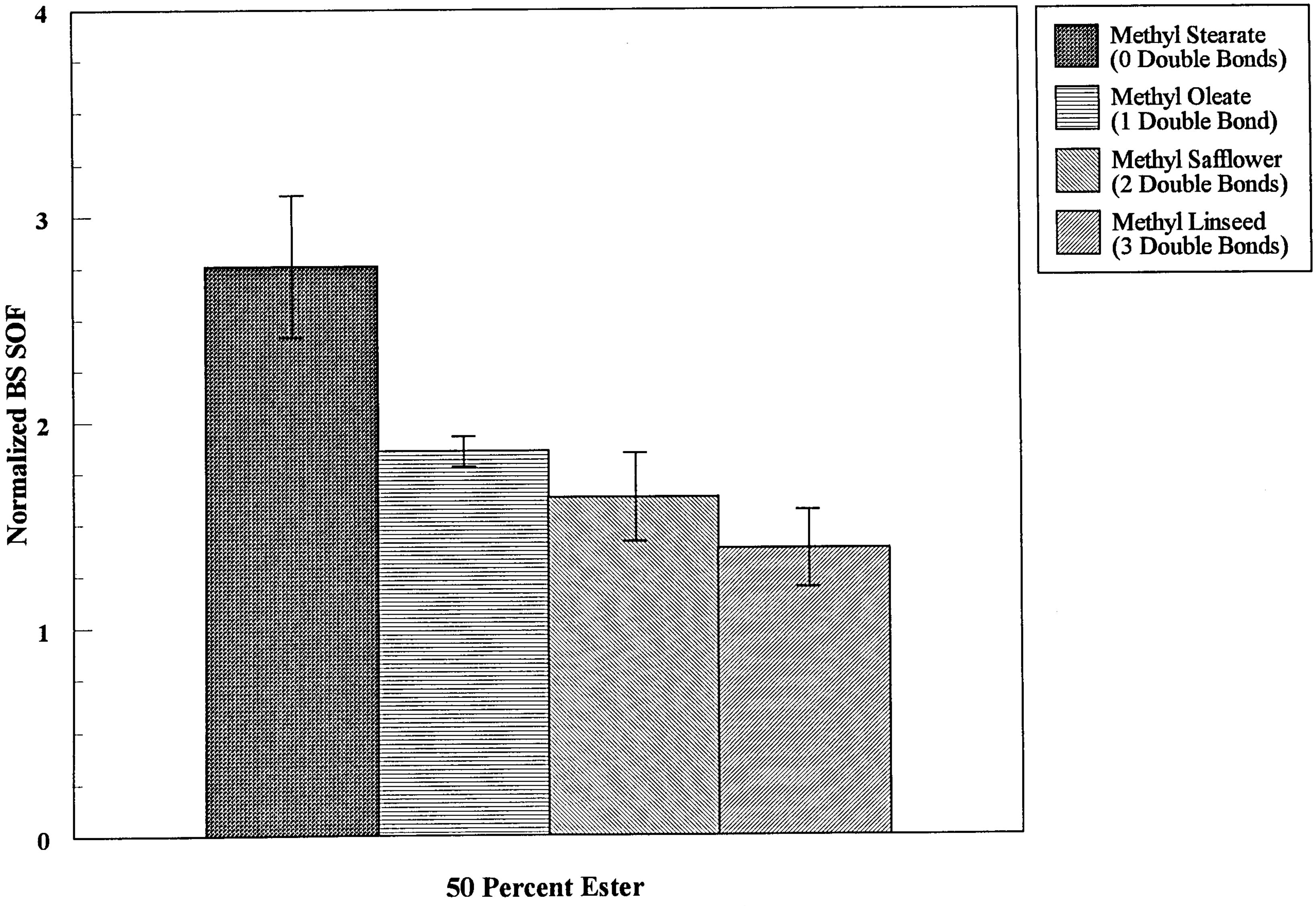

Figure 4.16. Normalized BS SOF for fatty esters with increasing unsaturation.

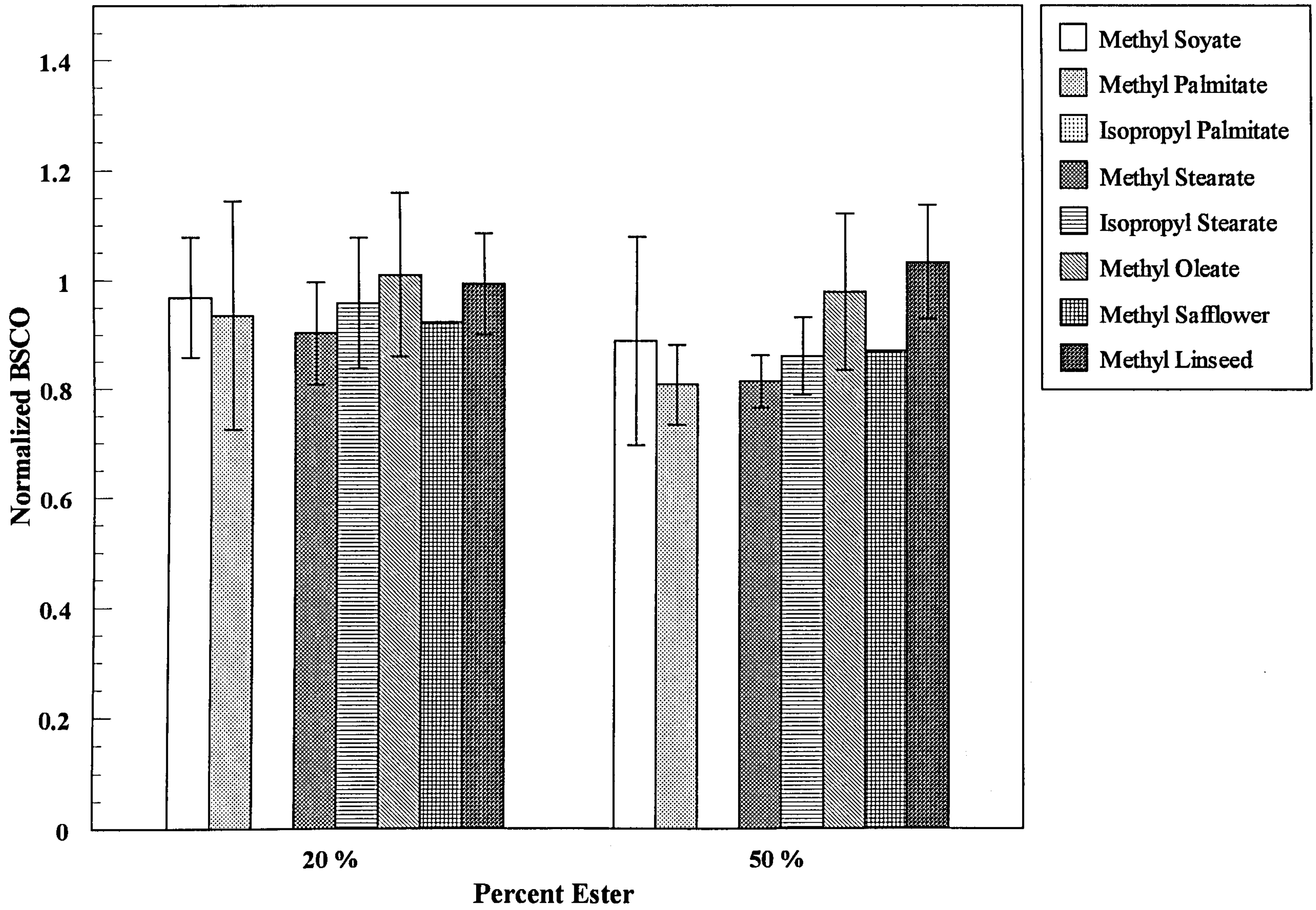

Figure 4.17. Normalized BSCO for fatty esters.

their oxygen content, lowering the overall fuel-air ratio. The size of error bars in Figure 4.17 indicate that the CO data was not very high quality. The CO meter presented problems on a daily basis and the CO data should not be taken as definitive. Carbon monoxide data for isopropyl palmitate is not available due to equipment failure during the test.

4.3.3 Unburned Hydrocarbon

The normalized brake specific hydrocarbon emissions are shown in Figure 4.18. The HC emissions decrease as the percent ester increases for all of the esters. The hydrocarbon reduction is most significant for methyl stearate and methyl palmitate esters. For a 50/50 ester blend, the methyl palmitate and methyl stearate reduce the unburned hydrocarbon by approximately 30 percent. However, methyl soyate reduces HC more than the other esters for a 50/50 blend.

Figure 4.19 shows the HC emissions for the four saturated esters used in this study. The isopropyl esters had higher HC emissions than the methyl esters, but they were not significantly higher. Also, Figure 4.20 illustrates the HC emissions for the 18 carbon length esters. The saturated ester, methyl stearate, had a significantly lower HC emission than the three unsaturated esters. As discussed earlier, it is suspected that saturated esters may be less volatile than unsaturated esters. One possible explanation for these lower HC emission levels may be related to the volatility of the fuel and how HC is measured. Part of the less volatile esters may condense in the sample line before the sample reaches the HFID, which results in a lower HC reading.

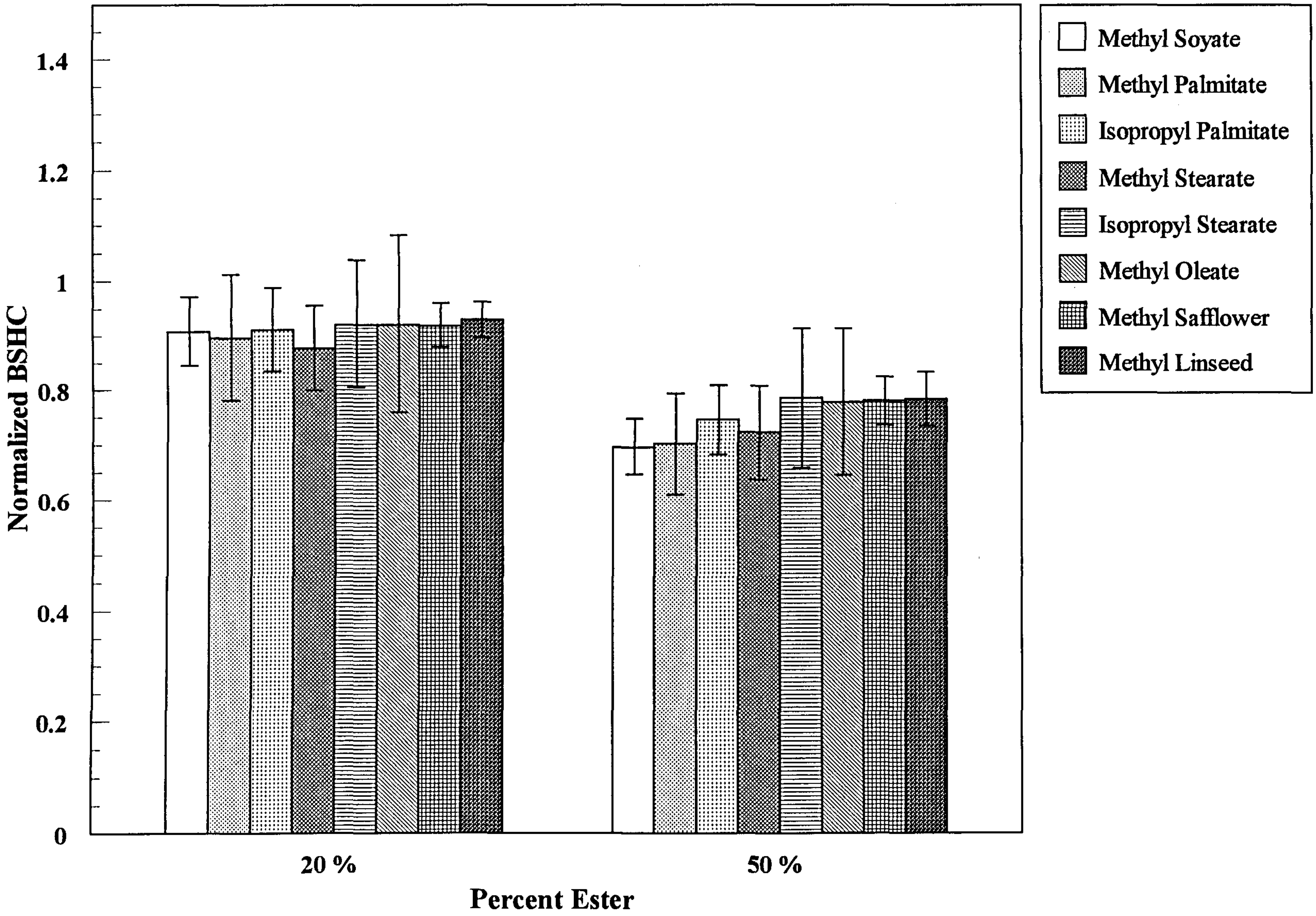

Figure 4.18. Normalized BSHC for fatty esters.

