

***BIOBLENDED FUEL  
FOR USE IN  
LIGHT DUTY COMPRESSION  
IGNITION ENGINES***

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*Presented To*

*The Great Lakes Regional  
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*by*

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## INTRODUCTION

Bio-fuels have been the focus of much discussion and research as of late. Due to the need to clean up the vehicles currently on the road, impact on the environment in the event of a spill, and to lessen the need for foreign oil supplies, the industry has examined the use of bio-fuels. Ethanol was used as a fuel extender in the 70's during the Arab Oil Embargo. It is currently being used in concentration of 10% mixed with petroleum gasoline as an oxygenate, which means when the fuel is ignited it provides oxygen to support better combustion. This helps the fuel to burn more completely, causing the HC and CO emissions to decrease. In a compression ignition engine there is an excess of oxygen, due to it running at leaner than stoichiometric air to fuel ratios, so the addition of ethanol would seem to serve no purpose. Although with the addition of ethanol to diesel fuel the benefit may be a decrease in NO<sub>x</sub> emissions. The ethanol, due to its lower cetane number, theoretically should cause a cooling effect on combustion. This in turn should cause a reduction in NO<sub>x</sub> emissions, because NO<sub>x</sub> is caused by high combustion temperatures.

A bio-fuel that has recently been introduced to the compression ignition engine is *Biodiesel*. The main reason biodiesel has come into the market is to meet lower tailpipe emissions standards set by the Clean Air Act Amendment (CAAA) of 1990. (There are also industries such as mining, forestry, and boating that will benefit from a cleaner burning fuel and a more environmentally safe fuel in case of a spill). The new standards are to be met by 1996 for diesel fleet vehicles. They call for a reduction in particulate and sulfur emissions. This is where the need for biodiesel has come from. Biodiesel is a diesel substitute made from organic stock such as soybeans, rapeseed, and animal tallow. The oils from these sources are put through a process called transesterification. This process purifies the oil, removing the fatty particles that cause coking and other problems in a diesel engine. The biodiesel is an easy way around replacing existing diesel engines. A 20% mixture of biodiesel added to regular #2 diesel has demonstrated the ability to meet the CAAA standards by producing less particulate emissions. An economic problem associated with biodiesel is that its current price is approximately \$2.50 per

gallon. The National Biodiesel Board estimates that with a more efficient transesterification process, the price will be more competitive with #2 diesel fuel.

#### STATEMENT OF THE PROBLEM

The problem of this study was to experimentally compare the characteristics of material compatibility, exhaust gas emissions, opacity, horsepower, and fuel economy of 100; 90/10; 80/20; 70/30; 60/40; 50/50; 40/60 percent concentrations of #2 diesel fuel, biodiesel derived from soybeans. In addition, the study also examined concentrations of 100; 90/10; 80/20; 70/30; 60/40; 50/50; 40/60 percent biodiesel and ethanol (E95), respectively. The **study** attempted to answer the following:

- Were the stock fuel system parts compatible with the different fuel mixtures?
- What concentrations of the fuel mixtures gave the cleanest emission performance?
- What concentrations produced the lowest particulate emissions
- Which concentrations proved to be the most fuel efficient?
- Were there any cold start or driveability problems using any of the test mixtures?

#### STATEMENT OF THE PURPOSE

The purpose of this study was to compare selected mixtures of #2 diesel fuel, biodiesel, and ethanol alcohol in an unmodified compression ignition engine. The study was designed to identify mixtures that possess the following characteristics.

- Which mixtures were compatible with fuel system components including rubber fuel line and fuel pump seals, gasket materials, and steel fuel tank material?
- Which mixtures yielded the largest reduction in emission levels?

- Which mixtures yielded the largest reduction in particulate emission?
- Which mixtures yielded the best fuel efficiency results?
- Did any of the mixtures yield undesirable cold start or driveability problems?