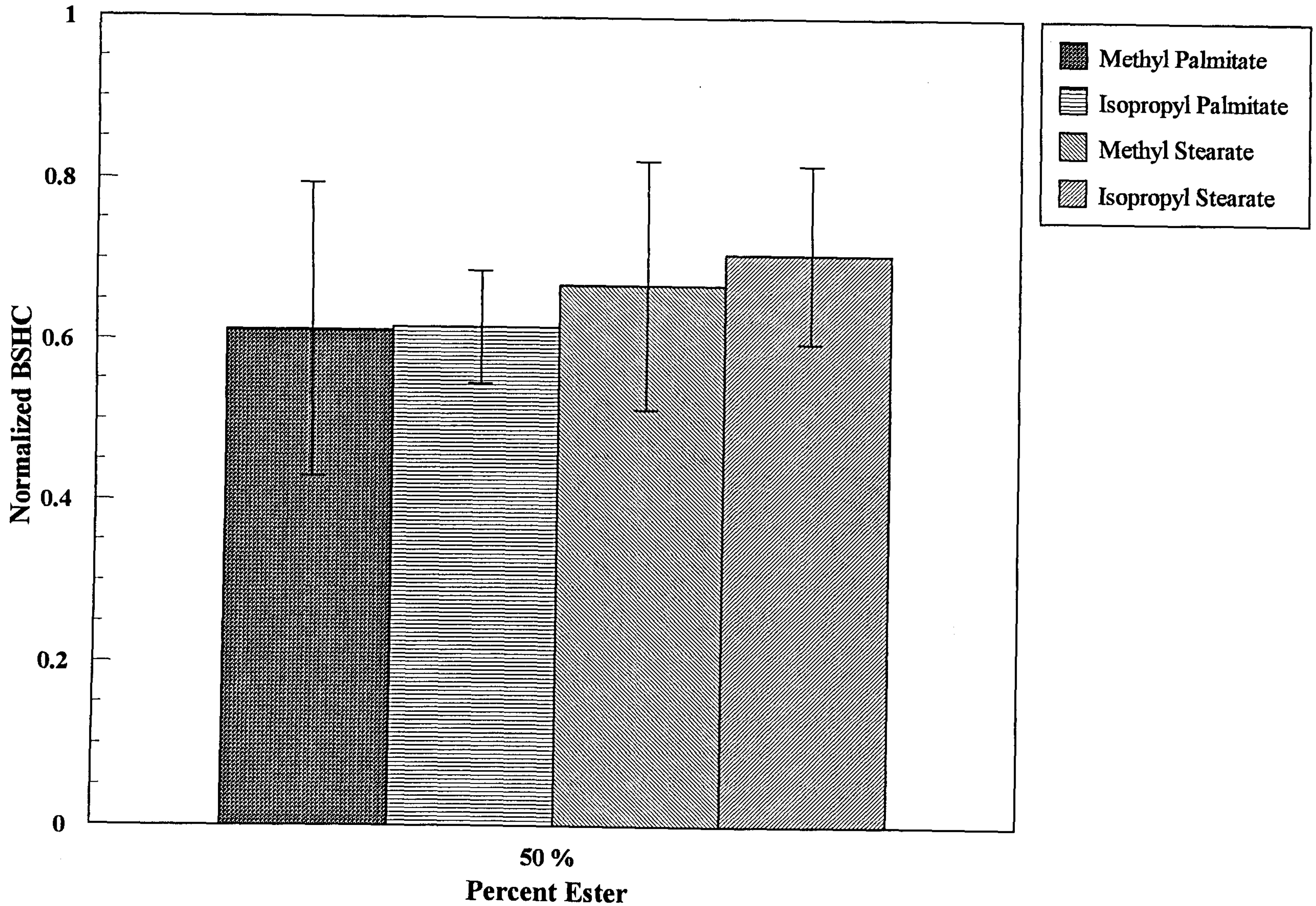

Figure 4.19. Normalized BSHC for saturated methyl and isopropyl esters.

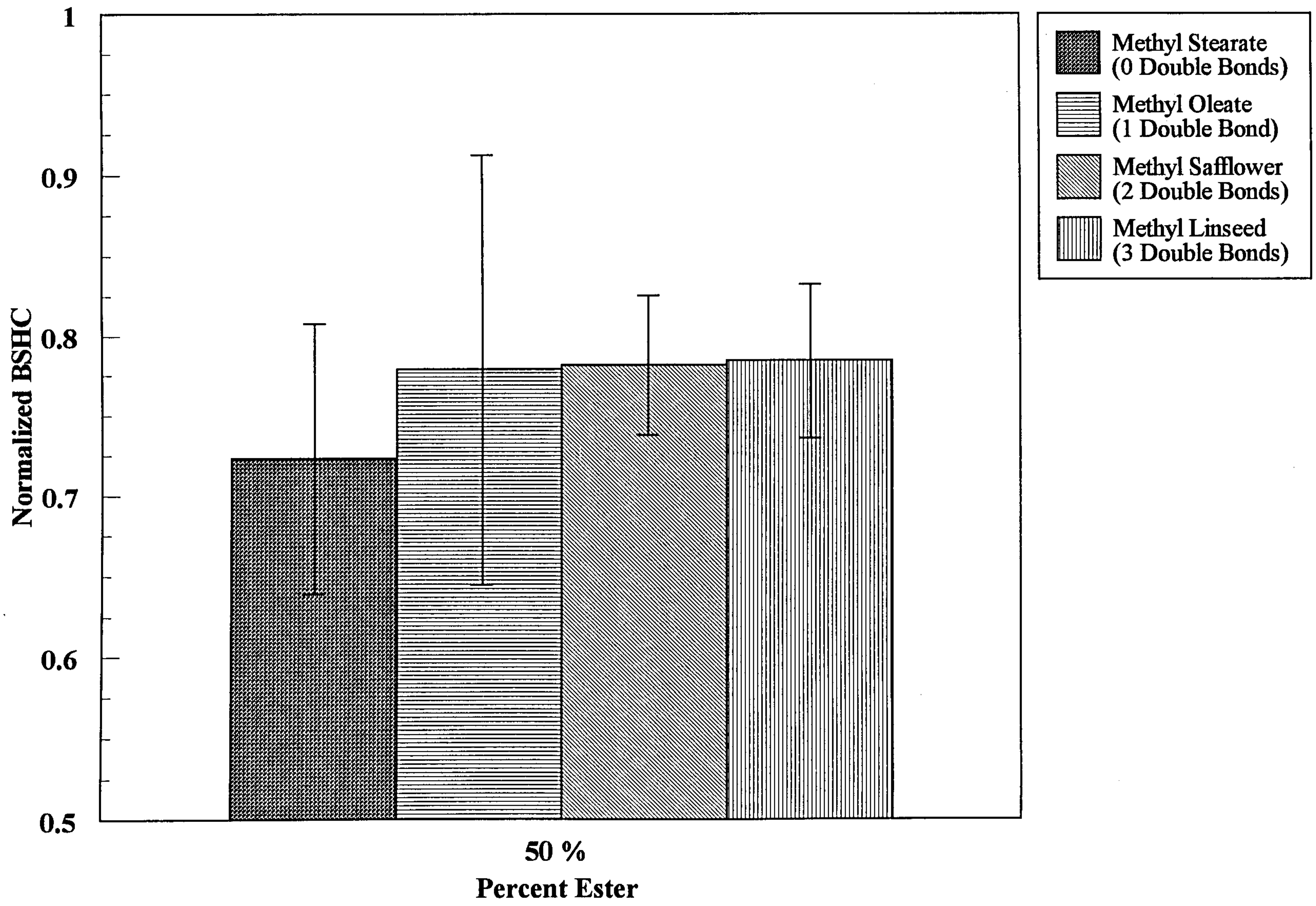

Figure 4.20. Normalized BSHC for fatty esters with increasing unsaturation.

4.3.4 Oxides of Nitrogen

The normalized brake specific NO_x emissions are shown in Figure 4.21. The NO_x emissions did not change significantly for any of the esters. NO_x levels generally increase under conditions of high temperature and lean operation where oxygen is present. Although the combustion temperature of the fuel blends was probably lower for the esters than for diesel fuel, due to the lower energy content of the esters, more oxygen was available in the reaction zone during combustion. The combination of these two effects resulted in only small changes in NO_x levels for the esters.

4.3.5 Engine Performance

The fuel consumption and power were measured for all of the engine tests. The esters generally produced less power than diesel fuel. Figure 4.22 illustrates that as the amount of ester in the fuel increased, the BSFC also increased. This is primarily due to the lower energy content of ester fuels. For instance, methyl soyate has a lower heating value (LHV) of 37.2 MJ/kg, but No. 2 diesel has a LHV of 42.4 MJ/kg. Furthermore, Figure 4.23 illustrates the thermal efficiency of the engine for all of the esters. The thermal efficiency remained nearly constant for all of the esters. This indicates that the engine converts the fuel energy from chemical to mechanical energy equally as well for the esters as for diesel fuel.

4.4 Optimum Fatty Ester

One of the primary goals of this study was to arrive at the optimum ester of fatty acids found in soybean oil for reducing engine exhaust emissions. The selection of the optimum ester was based on the emissions characteristics of each ester blended with No. 2 diesel fuel.

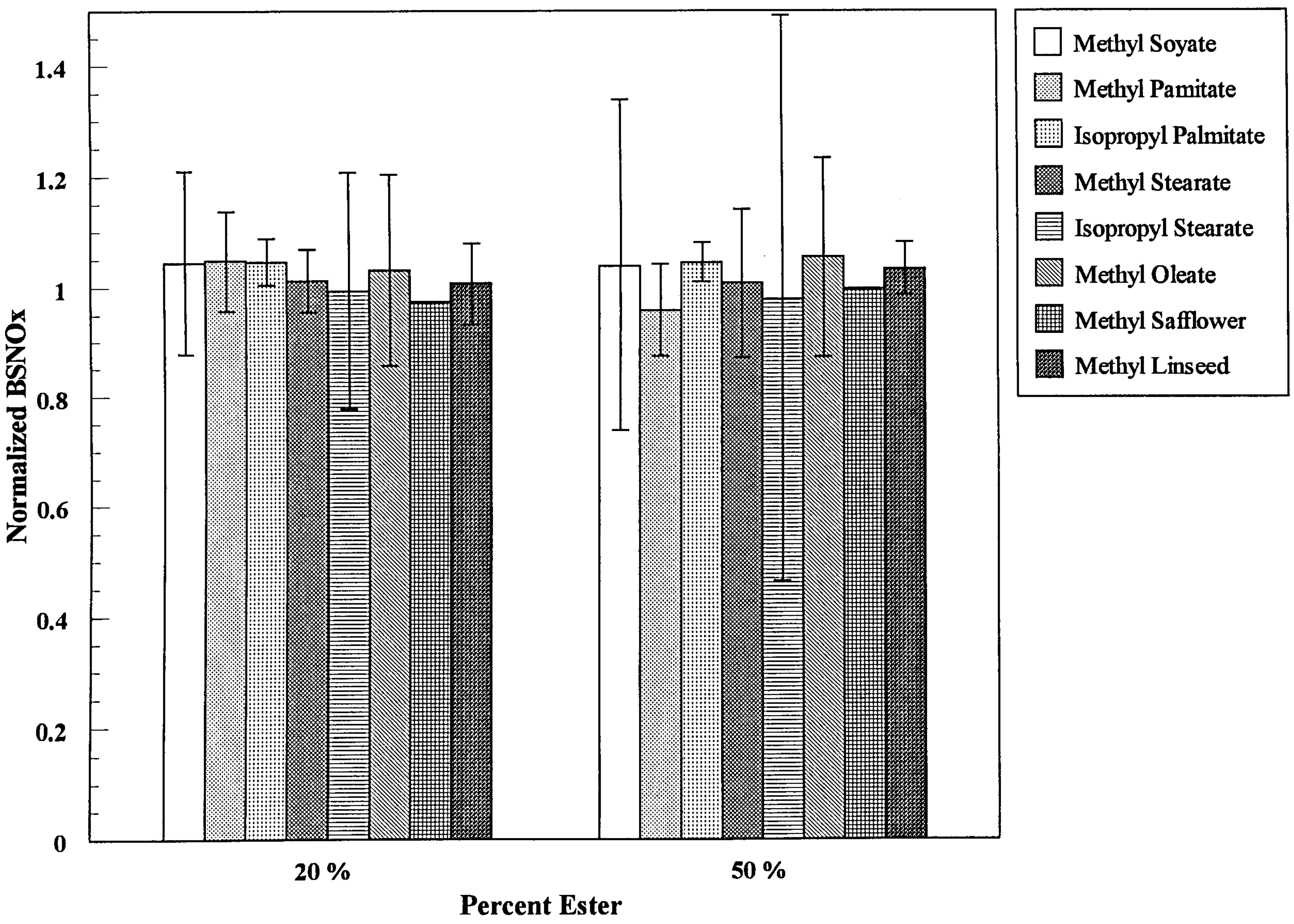

Figure 4.21. Normalized BSNOx for saturated methyl and isopropyl esters.

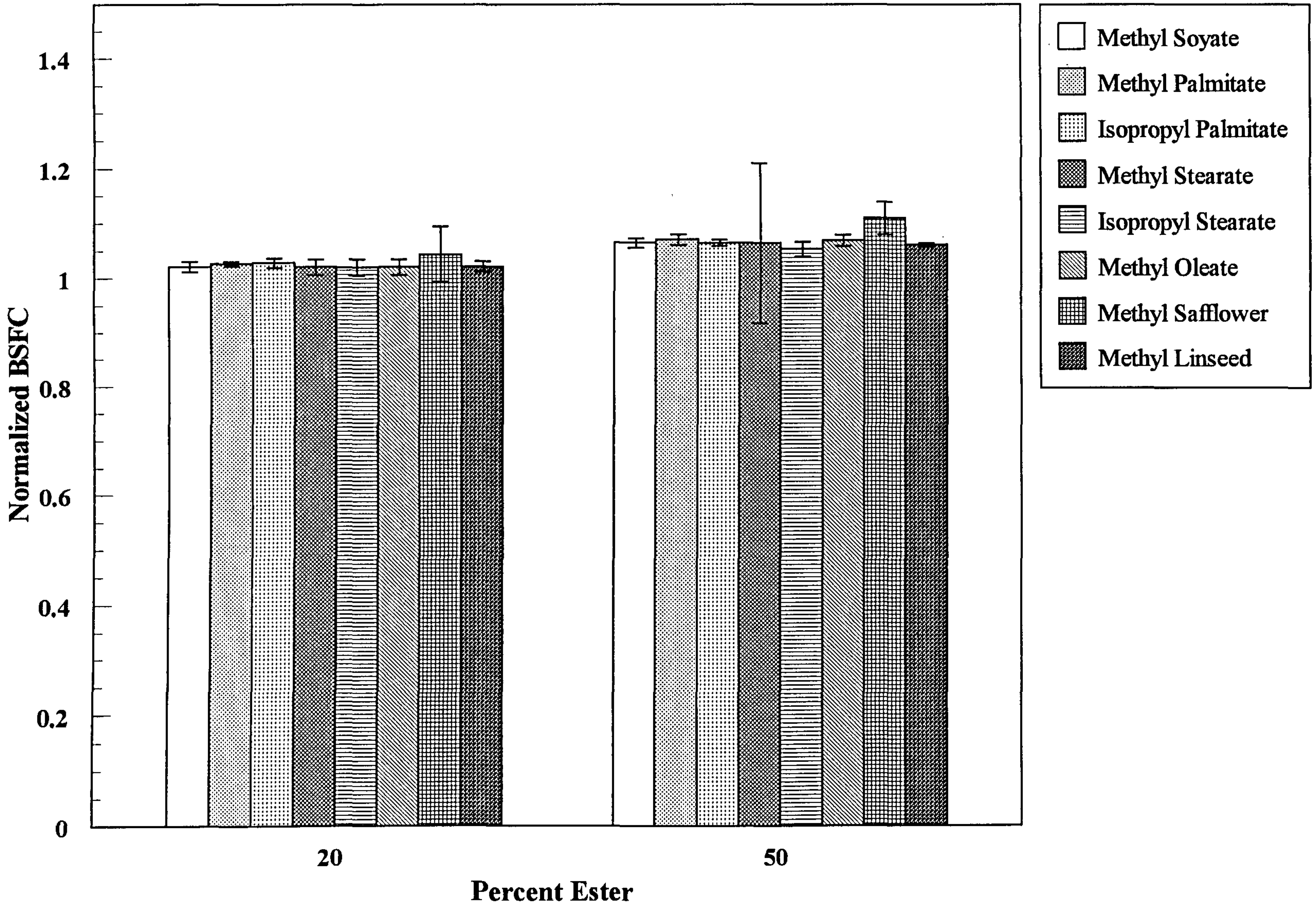

Figure 4.22. Normalized BSFC for fatty esters.

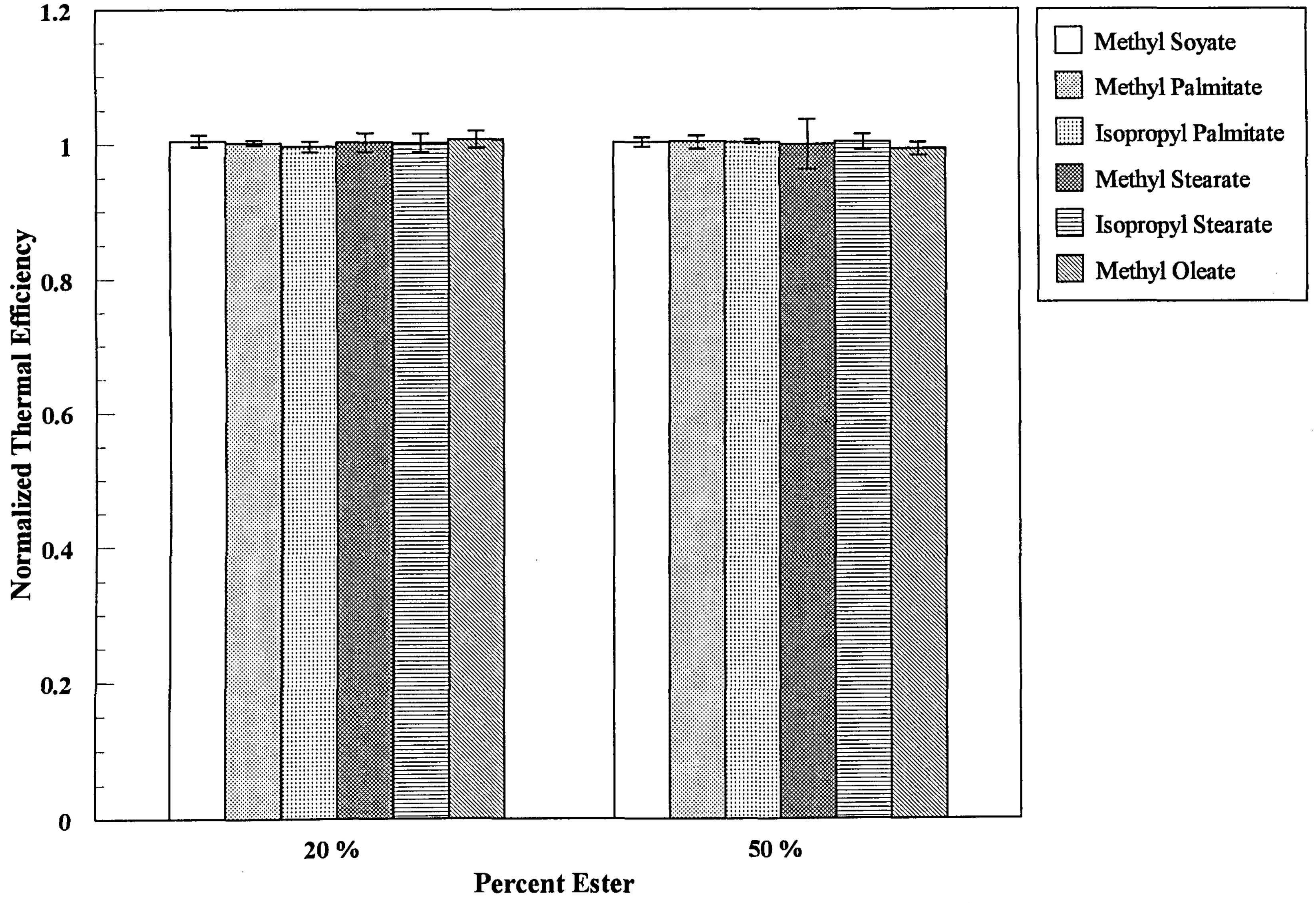

Figure 4.23. Normalized thermal efficiency for fatty esters.

The most significant benefit associated with the use of biodiesel is its particulate reduction capability. Figure 4.13 shows that methyl palmitate reduced total particulate emissions more than any of the other esters. Figure 4.14 shows that the 50% blends of the methyl and isopropyl palmitates had the lowest solid carbon emissions of all the esters. Also, Figure 4.15 illustrates that the 50% methyl palmitate blend had the lowest SOF of the esters evaluated in this study.

Figure 4.17 shows that CO emissions were the lowest for the 50% methyl palmitate fuel. Also, Figure 4.18 shows that HC emissions is lower for methyl palmitate than for any of the other individual esters studied.

Based on the above discussion, the logical choice for the optimum ester in the methyl ester of soybean oil is methyl palmitate. It reduces particulate more than any other ester and provides low CO and HC emissions. In processing or breeding soybeans, anything that will maximize the amount of palmitic acid should improve the value of the soybean oil as a biodiesel feedstock.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The first part of this study involved investigating three possible reasons why an ester of soybean oil reduces emissions. The impact of the fuel's oxygen content, long chain hydrocarbons and cetane improver were evaluated. The results indicate that:

1. The solid portion of the particulate decreased by 33% as the oxygen content of the intake air was increased from 20.5% to 22.0%.
2. Oxides of nitrogen emissions increased by 25% as the oxygen content of the intake air was increased from 20.5% to 22.0%.
3. Emissions were measured with ethylhexyl nitrate added to increase the cetane number by 10.3 points. This reduced total particulate emissions by 6% but had no effect on oxides of nitrogen emissions.
4. Using octadecane as a long chain hydrocarbon decreased particulate and unburned hydrocarbon emissions but did not change oxides of nitrogen emissions. For a 50% octadecane/diesel fuel blend, particulate emissions decreased by 21% and hydrocarbon emissions decreased by 22%.

The second part of this study involved evaluating the emission and performance characteristics of the fatty esters found in the ester of soybean oil. The results indicate that:

5. Particulate emissions were significantly reduced when the diesel engine was fueled with blends of methyl palmitate with diesel fuel. The 50% blend of methyl palmitate gave the largest particulate reduction of 30%.

6. The soluble portion of the particulate decreased with increasing ester unsaturation.
7. NO_x emissions for all of the 50% fatty ester blends with diesel fuel, except methyl palmitate and isopropyl stearate, increased between 0 and 5%. 50% Methyl palmiate and 50% isopropyl stearate reduced NO_x emissions 2 to 3%.
8. All of the esters demonstrated a significant reduction in hydrocarbon emissions.
9. Unburned hydrocarbon emissions are 8 to 9% higher for unsaturated esters than for saturated esters.
10. Brake specific fuel consumption increases for all of the fatty esters, but thermal efficiency of the engine does not change when esters are used.

5.2 Recommendations for Future Work

To further investigate the mechanisms that reduce emissions for esters of vegetable oils, some specific tests should be conducted.

1. Other oxygen containing fuels should be blended with diesel fuel to determine which oxygenate produces the most desirable results. Possible oxygenates would be alcohols and ethers. Alcohols may not provide the particulate reductions that esters do because alcohols generally have only one oxygen atom, where esters and ethers have two. This could be overcome by using di-alcohols instead of an alcohol with only one oxygen atom.
2. Combinations of the fatty esters found in soybean oil could be tested to determine which combinations and concentrations provide the most desirable characteristics. Using eutectic mixtures of esters will reduce the melting point and improve cold flow properties.

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APPENDIX A. ENGINE SETUP

The table below lists the thermocouples used to measure temperatures on the engine and emission sampling system.

Table A.1. Themocouples used on engine and emissions equipment.