The knowledge learned from this study will be disseminated to groups and individuals considering the use of these alternative fuels. The information learned as a part of this study can aid individuals in the selection of a specific mixture; expected emission reductions associated with that mixture; estimation of any cost of operation differences; and any driveability concerns that may exist.

### **STATEMENT OF THE HYPOTHESIS**

The following hypotheses were developed at the start of the study.

- Mixtures of biodiesel and # 2 diesel fuel would not affect the stock fuel system components.
- Mixtures of biodiesel and ethanol would not affect the stock fuel system components.
- As the concentration of biodiesel mixed with # 2 diesel increased, NO<sub>x</sub>, HC, CO, CO emissions would be reduced.
- As the concentration of biodiesel mixed with # 2 diesel increased, further reductions in particulate emissions would be observed.
- The fuel efficiency of the vehicle would decrease as the concentrations of biodiesel increased.
- The addition of ethanol would yield lower fuel efficiency than 100% biodiesel.

- As the concentration of biodiesel increased, cold engine starting performance would decrease.
- There would be no reduction in driveability performance observed with the test fuels.

### **STATEMENT OF ASSUMPTIONS**

The following assumptions were made at the beginning of the study.

- The test methods developed would produce repeatable and reliable data.
- There were no mechanical changes to the test vehicle, once testing began, that would effect the results of the study.
- Any changes in the emissions, fuel efficiency, or driveability results due to the fuels.

### **STATEMENT OF LIMITATIONS**

The following limitations were inherent in the study:

- The vehicle used to conduct the tests was a 1987 Ford, 3/4 ton, pickup, with a 7.3 liter pre-chamber diesel engine manufactured by Navistar. At the start of the study the engine had 150,000 miles of operation. A compression test showed no sign of mechanical problems, the fuel injection pump was rebuilt and timed, and new fuel injectors and glow plugs were installed at the start of the study.
- Only #2 diesel, ethanol, and soybean biodiesel were used in the study.
- The particulate emissions were measured using an OTC 3405 Smoke Opacity Meter at steady state load and speed, and under full throttle acceleration.

- Hydrocarbon, carbon monoxide, carbon dioxide, nitrogen oxide, and oxygen tailpipe emissions were measured using an OTC 5 Gas Infra-Red Exhaust Analyzer.
- Material compatibility testing was conducted by steel braided rubber fuel hose, neoprene hose, gasket and seal materials, and fuel tank material in samples of each type of fuel. Weekly examinations of the weight, thickness, and physical condition of each sample were conducted and the results to identify any changes due to swelling, deterioration, or absorption.

### STATEMENT OF TERMINOLOGY

- **biodiesel** - A diesel substitute made from plant oils or animal tallow. Biodiesel made from soybeans was used in this study.
- **Ethanol** - An alcohol made from corn which is used as an oxygenate in spark ignition engines. The ethanol used in this study was denatured by the addition of 5% gasoline.
- **Opacity Meter** - A meter which attaches to the tailpipe of a running diesel vehicle to check for excess smoke (particulate). The opacity is determined by a measurement of the amount of light that will pass through the exhaust stream.
- **Steady State** - When the vehicle is being driven on the dynamometer or on the road at a steady speed and load.
- **Transient Course** - When the vehicle is being operated at varying loads and speeds during a driving course.
- **Emissions** - The products of combustion in an internal combustion engine.
- **HC** - Hydrocarbons, organic combustible material used for fuels.
- **CO** - Carbon monoxide, colorless, odorless gas that poses health risks.

- **NO<sub>x</sub>** - Oxides of nitrogen, generally comprised of NO<sub>2</sub> and NO<sub>3</sub>
- CO<sub>2</sub> - Carbon Dioxide

## **STATEMENT OF PROCEDURE**

### **I. Fuel Mixing Procedure**

Fuel samples for each component of this research were prepared using the following procedure. All concentrations were based on volume ie. 90% #2 diesel / 10% biodiesel. A balance was used to measure the correct weight of fuel necessary to obtain the proper concentration. Concentrations of biodiesel in 10% intervals were calculated based on the specific gravity of each fuel. The fuels were pumped out of 55 gallon barrels using a standard in-tank fuel pump into fuel test cells placed on a digital balance to measure out the correct amount of fuel with .001 gram accuracy.

- A. The density of each of the fuel samples was determined by measuring the specific gravity measured with a hydrometer.
- B. The percentage of each fuel in each mixture was calculated by volume.
  1. % Biodiesel x 946.3 cc/qt x density of Biodiesel = weight of Biodiesel in grams to mix for that concentration
  2. % Ethanol x 946.3 cc/qt x density of ethanol = weight of ethanol to be mixed for that concentration
  3. % #2 Diesel x 946.3 cc/qt x density of #2 diesel = weight of #2 diesel in grams to mix for that concentration

*90% Biodiesel x 946.3 cc/qt x 0.855 g/cc = 728.178 g of Biodiesel to mix  
with 10% Ethanol 946.3 cc/qt x .794 g/cc = 751.362 g/qt x .1(10%) =  
75.136g of Ethanol for a 90%bio/10%E fuel mixture*

addition, the color of the fuel samples was examined for any indications of change; such as darkening, lightening, or cloudiness due to fuel interaction. fuel breakdown, or any particles from the test materials trapped in suspension.

### **Fuel Compatibility Testing Steps**

#### **A. Initial set up**

1. Mix up the different fuels by volume as described above.
2. Weigh and measure the thickness of the test sample materials.
3. Immerse fuel system components in fuel samples.

#### **B. Weekly inspection of the parts**

1. Weigh and measure the parts.
  - a. Dry the parts using compressed air and paper towels.
  - b. Let the parts sit for about 10 minutes to let the excess fuel evaporate.
  - c. Weigh the parts on a digital scale.
  - d. Measure the parts using a micrometer.
2. Inspect the parts for corrosion and flexibility.
  - a. Bend the gasket and hoses to detect hardening or softening of the material.
  - b. Inspect the fuel tank sample for corrosion.
3. Inspect the fuel for changes in color by comparing them to the control fuel samples.

### **III. Emissions and Fuel Economy Testing**

All emission and fuel economy testing was conducted at Mankato State University's Chassis Dynamometer Lab located in Nelson Hall room 104. A test procedure was developed that allowed the researchers to collect both emissions and fuel economy data simultaneously.

The levels of HC, CO, NO<sub>x</sub>, CO<sub>2</sub>, and O<sub>2</sub> were measured using an OTC live gas infrared exhaust gas analyzer intended for use with gasoline vehicles due to the fact that diesel engines emit a significantly larger amount of particulate material than gasoline

engines, the analyzer was modified. A filter assembly was designed that was placed in the sample line to trap particulate emissions before they entered the analyzer.

Particulate material emissions were measured using a microprocessor based Smoke Opacity Meter manufactured by OTC. The meter is placed at the exhaust outlet of the engine being tested (see figure 1). A beam of light is emitted from one side of the device that must pass through the exhaust stream to the sensor. The intensity of the light is detected by the sensor the on opposite side of the light source. The range of the meter is 0 – 100, with 0 indicating the highest intensity and 100 indicating the lowest. The meter measures peak opacity during a 20-second test then averages and records the top 5 readings. The level of particulate material can thus be compared on this scale of 0 – 100. Under identical test conditions a lower opacity value indicates a lower amount of particulate material present in the exhaust.

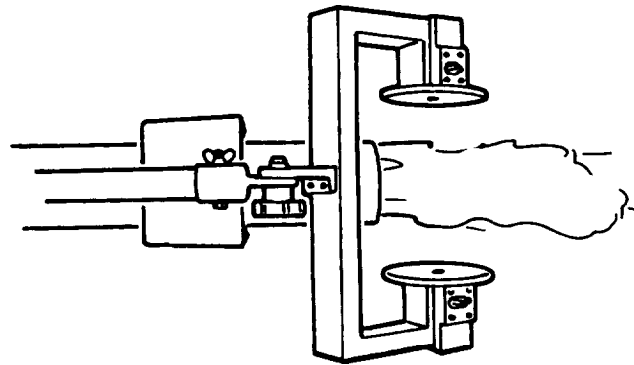


Figure 1

Three specific test conditions were established to test each fuel's performance. The test conditions selected included a simulated steady state 30 mph test, a steady state 55 mph test, and a full throttle acceleration test, all conducted on the chassis dynamometer.