Thermocouple	Location
1	Inlet dry bulb temperature
2	Inlet wet bulb temperature
3	Intake manifold temperature
4	Fuel temperature
5	Oil temperature
6	Inlet coolant temperature
7	Outlet coolant temperature
8	Exhaust manifold temperature
9	Exhaust temperature (shielded thermocouple)
10	Exhaust temperature (thermocouple shield)
11	Exhaust temperature (unshielded)
13	Building cooling water inlet temperature
14	Building cooling water outlet temperature
15	Static temperature of 1st dilution tunnel
16	Static temperature of 2nd dilution tunnel
17	Filter chamber temperature
18	Temperature at ROOTS meter
19	Dilution tunnel temperature, sampling point 1
20	Dilution tunnel temperature, sampling point 2

APPENDIX B. EMISSION DATA

The following tables contain the emission data accumulated for the fuels investigated in this study.

Table B.1. Brake specific emissions for Oxygen test.

Intake O_2 Percentage	BSCO	BSHC	BSNO	BSNO$_x$	BSPM	BS SOL	SOF, %	BSFC	Th. Eff.
20.5	1.1803	0.5360	12.1034	23.1401	0.3973	0.3193	19.8513	225.041	0.3769
20.8	1.1996	0.5336	12.4645	23.6828	0.3951	0.3181	19.5185	224.011	0.3787
21.0	1.1496	0.5121	13.6603	26.3764	0.3740	0.3045	18.6626	225.328	0.3766
21.3	1.1054	0.5159	15.5544	28.4421	0.3540	0.2881	18.3749	223.404	0.3797
21.7	1.0265	0.5091	13.6978	29.3856	0.3029	0.2361	22.0087	223.236	0.3800
22.0	0.9963	0.5102	16.4166	29.8686	0.2714	0.2022	25.5538	228.036	0.3723

Table B.2. Brake specific emissions for vegetable oil esters.

Test	Fuel	BSCO	BSHC	BSNO	BSNO$_x$	BSPM	BS SOL	SOF, %	BSFC	Th. Eff.
Methyl Soyate	D2	3.8539	0.4159	10.9823	18.6179	0.3165	0.2291	27.6952	221.400	0.3828
	20 %	3.7325	0.3773	11.3413	19.4477	0.2869	0.1880	34.6069	226.143	0.3844
	50 %	3.4238	0.2897	11.2081	19.3126	0.2909	0.1567	46.1365	235.665	0.3836
Methyl Palmitate	D2	3.7136	0.4511	11.5051	19.9404	0.3445	0.2865	18.7879	223.604	0.3780
	20 %	3.4741	0.4041	11.8074	20.9092	0.2951	0.2332	24.2371	229.498	0.3786
	50 %	2.9993	0.3171	11.3430	19.0974	0.2384	0.1756	30.2207	239.369	0.3790
Isopropyl Palmitate	D2	*******	0.4662	10.8624	19.1343	0.3349	0.2725	20.6185	222.158	0.3805
	20 %	*******	0.4250	11.3832	20.0245	0.2953	0.2082	32.1912	228.470	0.3794
	50 %	*******	0.3479	11.3927	19.9817	0.3004	0.1679	48.3339	236.318	0.3814
Methyl Stearate	D2	4.0433	0.3794	10.9130	18.2521	0.3458	0.2777	19.8692	222.998	0.3801
	20 %	3.6504	0.3327	11.0136	18.4758	0.3077	0.2708	30.9219	227.596	0.3814
	50 %	3.2890	0.2745	10.9485	18.3784	0.3738	0.1858	50.3846	237.156	0.3798
Isopropyl Stearate	D2	3.6459	0.5592	11.7868	20.1470	0.4559	0.4168	15.0015	223.725	0.3788
	20 %	3.4927	0.5148	11.7166	20.0109	0.4462	0.3557	22.7056	228.167	0.3796
	50 %	3.1326	0.4398	11.5553	19.7099	0.4659	0.2947	42.1854	235.653	0.3799

Table B.2 (continued)

Test	Fuel	BSCO	BSHC	BSNO	BSNO$_x$	BSPM	BS SOL	SOF, %	BSFC	Th. Eff.
Methyl Oleate	D2	4.4056	0.5041	10.6744	18.0231	0.3747	0.3048	18.5985	222.190	0.3815
	20 %	4.4454	0.4641	11.0305	18.5850	0.3333	0.2511	24.6629	226.864	0.3842
	50 %	4.3103	0.3926	11.2747	19.0072	0.3321	0.2024	39.1571	237.341	0.3789
Methyl Safflower	D2	0.7891	0.5470	8.2121	19.9524	0.3496	0.2557	26.8523	232.998	*******
	20 %	0.7283	0.5026	7.6906	19.4399	0.3546	0.2414	31.9966	242.914	*******
	50 %	0.6865	0.4275	8.3519	19.8815	0.3410	0.1879	44.9417	258.537	*******
Methyl Linseed	D2	0.9355	0.5698	8.3754	20.2690	0.4143	0.3173	23.4236	240.439	*******
	20 %	0.8558	0.5300	8.3208	20.4108	0.3916	0.2758	29.5591	245.510	*******
	50 %	0.8249	0.4469	8.6463	20.9405	0.3432	0.2091	39.0829	255.050	*******

Table B.3. Brake specific emissions for cetane improver/octadecane test.

Fuel	BSCO	BSHC	BSNO	BSNO$_x$	BSPM	BS SOL	SOF, %	BSFC	Th. Eff.
D2	3.4968	0.4586	10.7314	18.0652	0.3844	0.3223	16.1177	221.482	0.3827
0.5 % CI	3.7087	0.4574	10.7759	18.1245	0.3615	0.2951	18.2955	222.064	0.3817
50 % MS	2.9903	0.3298	11.5135	19.3154	0.2797	0.1773	36.6296	236.312	0.3825
50 % C$_{18}$	2.9260	0.3587	10.3450	17.4019	0.3026	0.2437	19.3563	217.756	0.3838

APPENDIX C. STATISTICAL SIGNIFICANCE PROBABILITIES

This appendix includes tables with the probabilities of the emission values being statistically different. Statistically different data sets are marked with boldfaced probabilties.

Table C.1. Probabilities of emission data for oxygen test being significantly different.

Emission	O_2 Concentration	20.8%	21.0%	21.3%	21.7%	22.0%
BSPM	20.5%	0.0801	0.6482	0.7988	**0.9758**	**0.9930**
	20.8%		0.8159	0.8642	**0.9901**	**0.9981**
	21.0%			0.5515	**0.9685**	**0.9939**
	21.3%				0.8565	**0.9655**
	21.7%					0.7312
BS SOL	20.5%	0.0330	0.3646	0.6838	**0.9499**	**0.9854**
	20.8%		0.5236	0.8945	**0.9874**	**0.9979**
	21.0%			0.5888	**0.9651**	**0.9936**
	21.3%				**0.9440**	**0.9928**
	21.7%					0.1825
BS SOF	20.5%	0.0867	0.2730	0.2981	0.3685	0.8774
	20.8%		0.6533	0.5755	0.5588	0.7253
	21.0%			0.2025	0.1632	0.0321
	21.3%				0.0370	0.1911
	21.7%					0.1500
BSNO	20.5%	0.2689	0.8035	0.8968	0.7772	**0.9643**
	20.8%		0.7385	0.8767	0.7050	**0.9598**
	21.0%			0.6973	0.0268	0.8912
	21.3%				0.6721	0.3323
	21.7%					0.8726

Table C.1 (Continued)

Emission	O_2 Concentration	20.8%	21.0%	21.3%	21.7%	22.0%
BSNO$_x$	20.5%	0.1810	0.7708	0.7606	0.8845	0.8970
	20.8%		0.7980	0.8257	**0.9394**	**0.9424**
	21.0%			0.4204	0.8426	0.7382
	21.3%				0.1958	0.3171
	21.7%					0.1292
BSHC	20.5%	0.0817	0.8217	0.5801	0.7901	0.7631
	20.8%		0.6529	0.4617	0.6573	0.6304
	21.0%			0.1366	0.1389	0.0879
	21.3%				0.2145	0.1797
	21.7%					0.0388

Table C.2. Probabilities of particulate data for esters being significantly different.

Fuel Test		BSPM		BS SOL		BS SOF	
	Fuel	20 %	50 %	20 %	50 %	20 %	50 %
Methyl Soyate	Diesel	0.7998	0.7998	**0.9149**	**0.9922**	**0.9782**	**0.9997**
	20 %		0.2734		**0.931**		**0.9922**
Methyl Palmitate	Diesel	**0.9142**	**0.9967**	**0.9434**	**0.9975**	**0.9838**	**0.9958**
	20 %		**0.9682**		**0.9871**		**0.9744**
Isopropyl Palmitate	Diesel	**0.9946**	**0.9677**	**0.9997**	**0.9999**	**0.9995**	**>0.9999**
	20 %		0.3446		**0.9990**		**>0.9999**
Methyl Stearate	Diesel	0.7770	0.7034	0.0699	**0.9824**	**0.9333**	**0.9999**
	20 %		**0.9570**		0.6974		**0.9890**
Isopropyl Stearate	Diesel	0.3723	0.1089	**0.9255**	**0.9588**	**0.9964**	**0.9988**
	20 %		0.2660		0.8494		**0.9957**

Table C.2 (Continued)

Fuel Test		BSPM		BS SOL		BS SOF	
	Fuel	20 %	50 %	20 %	50 %	20 %	50 %
Methyl Oleate	Diesel	**0.9534**	**0.9571**	**0.9926**	**0.9960**	**0.9983**	**0.9953**
	20 %		0.1383		**0.9664**		**0.9840**
Methyl Safflower	Diesel	0.3909	0.8653	0.6475	**0.9981**	**0.9020**	**0.9998**
	20 %		0.7964		**0.9794**		**0.9912**
Methyl Linseed	Diesel	0.8300	**0.9931**	**0.9618**	**0.9986**	**0.9607**	**0.9987**
	20 %		**0.9988**		**>0.9999**		**>0.9999**

Table C.3. Probabilities of oxides of nitrogen and hydrocarbon data for esters being statistically different.

Fuel Test		BSNO		BSNO_x		BSHC	
	Fuel	20 %	50 %	20 %	50 %	20 %	50 %
Methyl Soyate	Diesel	**0.9437**	0.3909	**0.9103**	0.7434	**0.9861**	**0.9999**
	20 %		0.2455		0.2014		**0.9996**
Methyl Palmitate	Diesel	0.5770	0.3044	0.8283	0.7786	**0.9341**	**0.9985**
	20 %		**0.9081**		**0.9905**		**0.9950**
Isopropyl Palmitate	Diesel	0.8961	**0.9290**	**0.9730**	**0.9807**	**0.9608**	**0.9991**
	20 %		0.0369		0.1232		**0.9995**
Methyl Stearate	Diesel	0.3990	0.1214	0.5735	0.2958	**0.9885**	**0.9990**
	20 %		0.3110		0.3569		**0.9923**
Isopropyl Stearate	Diesel	0.1406	0.2804	0.2002	0.3294	0.8739	**0.9894**
	20 %		0.2148		0.2384		**0.9578**
Methyl Oleate	Diesel	0.8514	**0.9731**	0.8795	**0.9716**	0.7556	**0.9787**
	20 %		0.6579		0.6951		**0.9634**

Table C.3 (Continued)

Fuel Test		BSNO		BSNO$_x$		BSHC	
	Fuel	20 %	50 %	20 %	50 %	20 %	50 %
Methyl Safflower	Diesel	0.6510	0.4901	0.6590	0.7859	**0.9965**	**>0.9999**
	20 %		0.5144		0.6733		**0.9996**
Methyl Linseed	Diesel	0.2709	0.8927	0.3826	**0.9468**	**0.9962**	**0.9997**
	20 %		0.8690		**0.9925**		**0.9995**

Table C.4. Probabilities of emissions data for Cetane Improver/Octadecane test being statistically different.

	BSNO			BSNO$_x$		
Fuel	0.5 CI	50 MS	50 C_{18}	0.5 CI	50 MS	50 C_{18}
Diesel	0.6701	**0.9983**	**0.9943**	0.4595	**0.9996**	**0.9973**
0.5 % CI		**0.9979**	**0.9964**		**0.9990**	**0.9958**
50 % MS			**0.9994**			**0.9998**
	BSHC			BSPM		
Fuel	0.5 CI	50 MS	50 C_{18}	0.5 CI	50 MS	50 C_{18}
Diesel	0.0530	**0.9986**	**0.9979**	0.6435	**0.9926**	**0.9859**
0.5 % CI		**0.9985**	**0.9977**		**0.9916**	**0.9816**
50 % MS			**0.9045**			0.8301
	BS SOF			BS SOL		
Fuel	0.5 CI	50 MS	50 C_{18}	0.5 CI	50 MS	50 C_{18}
Diesel	0.8190	**0.9976**	0.7481	0.8558	**0.9989**	**0.9961**
0.5 % CI		**0.9957**	0.2960		**0.9990**	**0.9967**
50 % MS			**0.9901**			**0.9952**

APPENDIX D. FUEL PROPERTIES

The following tables contain the properties of the fuels used in this study. All fuel analysis was conducted by Phoenix Chemical Laboratory, Inc. and Southwest Research Institute.