During the 30 mph and 55 mph test sessions fuel economy, exhaust emissions, and particulate material data was collected. The full throttle acceleration testing, starting at 30 mph with a 15 HP load, was used to collect only exhaust emission and particulate material data.

The SAE Coast-Down Method was used to determine the horsepower required by the test vehicle at 55 mph. This procedure was used to establish the load at 55 mph. The chassis dynamometer used in the study automatically adjusts the load on the vehicle for the 30 mph and the acceleration tests. The following steps were used to determine the total road horsepower required by the vehicle at 55 mph.

- A. Calculate the frontal area of the vehicle.

$$\text{Frontal Area} = .8 \times H \times W / 144 = 30.01\text{ft}^2$$

- B. The vehicle was accelerated to 65 mph on a flat stretch of road. The transmission was placed in neutral. The time for the vehicle to decelerate from 60 to 50 mph and from 15 to 5 mph was recorded.

$$\text{Average Coast Down Time from 60 to 50 mph} = 11.84\text{s.}$$

$$\text{Average Coast Down Time from 15 to 5 mph} = 41.34\text{s}$$

- C. The results were used to determine the Road HP at 55 mph.

$$\text{Total Weight} = 5782 \text{ lb.}$$

$$\text{Deceleration Average} = \text{(high) } 0.839 \text{ mph/sec}$$

$$\text{(low) } 0.242\text{mph/sec}$$

$$\text{Velocity Average} = \text{(high) } 55\text{mph}$$

$$\text{(low) } 10\text{mph}$$

$$\text{Coefficient of AREO drag} =$$

$$18.162 \times \text{wt} \times (\text{DAH} - \text{DAL}) / A(\text{VAH} - \text{VAL})$$

$$18.162 \times 5782 \times (.839 - .242) / 30.01(55 - 10) = 0.714$$

$$\text{Aero HP} =$$

$$4.695 \times \text{CD} \times A \times \text{VAH}^3 / 1000000$$

$$6.695 \times 0.714 \times 30.01 \times 55^3 / 1000000 = 23.867 \text{ hp}$$

**Coefficient of Rolling Resistance =**

$$45.63 \times [(DAL \times VAH^2) - (DAH \times VAL^2)] / VAL^3 (VAH^2 - VAL^2)$$
$$45.63 \times [(0.242 \times 55^2) - (0.839 \times 10^2)] / 10^3 (55^2 - 10^2)$$
$$= 0.0101$$

**Rolling Friction HP =**

$$CR \times wt \times VAH \ 1373.67$$
$$0.0101 \times 5782 \times 55 \ 1373.67 = 8.6 \text{ hp}$$

**Total Road HP =**

$$AHP + RHP$$
$$23.867 + 8.6 = 32.467 \text{ hp}$$

Based on the calculations above, a 32 horsepower load was used for steady state testing at 55 mph and a 6 horsepower load for 30 mph testing. The researchers selected a starting point of 15 horsepower at 30 mph for the acceleration testing. The vehicle was accelerated at wide-open throttle for 20 seconds from starting point of 15 hp @ 30 mph.

One modification to the vehicle fuel system was designed and implemented to conduct the testing. As shown in Figure 2, an auxiliary fuel tank and two control valves were added; one on the fuel supply line and the other on the fuel return line. This allowed the researchers to eliminate the stock fuel tanks and use an auxiliary fuel tank placed on a digital scale to measure the weight of the fuel consumed during the fuel economy runs. This technique not only allowed the weight flow rate of fuel consumed during a test run to be recorded, but also ensured that no mixing of test fuels occurred due to not completely emptying the fuel tank out between test.