Table D.1. Fuel properties for esters, ester blends, and octadecane blend with diesel fuel.

Fuel	Cetane No.	HHV (Btu/lb)	LHV (Btu/lb)	% Carbon	% Hydrogen	% Sulfur
100% Methyl Soyate	50.7	18366	17256	81.17	12.16	0.011
50% Methyl Palmitate in LSB	61.0	18254	17103	80.75	12.61	0.014
50% Isopropyl Palmitate in LSB	56.8	18371	17216	80.73	12.66	0.013
30% Methyl Stearate in LSC	54.6	18819	17659	83.94	12.71	0.017
50% Isopropyl Stearate in LSC	55.0	18497	17332	82.04	12.077	0.014
50% Methyl Oleate in LSC	50.7	18366	17256	81.17	12.16	0.011
50% Octadecane in LSC	73.8	19840	18567	85.48	13.95	0.012

Table D.2. Fuel properties for diesel fuels.

Fuel Property	High Sulfur A (HSA)	Low Sulfur A (LSA)	Low Sulfur B (LSB)	Low Sulfur C (LSC)	Low Sulfur D (LSD)
Cetane Number	47.8, 45.7	48, 47.4, 44.4, 43.4	45.7, 44.5, 45.6, 46.5,	43.2, 43.3, 45.5, 43.2	42.2, 39.2
Molecular Weight	191	195			
API Gravity	34.1	33.5	35.4		
% Carbon	86.87	86.41	86.94, 86.68	87.28, 86.84	87.15
% Hydrogen	12.63	12.97	13.22, 12.35	13.04, 12.74	12.65
C/H Ratio	6.878	6.662	7.019	6.816	6.89
% Sulfur	0.26	0.045, 0.043	0.034	0.028	0.027
% Ash	0	0.001	0	0	
Viscosity (sSt @ 40°C)	2.57	3.65	2.58, 2.3, 2.57	2.7, 2.5, 2.69	2.79
HHV (Btu/lb)	19461	19488	19530, 19522	19482, 19486	20190
LHV (Btu/lb)	18309		18323, 18395	18292, 18324	19036
% Paraffins	63.2	60.3	57.6	51.1	55.3
% Olefins	2.6	0.5	4.4	4.6	2.2
% Aromatics	34.2	39.2	38	44.3	42.5
Distillation (ASTM D86), °F					
Initial Boiling Point	363	354	340	322	367
5%	397	390	386	376	409
10%	413	410	417	421	428
20%	442	440	442	451	454
30%	463	462	465	473	476
40%	484	483	486	492	495
50%	502	503	504	511	512
60%	520	523	526	530	531
70%	541	544	548	552	552
80%	565	565	574	577	575
90%	592	598	609	612	609
95%	617	618	635	642	632
End Point	643	653	650	655	663
Recovery, %	98	98	97.5	97.5	98.0
Residue, %	1.9	1.9	1	1	1.9
Loss, %	0.1	0.1	1.5	1.5	0.1

APPENDIX E. TEST DATA

The following tables contain the raw data collected for this study.

Date	11/23/94	11/23/94	11/23/94	11/23/94	11/23/94	11/23/94	11/23/94	11/23/94	11/23/94	11/23/94	11/23/94	11/23/94
Test	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen
Rep. Number	1	1	1	1	1	1	2	2	2	2	2	2
Fuel	20.5	20.8	21.0	21.3	21.7	22.0	20.5	20.8	21.0	21.3	21.7	22.0
Engine Speed (RPM)	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
% of rated load	100	100	100	100	100	100	100	100	100	100	100	100
Brake Torque (ft-lb)	219.0	218.5	220.3	219.0	219.5	219.0	219.8	218.5	218.5	219.0	218.5	219.0
Time (sec)	916	906	905	901	901	904	900	915	901	900	900	900
Fuel Mass (kg)	2.47	2.45	2.45	2.44	2.44	2.6	2.44	2.47	2.51	2.43	2.43	2.43
Coolant Counts	19147	19269	19003	19267	19860	28541	20472	122424	1321191	121322	121381	121584
P_{atm} (mm Hg)	733	733	733	733	733	733	733	733	733	733	733	733
Exhaust Pressure (psi)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Boost Pressure (psi)	48	48	48	48	48	48	48	48	48	48	48	48
Oil Pressure (psi)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Pressure Drop, LFE (in H_2O)	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
1. Inlet Air Temp (F)	72	77	75	81.5	84	84	82	81	83	81	80	82
2. Inlet Wet Bulb (F)	53	72	76.5	81.5	76	84	73	57	76	83	73	73
3. Inlet Manifold Temp (F)	136.5	145	140.5	137	145	150	150	152	152	152	150	151
4. Fuel Temp (F)	103.9	102.9	103	104.5	105.5	104.1	103.8	104.2	104.6	104	105.0	102.9
5. Oil Temp (F)	184	184.5	184	183.5	185	177	125	124	125	125	126	125
6. Cooling Water Inlet Temp (F)	157	157.5	157.5	157.5	158	160	159	158	159	158	159	159
7. Cooling Water OutTemp (F)	177	177.5	177.5	177.5	178	179	178	178	178	179	179	179
8. Exhaust Manifold Temp (F)	874	886.5	881.5	890.5	887	893	895	896	897	895	891	894
9. Exhaust Temp,, Shielded (F)	914	926.5	920	930	925	931	935	936	936	936	932	933
10. TC Shield Temp (F)	923	935.5	929	938	933	940	944	944	946	945	941	941
11. Exhaust Temp, Unshielded	934	947.5	940.5	951	945	953	956	957	959	958	954	954
13. Building Cooling Inlet (F)	56	56	56	56	56	56	56	56	57	56	56	56
14. Building Cooling Outlet (F)	77	79	78	78	78	80	79	80	80	79	79	80
15. Temp of 1st Dil. Tunnel (F)	66	67	67	67	67	67	67	67	67	67	68	68
Press. of 1st Dil. Tunnel (psi)	35	35	35	35	35	35	35	35	35	35	35	35
Press. of 1st Dil. Tunnel (mV)	2.855	2.865	2.85	2.845	2.86	2.85	2.85	2.85	2.85	2.85	2.85	2.85
17. Filter Chamber Temp (F)	108	110.5	113.5	112.5	113	113	115	112	113	115	115	114
18. ROOTS Temp (F)	96.5	99	108.5	107	106	106	107	105	106	116	113	111
19. Dil Tunnel Temp (F)	117	117	117	117	117	118	117	119	119	119	118	116
20. Dil. Tunnel Temp (F)	153	151	151	149	151	151	149	152	155	155	153	146
Part. Sample Flow (ft^3) -Pre	105.0	105.0	105.0	105.0	105.0	105.0	105.0	105.0	105.0	105.0	105.0	105.0
Part. Sample Flow (ft^3) -Test	105.5	105.0	105.0	105.0	105.0	105.0	105.0	105.0	105.0	105.0	105.0	105.0
Total Particulate Collected (mg)	14.540	15.675	14.630	14.430	12.115	11.745	17.170	16.170	15.725	15.290	13.325	11.180
Extracted SOF (mg)	3.390	3.400	3.250	3.090	1.880	2.725	2.535	2.825	2.545	3.095	3.405	3.110
CO (ppm)	231.37	252.66	226.70	234.81	214.04	217.46	253.80	255.51	249.25	234.61	222.91	209.80
NO (ppm)	2184.70	2307.60	2313.50	2439.20	2605.00	2815.40	2376.60	2307.60	2473.70	2722.60	2148.80	2951.00
NOx (ppm)	2801.80	2924.7	2797.10	2873.70	3152.50	3382.90	2892.60	2865.20	2950.80	3250.00	3503.70	3309.50
HC (ppm)	34.80	35.46	33.00	34.66	33.56	33.74	34.08	34.05	32.97	33.16	32.92	32.92
O2 (%)	7.908	7.799	7.996	7.968	8.300	8.489	7.596	7.699	7.695	7.600	8.373	8.208

Date	11/23/94	11/23/94	11/23/94	11/23/94	11/23/94	11/23/94	3/23/95	3/23/95	3/23/95	3/23/95	3/23/95	3/23/95
Test	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen	Oxygen	Iso Palm.	Iso Palm.	Iso Palm.	Iso Palm.	Iso Palm.	Iso Palm.
Rep. Number	3	3	3	3	3	3	1	1	1	2	2	2
Fuel	20.5	20.8	21.0	21.3	21.7	22.0	Diesel	20%	50%	Diesel	20%	50%
Engine Speed (RPM)	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
% of rated load	100	100	100	100	100	100	100	100	100	100	100	100
Brake Torque (ft-lb)	219.0	220.0	220.5	220.3	220.8	220.5	219.0	214.0	206.0	218.8	213.5	206.0
Time (sec)	901	900	900	900	900	900	900	900	900	900	900	900
Fuel Mass (kg)	2.48	2.45	2.44	2.44	2.44	2.04	2.42	2.42	2.42	2.41	2.43	2.42
Coolant Counts	121311	115368	114562	114763	114625	114576	107699	104827	99751	104481	103062	98155
P$_{atm}$ (mm Hg)	733	733	733	733	733	733	731	731	731	733	733	734
Exhaust Pressure (psi)	3.4	3.4	3.4	3.4	3.4	3.4	3.5	3.4	3.4	3.5	3.4	3.4
Boost Pressure (psi)	48	48	48	48	48	48	3.5	3.4	3.2	3.4	3.3	3.2
Oil Pressure (psi)	3.2	3.2	3.2	3.2	3.2	3.2	48	49	49	49	49	49
Pressure Drop, LFE (in H_2O)	2.4	2.4	2.4	2.4	2.4	2.4	2.36	2.36	2.36	2.36	2.36	2.36
1. Inlet Air Temp (F)	72	73	78	74	75	72	76	77	79	82	80	81
2. Inlet Wet Bulb (F)	60	58	57	53	57	52	54	55	57	59	58	57
3. Inlet Manifold Temp (F)	141	141	139	140	140	1389	132	132	130	136	134	131
4. Fuel Temp (F)	102.7	103.5	103.8	103.7	103.7	104.1	104.4	105.1	105.6	104.7	105.3	105.6
5. Oil Temp (F)	124	124	124	124	124	124	158	159	159	163	163	162
6. Cooling Water Inlet Temp (F)	158	157	156	157	157	157	154	154	153	156	155	154
7. Cooling Water OutTemp (F)	173	177	177	177	177	177	174	175	175	177	176	176
8. Exhaust Manifold Temp (F)	884	884	993	884	884	882	862	848	821	870	850	824
9. Exhaust Temp,, Shielded (F)	924	923	922	922	920	918	903	886	862	907	888	862
10. TC Shield Temp (F)	933	932	931	931	929	927	911	895	870	916	897	871
11. Exhaust Temp, Unshielded	945	945	945	944	942	940	922	905	879	927	907	880
13. Building Cooling Inlet (F)	56	56	56	55	56	56	49	49	50	50	50	50
14. Building Cooling Outlet (F)	78	77	78	78	78	77	72	73	73	73	73	73
15. Temp of 1st Dil. Tunnel (F)	67	67	67	67	67	67	65	66	66	67	66	66
Press. of 1st Dil. Tunnel (psi)	35	35	35	35	35	65	35	35	35.0	36.0	35.8	35.8
Press. of 1st Dil. Tunnel (mV)	2.845	2.84	2.84	2.84	2.83	2.84	2.375	2.37	2.355	2.375	2.375	2.36
17. Filter Chamber Temp (F)	112	114	104	115	114	116	107	109	109	111	110	110
18. ROOTS Temp (F)	103	111	105	108	107	108	95	101	101	103	103	102
19. Dil Tunnel Temp (F)	120	120	119	119	119	119	114	114	113	115	115	113
20. Dil. Tunnel Temp (F)	152	154	155	154	152	153	143	141	140	141	140	137
Part. Sample Flow (ft^3) -Pre	105.0	105.0	105.0	105.0	105.0	105.0	105.329	105.525	105.374	105.629	104.925	104.925
Part. Sample Flow (ft^3) -Test	105.5	105.0	105.0	105.0	105.0	105.0	106.914	106.914	107.822	105.651	104.277	104.277
Total Particulate Collected (mg)	16.205	15.520	14.640	12.770	11.000	9.730	14.960	12.890	13.360	14.935	11.970	11.625
Extracted SOF (mg)	3.480	3.010	2.575	1.720	2.745	2.495	3.300	4.270	6.575	2.895	3.660	5.660
CO (ppm)	227.69	218.71	225.54	205.62	189.64	180.79						
NO (ppm)	2318.10	2543.50	2526.60	2657.20	2764.30	2929.80	2351.01	2281.08	2188.99	2290.36	2341.49	2273.00
NOx (ppm)	41.90	3072.00	1247.10	3210.60	737.80	3642.50	2662.19	2636.70	2511.37	2625.66	2680.85	2596.05
HC (ppm)	32.18	31.46	31.51	30.54	30.57	30.38	28.63	26.18	21.70	30.90	27.25	21.57
O2 (%)	8.309	8.000	8.011	8.186	8.493	8.758	7.440	7.480	7.640	7.000	7.010	7.200

Date	3/23/95	3/23/95	3/23/95	3/25/95	3/25/95	3/25/95	3/25/95	3/25/95	3/25/95	3/25/95	3/25/95	3/25/95
Test	Iso Palm.	Iso Palm.	Iso Palm.	M Palm.	M Palm.	M Palm.	M Palm.	M Palm.	M Palm.	M Palm.	M Palm	MPalm
Rep. Number	3	3	3	1	1	1	2	2	2	3	3	3
Fuel	Diesel	20%	50%	Diesel	20%	50%	Diesel	20%	50%	Diesel	20%	50%
Engine Speed (RPM)	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
% of rated load	100	100	100	100	100	100	100	100	100	100	100	100
Brake Torque (ft-lb)	219.0	213.8	206.3	218.5	213.0	205.0	217.0	212.5	205.5	217.0	212.0	205.8
Time (sec)	900	900	900	900	900	900	900	900	900	900	900	900
Fuel Mass (kg)	2.42	2.43	2.42	2.43	2.43	2.43	2.41	2.42	2.44	2.41	2.42	2.46
Coolant Counts	103683	101029	97349	119492	119318	113281	119423	117247	109607	142885	121720	113211
P_{atm} (mm Hg)	734	734	734	734	734	734	734	732	732	732	732	732
Exhaust Pressure (psi)	3.5	3.4	3.4	3.5	3.4	3.4	3.45	3.4	3.3	3.45	3.4	3.4
Boost Pressure (psi)	3.4	3.4	3.2	3.5	3.4	3.2	3.45	3.3	3.2	3.4	3.3	3.2
Oil Pressure (psi)	49	49	49	49	49	49	49	49	49	49	49	49
Pressure Drop, LFE (in H_2O)	2.36	2.36	2.35	2.36	2.36	2.35	2.38	2.37	2.35	2.38	2.38	2.32
1. Inlet Air Temp (F)	81	79	81	76	76	80	82	85	84	86	85	79
2. Inlet Wet Bulb (F)	58	57	57	53	53	55	56	57	56	57	58	59
3. Inlet Manifold Temp (F)	138	134	131	134	132	132	137	138	134	141	137	131
4. Fuel Temp (F)	105.5	106.0	105.3	103.6	104.6	107.8	102.4	102.4	107.9	103.8	106.5	107.5
5. Oil Temp (F)	164	162	162	165	160	159	159	158	157	160	158	146
6. Cooling Water Inlet Temp (F)	156	155	154	157	157	157	160	158	156	164	159	157
7. Cooling Water OutTemp (F)	177	176	176	176	177	176	179	177	176	181	177	176
8. Exhaust Manifold Temp (F)	872	849	824	865	847	826	872	856	828	876	855	831
9. Exhaust Temp,, Shielded (F)	909	887	860	904	884	861	908	891	863	911	889	861
10. TC Shield Temp (F)	919	896	868	912	893	870	917	899	871	920	899	870
11. Exhaust Temp, Unshielded	930	907	878	923	903	879	928	910	881	932	909	879
13. Building Cooling Inlet (F)	50	50	50	51	50	50	50	50	51	51	50	50
14. Building Cooling Outlet (F)	72	72	73	80	81	80	80	80	80	87	81	80
15. Temp of 1st Dil. Tunnel (F)	66	66	66	69	69	69	69	69	69	71	69	69
Press. of 1st Dil. Tunnel (psi)	36.0	36.0	35.8	37.5	35.13	35.13	35.25	35.38	35.25	35.0	35.18	35.1
Press. of 1st Dil. Tunnel (mV)	2.395	2.37	2.36	2.385	2.37	2.355	2.39	2.39	2.375	2.405	2.395	2.36
17. Filter Chamber Temp (F)	111	112	111	111	113	113	115	113	113	119	115	112
18. ROOTS Temp (F)	105	107	100	100	102	104	106	105	105	106	107	104
19. Dil Tunnel Temp (F)	116	114	113	116	117	115	118	118	116	120	118	116
20. Dil. Tunnel Temp (F)	142	139	138	145	145	140	144	142	139	146	143	142
Part. Sample Flow (ft^3) -Pre	106.000	105.529	105.496	105.329	105.129	105.707	105.525	105.370	105.370	105.599	105.570	106.925
Part. Sample Flow (ft^3) -Test	101.266	121.781	105.159	105.362	104.399	104.933	106.248	107.596	107.596	104.711	105.562	106.362
Total Particulate Collected (mg)	13.570	14.770	12.325	16.290	11.150	9.100	13.910	13.370	10.230	14.430	12.725	10.215
Extracted SOF (mg)	2.770	4.855	5.805	2.690	2.785	2.580	2.820	3.335	3.410	2.825	2.900	2.960
CO (ppm)				775.00	674.59	579.11	725.81	729.97	614.01	798.48	195.04	582.87
NO (ppm)	2201.03	2358.37	2259.81	2295.85	2412.30	2296.13	2486.95	2488.74	2350.48	2512.20	2404.31	2150.37
NOx (ppm)	2572.58	2691.60	2581.27	2611.60	2746.60	2494.78	2803.86	2822.72	2585.78	2830.39	2866.88	2382.29
HC (ppm)	31.41	27.27	20.85	27.65	23.94	18.63	28.55	26.87	20.75	30.91	25.64	19.16
O2 (%)	7.440	6.750	6.920	7.960	8.110	8.220	7.370	7.450	7.690	6.970	7.440	7.550

Date	3/30/95	3/30/95	3/30/95	3/30/95	3/30/95	3/30/95	3/30/95	3/30/95	3/30/95	4/4/95	4/4/95	4/4/95
Test	M Stearate	M Stearate	M Stearate	M Stearate	M Stearate	M Stearate	M Stearate	M Stearate	M Stearate	M Soyate	M Soyate	M Soyate
Rep. Number	1	1	1	2	2	2	3	3	3	1	1	1
Fuel	Diesel	20%	50%	Diesel	20%	50%	Diesel	20%	50%	Diesel	20%	50%
Engine Speed (RPM)	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
% of rated load	100	100	100	100	100	100	100	100	100	100	100	100
Brake Torque (ft-lb)	221.0	216.0	208.5	220.5	216.0	209.0	220.0	215.3	208.5	223.5	219.0	213.5
Time (sec)	900	900	900	900	900	900	900	900	900	900	900	900
Fuel Mass (kg)	2.43	2.44	2.80	2.45	2.44	2.45	2.45	2.44	2.47	2.46	2.46	2.50
Coolant Counts	126781	126024	121470	136130	135559	129222	142001	138469	128295	127750	120291	118341
P_{atm} (mm Hg)	738	738	738	738	738	738	738	738	732	741	741	742
Exhaust Pressure (psi)	3.6	3.5	3.4	3.6	3.5	3.4	3.6	3.55	3.4	3.7	3.6	3.5
Boost Pressure (psi)	3.6	3.5	3.4	3.6	3.5	3.35	3.6	3.55	3.4	3.7	3.95	3.6
Oil Pressure (psi)	49	49	49	49	49	49	49	49	49	49	49	49
Pressure Drop, LFE (in H_2O)	2.36	2.335	2.32	2.34	2.35	2.31	2.33	2.325	2.315	2.31	2.31	2.31
1. Inlet Air Temp (F)	67	68	65	70	68	70	68	65	65	57	59	58
2. Inlet Wet Bulb (F)	50	49	48	50	49	49	49	48	49	40	43	42
3. Inlet Manifold Temp (F)	127	125	123	128	127	123	128	123	123	121	119	117
4. Fuel Temp (F)	106.1	109.0	112.9	106.0	107.4	107.1	104.1	108.2	110.6	100.8	105.6	102.9
5. Oil Temp (F)	184	184	183	185	185	165	179	161	164	205	191	193
6. Cooling Water Inlet Temp (F)	159	160	160	164	163	161	165	162	160	160	159	158
7. Cooling Water OutTemp (F)	177	177	178	181	179	178	181	179	177	177	177	177
8. Exhaust Manifold Temp (F)	855	839	814	857	838	816	858	841	818	842	830	814
9. Exhaust Temp,, Shielded (F)	895	877	854	898	880	855	899	880	855	883	869	848
10. TC Shield Temp (F)	904	886	863	907	889	863	908	889	863	892	878	856
11. Exhaust Temp, Unshielded	915	895	872	918	900	873	920	900	874	902	887	865
13. Building Cooling Inlet (F)	51	51	51	57	51	51	51	51	51	50	50	50
14. Building Cooling Outlet (F)	81	81	83	85	84	84	86	84	83	82	80	79
15. Temp of 1st Dil. Tunnel (F)	65	65	66	65	66	65	66	65	66	66	66	65
Press. of 1st Dil. Tunnel (psi)	35.25	35.25	35.5	35.5	35.5	35.5	35.5	36.1	36.38	35.0	35.0	34.8
Press. of 1st Dil. Tunnel (mV)	2.36	2.34	2.32	2.345	2.345	2.325	2.355	2.335	2.325	2.32	2.315	2.30
17. Filter Chamber Temp (F)	108	110	111	111	112	112	112	114	111	109	111	111
18. ROOTS Temp (F)	94	96	97	99	99	96	100	98	95	88	90	90
19. Dil Tunnel Temp (F)	114	114	113	115	114	112	115	114	113	115	114	113
20. Dil. Tunnel Temp (F)	144	140	138	143	141	139	144	143	139	147	144	142
Part. Sample Flow (ft^3) -Pre	105.459	105.762	105.633	106.396	105.633	105.729	105.733	105.714	105.440	105.588	105.548	105.188
Part. Sample Flow (ft^3) -Test	104.962	104.425	105.662	105.440	106.344	105.729	105.337	106.203	104.496	104.237	104.237	104.196
Total Particulate Collected (mg)	14.500	12.980	15.980	14.715	13.820	14.845	16.950	23.460	16.685	15.710	13.365	12.780
Extracted SOF (mg)	3.040	4.610	8.300	3.225	4.775	7.655	2.835	5.325	7.950	4.225	4.305	6.265
CO (ppm)	789.95	695.93	661.02	853.01	722.46	646.85	849.41	780.96	620.55	773.68	723.61	635.63
NO (ppm)	2319.07	2295.98	2212.46	2254.54	2259.17	2169.90	2304.20	2229.49	2184.00	2330.60	2336.36	2336.93
NOx (ppm)	2522.87	2501.66	2403.30	2468.25	2471.84	2385.77	2511.15	2449.16	2399.73	2575.01	2585.63	2574.29
HC (ppm)	25.12	21.84	17.79	23.79	20.25	16.50	24.04	20.51	16.30	26.12	23.18	17.33
O2 (%)	8.064	8.023	8.160	7.520	7.574	7.780	7.190	7.310	7.520	8.800	8.560	8.710

Date	4/4/95	4/4/95	4/4/95	4/4/95	4/4/95	4/4/95	974/13/95	4/13/95	4/13/95	4/13/95	4/13/95	4/13/95
Test	M Soyate	M Soyate	M Soyate	M Soyate	M Soyate	M Soyate	M Oleate	M Oleate	M Oleate	M Oleate	M Oleate	M Oleate
Rep. Number	2	2	2	3	3	3	1	1	1	2	2	2
Fuel	Diesel	20%	50%	Diesel	20%	50%	Diesel	20%	50%	Diesel	20%	50%
Engine Speed (RPM)	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
% of rated load	100	100	100	100	100	100	100	100	100	100	100	100
Brake Torque (ft-lb)	223.5	219.3	213.0	222.0	218.3	212.3	222.0	218.0	210.0	221.0	217.0	210.0
Time (sec)	900	900	900	900	900	900	900	900	900	900	900	900
Fuel Mass (kg)	2.45	2.46	2.49	2.45	2.46	2.49	2.45	2.45	2.48	2.43	2.46	2.48
Coolant Counts	124714	124224	121511	130068	129352	125282	123697	124211	117489	126873	126211	122790
P_{atm} (mm Hg)	742	742	742	740	740	740	736	736	736	736	736	736
Exhaust Pressure (psi)	3.7	3.6	3.45	3.6	3.55	3.4	3.6	3.5	3.3	3.6	3.45	3.3
Boost Pressure (psi)	3.7	3.7	3.55	3.6	3.55	3.45	3.65	3.4	3.3	3.4	3.4	3.55
Oil Pressure (psi)	49	49	49	49	49	49	48	48	48	48	48	48
Pressure Drop, LFE (in H_2O)	2.31	2.31	2.31	2.325	2.33	2.31	2.35	2.35	2.35	2.38	2.39	2.39
1. Inlet Air Temp (F)	63	60	62	66	63	66	66	72	76	77	82	82
2. Inlet Wet Bulb (F)	44	44	44	46	45	45	51	54	55	55	58	59
3. Inlet Manifold Temp (F)	123	122	120	126	124	122	128	131	132	138	140	139
4. Fuel Temp (F)	101.5	107.6	100.9	104.3	103.7	104.0	104.7	104.3	105.7	104.2	105.5	106.5
5. Oil Temp (F)	177	119	109	113	111	106	115	116	115	117	116	116
6. Cooling Water Inlet Temp (F)	162	161	160	164	162	160	158	160	158	162	161	160
7. Cooling Water OutTemp (F)	179	179	177	180	179	178	176	178	176	180	179	178
8. Exhaust Manifold Temp (F)	847	833	818	857	840	822	854	848	834	870	861	840
9. Exhaust Temp,, Shielded (F)	887	873	853	895	880	860	897	890	866	914	902	878
10. TC Shield Temp (F)	896	881	861	904	889	868	906	898	874	923	910	887
11. Exhaust Temp, Unshielded	907	891	871	914	899	878	916	908	882	934	920	896
13. Building Cooling Inlet (F)	51	52	51	52	52	51	50	50	50	50	51	51
14. Building Cooling Outlet (F)	83	83	81	83	81	81	80	81	79	82	81	81
15. Temp of 1st Dil. Tunnel (F)	66	67	66	67	67	66	65	65	65	65	65	65
Press. of 1st Dil. Tunnel (psi)	35.9	34.9	34.8	34.9	34.8	34.8	35.0	35.1	35.1	35.2	35.2	35.3
Press. of 1st Dil. Tunnel (mV)	2.33	2.33	2.31	2.34	2.33	2.32	2.37	2.365	2.365	2.39	2.405	2.40
17. Filter Chamber Temp (F)	110	112	113	112	115	112	112	114	114	116	115	114
18. ROOTS Temp (F)	93	94	891	97	95	95	97	103	101	108	107	106
19. Dil Tunnel Temp (F)	116	116	113	117	116	115	117	117	115	119	118	116
20. Dil. Tunnel Temp (F)	146	144	141	147	143	140	141	140	137	145	140	139
Part. Sample Flow (ft^3) -Pre	105.403	105.085	105.911	105.585	105.962	105.307	106.255	105.044	105.896	105.492	105.429	105.518
Part. Sample Flow (ft^3) -Test	104.911	105.311	100.918	105.033	103.477	105.344	104.748	106.637	104.129	106.351	103.929	105.118
Total Particulate Collected (mg)	13.035	12.005	12.035	14.595	12.955	12.870	15.425	14.315	13.435	17.170	14.360	13.900
Extracted SOF (mg)	3.770	4.575	5.465	3.980	4.340	5.660	2.695	3.660	6.220	3.265	3.390	4.915
CO (ppm)	759.06	724.86	628.71	859.81	814.54	762.51	841.69	851.40	802.27	920.35	927.80	886.85
NO (ppm)	2345.30	2389.90	2387.83	2407.60	2373.98	2158.49	2172.42	2196.70	2231.19	2228.48	2292.96	2269.30
NOx (ppm)	2569.34	2667.71	2664.82	2687.09	2686.97	2497.12	2400.71	2426.20	2447.76	2449.55	2519.72	2498.83
HC (ppm)	26.75	23.86	17.73	27.72	24.48	18.61	29.49	27.90	22.17	32.80	29.51	24.88
O2 (%)	8.080	8.090	8.260	7.520	7.590	7.830	8.530	8.430	8.420	7.580	7.500	7.670

Date	4/13/95	4/13/95	4/13/95	4/20/95	4/20/95	4/20/95	4/20/95	4/20/95	4/20/95	4/20/95	4/20/95	4/20/95
Test	M Oleate	M Oleate	M Oleate	Cet/$C_{18}H_{38}$	Cet/$C_{18}H_{38}$	Cet/$C_{18}H_{38}$	Cet/$C_{18}H_{38}$	Cet/$C_{18}H_{38}$	Cet/$C_{18}H_{38}$	Cet/$C_{18}H_{38}$	Cet/$C_{18}H_{38}$	Cet/$C_{18}H_{38}$
Rep. Number	3	3	3	1	1	1	1	2	2	2	2	3
Fuel	Diesel	20%	50%	Diesel	0.5% CI	50% MS	50% Oct.	Diesel	0.5% CI	50% MS	50% Oct.	Diesel
Engine Speed (RPM)	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
% of rated load	100	100	100	100	100	100	100	100	100	100	100	100
Brake Torque (ft-lb)	220.0	217.0	210.0	222.5	223.0	212.5	215.5	223.3	222.0	212.5	215.5	2230.
Time (sec)	900	900	900	900	900	900	900	900	900	900	900	900
Fuel Mass (kg)	2.44	2.44	2.47	2.45	2.45	2.50	2.32	2.46	2.46	2.49	2.33	2.45
Coolant Counts	129284		122988	122154	121304	116308	118543		118568	104688	105667	118396
P_{atm} (mm Hg)	736	736	736	726	726	726	726	726	723	723	723	722
Exhaust Pressure (psi)	3.5	3.4	3.25	3.6	3.6	3.3	3.4	3.6	3.6	3.4	3.4	3.6
Boost Pressure (psi)	3.4	3.55	3.2	3.4	3.4	3.2	3.2	3.4	3.3	3.3	3.4	3.5
Oil Pressure (psi)	48	48	48	48	48	48	48	48	48	48	48	48
Pressure Drop, LFE (in H_2O)	2.40	2.40	2.40	2.37	2.37	2.36	2.34	2.37	2.375	2.37	2.365	2.37
1. Inlet Air Temp (F)	82	81	83	71	69	72	70	72	71	73	74	72
2. Inlet Wet Bulb (F)	59	59	59	55	55	57	56	56	57	57	57	56
3. Inlet Manifold Temp (F)	145	142	139	133	130	130	129	132	133	129	130	133
4. Fuel Temp (F)	104.7	106.4	106.2	103.4	104.2	104.1	103.8	103.5	104.8	109.6	106.5	102.8
5. Oil Temp (F)	117	116	116	136	136	135	136	135	134	134	134	136
6. Cooling Water Inlet Temp (F)	163	161	159	158	158	158	161	158	157	154	156	161
7. Cooling Water OutTemp (F)	181	179	178	177	177	176	180	177	176	175	177	180
8. Exhaust Manifold Temp (F)	878	862	843	867	866	841	845	871	869	839	846	873
9. Exhaust Temp,, Shielded (F)	922	904	880	910	907	873	889	910	913	875	888	915
10. TC Shield Temp (F)	931	913	890	919	916	881	899	920	924	884	898	925
11. Exhaust Temp, Unshielded	941	923	899	929	927	890	910	932	935	895	909	937
13. Building Cooling Inlet (F)	51	51	51	50	50	51	51	50	51	51	51	52
14. Building Cooling Outlet (F)	82	81	81	76	77	79	83	79	78	74	74	75
15. Temp of 1st Dil. Tunnel (F)	65	65	65	65	66	65	66	66	66	66	66	66
Press. of 1st Dil. Tunnel (psi)	35.4	35.5	35.2	35.1	35.1	35.1	35.1	35.1	35.0	35.0	35.0	35.0
Press. of 1st Dil. Tunnel (mV)	2.43	2.42	2.395	2.37	2.365	2.35	2.34	2.375	2.375	2.355	2.355	2.37
17. Filter Chamber Temp (F)	117	116	113	113	117	113	111	116	117	113	116	118
18. ROOTS Temp (F)	110	106	104	101	104	99	97	103	104	99	102	105
19. Dil Tunnel Temp (F)	119	119	117	118	119	116	117	119	119	116	117	120
20. Dil. Tunnel Temp (F)	143	142	140	144	142	138	141	144	144	139	138	144
Part. Sample Flow (ft^3) -Pre	105.262	105.818	105.533	105.525	105.655	105.448	105.229	104.940	105.529	105.862	105.251	105.207
Part. Sample Flow (ft^3) -Test	106.081	104.707	104.703	105.103	104.974	105.381	106.114	104.999	105.440	105.337	105.218	105.237
Total Particulate Collected (mg)	16.625	14.105	13.905	16.305	14.695	11.085	12.585	15.895	16.275	11.745	13.520	18.280
Extracted SOF (mg)	3.210	3.500	4.980	2.440	2.425	3.750	1.860	2.555	2.915	4.990	3.020	3.165
CO (ppm)	962.99	933.37	858.16	722.20	584.36	513.06	528.52	674.63	895.38	662.32	626.06	812.58
NO (ppm)	2230.41	2253.99	2177.46	2217.69	2211.98	2262.84	2081.36	2242.11	2201.78	2247.22	2074.06	2230.95
NOx (ppm)	2451.82	2464.44	2395.41	2438.62	2428.17	2505.00	2293.08	2451.45	2403.62	2480.46	2277.61	2455.48
HC (ppm)	35.00	31.03	25.45	28.86	28.30	19.37	22.08	29.70	30.38	20.95	22.93	31.72
O2 (%)	6.980	7.240	7.420	8.062	7.915	8.162	7.872	7.519	7.367	7.781	7.539	7.061

Date	4/20/95	4/20/95	4/20/95	5/16/95	5/16/95	5/16/95	5/16/95	5/16/95	5/16/95	5/16/95	5/16/95	5/16/95
Test	Cet/$C_{18}H_{38}$	Cet/$C_{18}H_{38}$	Cet/$C_{18}H_{38}$	I Stearate	I Stearate	I Stearate	I Stearate	I Stearate	I Stearate	I Stearate	I Stearate	I Stearate
Rep. Number	3	3	3	1	1	1	2	2	2	3	3	3
Fuel	0.5% CI	50% MS	50% Oct.	Diesel	20%	50%	Diesel	20%	50%	Diesel	20%	50%
Engine Speed (RPM)1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
% of rated load	100	100	100	100	100	100	100	100	100	100	100	100
Brake Torque (ft-lb)	222.0	212.0	215.0	219.5	214.8	208.0	220.8	215.5	207.8	220.0	214.5	207.8
Time (sec)	900	900	900	900	900	920	900	900	961	900	900	900
Fuel Mass (kg)	2.45	2.49	2.34	2.45	2.44	2.48	2.44	2.43	2.60	2.45		
Coolant Counts	118212	111941	112479	125413	120960	152440	206475	204981	194137	209190	198777	173003
P_{atm} (mm Hg)	722	723	723	724	724	723	723	724	723	723	723	723
Exhaust Pressure (psi)	3.6	3.3	3.4	3.4	3.3	3.2	3.4	3.3	3.2	3.4	3.3	3.2
Boost Pressure (psi)	3.6	3.55	3.6	5.1	5.1	5.2	5.0	5.2	5.1	5.1	5.1	5.1
Oil Pressure (psi)	48	48	48	48	48	48	48	48	48	48	48	48
Pressure Drop, LFE (in H_2O)	2.38	2.37	2.37	2.41	2.41	2.41	2.41	2.405	2.40	2.41	2.41	2.40
1. Inlet Air Temp (F)	73	73	75	84	91	91	84	86	87	89	85	81
2. Inlet Wet Bulb (F)	75	59	59	70	73	73	71	72	73	77	71	66
3. Inlet Manifold Temp (F)	34	131	132	148	149	147	149	148	147	152	149	142
4. Fuel Temp (F)	.06	111.2	108.6	104.7	108.2	109.1	104.1	106.1	107.0	102.0	111.6	110.6
5. Oil Temp (F)	36	134	134	208	198	194	194	209	191	200	194	192
6. Cooling Water Inlet Temp (F)	61	157	158	159	159	163	175	174	169	175	171	167
7. Cooling Water OutTemp (F)	80	177	178	177	178	180	186	184	181	186	183	180
8. Exhaust Manifold Temp (F)	870	836	849	896	884	856	903	887	859	913	887	848
9. Exhaust Temp,, Shielded (F)	915	879	894	929	918	893	937	923	896	943	921	888
10. TC Shield Temp (F)	925	888	904	938	926	902	948	933	905	953	931	897
11. Exhaust Temp, Unshielded	938	899	916	948	937	912	959	945	916	965	943	908
13. Building Cooling Inlet (F)	52	52	52	54	54	55	54	55	55	55	55	55
14. Building Cooling Outlet (F)	80	80	80	79	80	85	91	88	89	91	87	86
15. Temp of 1st Dil. Tunnel (F)	67	67	67	68	69	68	68	68	68	68	68	68
Press. of 1st Dil. Tunnel (psi)	35.0	35.0	35.0	35.25	35.25	35.3	35.1	35.3	35.3	35.25	35.2	35.2
Press. of 1st Dil. Tunnel (mV)	2.38	2.355	2.365	2.44	2.445	2.435	2.43	2.44	2.435	2.46	2.425	2.41
17. Filter Chamber Temp (F)	119	114	116	117	119	118	119	115	117	120	119	117
18. ROOTS Temp (F)	106	103	102	113	118	116	117	111	113	117	116	109
19. Dil Tunnel Temp (F)	120	118	118	125	124	122	126	123	123	126	124	122
20. Dil. Tunnel Temp (F)	148	144	146	148	146	141	156	149	150	156	155	154
Part. Sample Flow (ft^3) -Pre	105.207	106.299	105.366	105.625	105.977	102.199	105.788	106.225	106.751	105.451	105.648	
Part. Sample Flow (ft^3) -Test	105.237	105.262	105.551	106.707	106.085	107.333	104.914	106.025	111.807	103.785	105.677	212.886
Total Particulate Collected (mg)	16.265	12.510	12.815	19.290	17.285	15.120	19.585	18.960	21.080	21.445	18.450	18.418
Extracted SOF (mg)	3.330	4.200	2.685	2.900	4.415	7.920	3.255	4.150	8.440	2.870	4.340	8.165
CO (ppm)	853.52	624.95	649.88	731.86	695.25	626.81	770.65	772.97	644.61	798.38	689.12	599.90
NO (ppm)	2229.46	2260.96	2087.34	2152.27	2112.40	1911.31	2191.86	2171.13	2068.65	2230.50	2210.96	2268.33
NOx (ppm)	2455.39	2423.76	2278.06	2419.14	2360.69	2122.96	2460.33	2416.00	2316.77	2451.34	2457.38	2510.27
HC (ppm)	30.99	21.71	23.69	38.52	34.73	29.14	36.12	33.33	28.05	35.21	30.95	24.61
O2 (%)	7.043	7.446	7.132	6.664	6.851	7.066	6.387	6.528	6.682	6.167	6.389	6.789

Date	5/23/95	5/23/95	5/23/95	5/23/95	5/23/95	5/23/95	5/23/95	5/23/95	5/23/95	6/2/95	6/2/95	6/2/95
Test	Meth Saff	Meth Saff	Meth Saff	Meth Saff	Meth Saff	Meth Saff	Meth Saff	Meth Saff	Meth Saff	Meth Saff	Meth Saff	Meth Saff
Rep. Number	1	1	1	2	2	2	3	3	3	4	4	4
Fuel	Diesel	20%	50%	Diesel	20%	50%	Diesel	20%	50%	Diesel	20%	50%
Engine Speed (RPM)	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400	1400
% of rated load	100	100	100	100	100	100	100	100	100	100	100	100
Brake Torque (ft-lb)	220.0	215.0	209.5	220.0	215.0	209.0	219.0	215.0	208.5	216.0	212.5	206.5
Time (sec)	900	900	900	900	900	900	900	900	900	900	900	900
Fuel Mass (kg)	2.57	2.595	2.605	2.565	2.565	2.845	2.495	2.44	2.605	2.565	2.595	2.615
Coolant Counts	130667	122625	119806	128786	127120	123246	130107	128049	124380	99095	98361	94081
P_{atm} (mm Hg)	734	734	734	733	733	733	735	734	734	731	731	731
Exhaust Pressure (psi)	3.5	3.4	3.4	3.5	3.4	3.3	3.5	3.4	3.3	3.5	3.3	3.2
Boost Pressure (psi)	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.4	4.5	4.4
Oil Pressure (psi)	48	48	48	48	48	48	48	48	48	48	48	48
Pressure Drop, LFE (in H_2O)	2.39	2.39	2.38	2.39	2.39	2.38	2.41	2.39	2.39	2.39	2.39	2.39
1. Inlet Air Temp (F)	74	83	77	80	81	80	83	82	83	82	84	84
2. Inlet Wet Bulb (F)	60	63	61	62	62	62	63	63	64	69	69	68
3. Inlet Manifold Temp (F)	137	141	136	139	139	136	145	142	140	142	141	140
4. Fuel Temp (F)	103.4	105.6	106.3	105.7	105.3	105.6	104.5	105.0	105.3	109.4	105.5	106.3
5. Oil Temp (F)	76	76	77	76	77	76	78	77	77	84	82	82
6. Cooling Water Inlet Temp (F)	159	158	159	163	161	159	162	161	159	151	151	150
7. Cooling Water OutTemp (F)	177	177	177	180	179	177	181	179	177	175	174	174
8. Exhaust Manifold Temp (F)	886	878	852	892	879	855	898	881	857	889	881	860
9. Exhaust Temp,, Shielded (F)	908	899	876	914	900	879	921	904	882	912	903	883
10. TC Shield Temp (F)	917	908	884	923	909	888	930	913	890	920	911	890
11. Exhaust Temp, Unshielded	929	918	894	935	920	897	942	924	900	931	921	898
13. Building Cooling Inlet (F)	57	56	55	56	56	56	56	56	56	57	57	57
14. Building Cooling Outlet (F)	77	80	80	80	81	77	80	81	80	77	75	77
15. Temp of 1st Dil. Tunnel (F)	68	67	68	69	68	69	69	68	68	69	69	69
Press. of 1st Dil. Tunnel (psi)	40.2	35.0	35.2	35.2	35.2	35.2	35.2	35.2	35.2	35.4	35.3	35.25
Press. of 1st Dil. Tunnel (mV)	2.395	2.39	2.37	2.39	2.395	2.38	2.42	2.40	2.39	2.41	2.405	2.40
17. Filter Chamber Temp (F)	114	117	116	119	120	119	121	121	119	116	121	116
18. ROOTS Temp (F)	101	105	104	109	109	107	107	110	108	109	114	108
19. Dil Tunnel Temp (F)	119	120	120	124	123	121	125	123	122	125	124	121
20. Dil. Tunnel Temp (F)	144	148	144	148	148	151	149	147	146	149	147	146
Part. Sample Flow (ft^3) -Pre	105.348	106.925	106.844	106.766	107.374	107.559	104.340	107.399	106.840	105.711	105.896	104.107
Part. Sample Flow (ft^3) -Test	105.648	105.418	104.855	105.137	105.581	106.955	106.270	105.392	106.240	105.785	105.455	105.470
Total Particulate Collected (mg)	14.565	14.725	13.675	15.715	15.150	14.445	15.145	15.265	14.405	15.780	13.755	12.005
Extracted SOF (mg)	3.800	5.395	6.455	4.300	4.610	6.505	4.105	4.415	6.135			
CO (ppm)	154.49	151.63	132.51	166.48	144.54	136.46	165.96	146.48	136.16	187.22	163.39	148.60
NO (ppm)	1166.93	1372.96	1279.81	1213.63	1174.89	1066.15	1755.86	1615.93	1542.61	1538.45	1426.22	1512.45
NOx (ppm)	1884.01	2287.32	2224.76	2156.91	2074.11	1907.74	2731.44	2543.38	1066.15	2437.74	2351.15	2348.06
HC (ppm)	34.73	31.44	24.84	34.76	31.32	27.00	35.44	32.39	26.59	33.22	30.30	25.27
O2 (%)	7.314	7.272	7.415	6.842	6.934	7.112	6.488	6.710	7.116	6.939	7.120	7.418

Date	6/2/95	6/2/95	6/2/95	6/2/95	6/2/95	6/2/95	6/2/95	6/2/95	6/2/95			
Test	M Linseed	M Linseed	M Linseed	M Linseed	M Linseed	M Linseed	M Linseed	M Linseed	M Linseed			
Rep. Number	1	1	1	2	2	2	3	3	3			
Fuel	Diesel	20%	50%	Diesel	20%	50%	Diesel	20%	50%			
Engine Speed (RPM)	1400	1400	1400	1400	1400	1400	1400	1400	1400			
% of rated load	100	100	100	100	100	100	100	100	100			
Brake Torque (ft-lb)	216.8	212.5	206.5	216.0	212.5	206.0	215.5	211.5	206.5			
Time (sec)	900	900	900	900	900	900	900	900	900			
Fuel Mass (kg)	2.585	2.595	2.615	2.580	2.580	2.610	2.580	2.590	2.620			
Coolant Counts	97940	97394	95669	99303	98328	96551	99020	98384	96270			
P_{atm} (mm Hg)	732	732	732	731	731	731	731	731	731			
Exhaust Pressure (psi)	3.5	3.3	3.2	3.4	3.3	3.2	3.4	3.3	3.2			
Boost Pressure (psi)	4.4	4.5	4.5	4.6	4.6	4.6	4.6	4.6	4.6			
Oil Pressure (psi)	48	48	48	48	48	48	48	48	48			
Pressure Drop, LFE (in H_2O)	2.40	2.40	2.40	2.415	2.415	2.41	2.41	2.41	2.40			
1. Inlet Air Temp (F)	84	86	90	92	92	94	89	91	88			
2. Inlet Wet Bulb (F)	71	70	70	71	70	71	71	70	70			
3. Inlet Manifold Temp (F)	144	143	142	148	147	145	147	144	142			
4. Fuel Temp (F)	104.1	107.0	105.5	106.1	106.2	105.6	106.9	105.7	104.7			
5. Oil Temp (F)	83	83	83	83	83	83	83	83	83			
6. Cooling Water Inlet Temp (F)	153	152	151	153	152	151	153	152	150			
7. Cooling Water OutTemp (F)	177	176	174	177	177	175	177	176	174			
8. Exhaust Manifold Temp (F)	905	887	867	907	891	871	910	893	869			
9. Exhaust Temp,, Shielded (F)	921	908	888	924	912	892	926	910	888			
10. TC Shield Temp (F)	929	916	897	933	920	900	935	919	896			
11. Exhaust Temp, Unshielded	939	926	905	944	930	908	946	930	906			
13. Building Cooling Inlet (F)	57	57	57	57	57	57	57	57	57			
14. Building Cooling Outlet (F)	78	78	77	78	77	75	75	77	75			
15. Temp of 1st Dil. Tunnel (F)	69	69	69	69	70	70	69	69	70			
Press. of 1st Dil. Tunnel (psi)	35.4	35.5	35.4	35.4	65.4	35.4	35.4	35.3	35.2			
Press. of 1st Dil. Tunnel (mV)	2.415	2.415	2.405	2.43	2.43	2.425	2.43	2.42	2.40			
17. Filter Chamber Temp (F)	121	120	118	125	121	120	123	122	119			
18. ROOTS Temp (F)	114	113	112	116	112	114	119	116	113			
19. Dil Tunnel Temp (F)	124	124	123	127	124	124	127	125	123			
20. Dil. Tunnel Temp (F)	148	147	144	149	147	147	149	147	143			
Part. Sample Flow (ft^3) -Pre	105.211	105.459	105.125	105.314	105.022	105.022	105.381	106.407	105.085			
Part. Sample Flow (ft^3) -Test	105.988	105.085	107.029	105.977	105.007	105.007	105.448	105.488	105.218			
Total Particulate Collected (mg)	16.385	15.915	14.165	17.790	16.235	13.855	17.720	15.865	13.390			
Extracted SOF (mg)	3.815	4.540	5.550	4.785	4.885	5.415	3.560	4.525	5.220			
CO (ppm)	190.70	175.77	171.42	202.66	165.87	161.50	184.62	177.20	154.08			
NO (ppm)	1562.68	1509.09	1551.43	1577.90	1551.17	1574.60	1579.98	1607.91	1601.02			
NOx (ppm)	2494.22	2479.89	2501.97	2481.87	2491.90	2498.68	2473.75	2495.42	2466.48			
HC (ppm)	35.63	33.36	28.34	37.26	33.24	27.09	36.27	33.29	26.77			
O2 (%)	6.698	6.744	6.886	6.301	6.470	6.638	6.160	6.361	6.603			