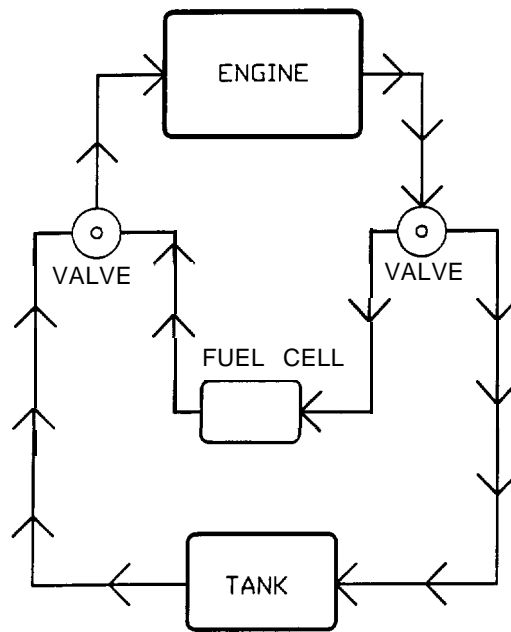


Figure 2

Fuel economy values for each fuel were determined by recording the specific gravity of each test fuel and the amount of fuel consumed during a single test session. For example, a test was run under the following conditions:

Test Fuel	#2 Diesel with a specific gravity of .845
Amount of Fuel Consumed	100 grams
Test Speed	55mph at a 32 horsepower load
Test Length	30 seconds

The following steps were used to determine the fuel economy of the vehicle at 55 mph.

- a. Convert the 100 grams of fuel used into gallons

$$[100 \text{ g of fuel} / (.845 \text{ g/cc} \times 946.3 \text{ cc/qt})] / 4\text{qt/gallon} = 0.0312647 \text{ gallons}$$

- b. Calculate the distance traveled in 30 seconds

$$(55 \text{ miles/hour} / 60 \text{ miles/hour}) \times 1 \text{ mile/minute} \times .5 = 0.4583332 \text{ miles}$$

- c. Calculate fuel economy in miles per gallon

$$0.4583332 \text{ miles} / 0.0312647 \text{ gallons} = 14.7 \text{ miles per gallon}$$

These results were also used to calculate the fuel efficiency in BTU's of heat energy used to travel a mile. Fuel economy based on the amount of heat energy used to travel a given distance is a more valid method of comparing fuels with different energy contents.

Heating values used were obtained from the Society of Automotive Engineers and the American Biofuels Association.

Three test sessions were conducted for each fuel sample at 30 mph, 55 mph, and wide open acceleration to obtain fuel economy, exhaust emissions, and particulate material data. Before each test session the following items were checked: oil level, coolant level, transmission fluid level, and tire pressure. Readings were not collected until an oil temperature of 192 degrees F was reached as using a digital thermometer coupled to the motor oil dip stick.

#### A. 6 hp @ 30 mph Testing Steps

1. Record the atmospheric conditions.
2. Connect test fuel tank to the vehicle.
3. Connect infrared analyzer and opacity meter to the exhaust system and load engine to 6 hp @ 30 mph.
4. Run vehicle at stabilized speed and load until oil temperature reached 192 degrees F.
5. When oil temperature reached 192 degrees F simultaneously start timer, zero fuel measurement scale, and begin storing data from the infra-red exhaust analyzer.
6. Record the amount of fuel in 30 second intervals.
7. At the beginning of the second, third and fourth minutes of testing conduct a 20 second steady flow opacity test.
8. After 5 minutes of testing record the final readings and reduced the speed and load on the engine.
9. Repeat steps 4-7 two more times for a total of three tests.
10. Repeat steps 1-8 for each fuel mixture in the study.

#### B. 32 hp @ 55 mph Testing Steps

1. Record the atmospheric conditions.
2. Connect test fuel tank to the vehicle.

3. Connect infra-red analyzer and opacity meter to the exhaust system and load engine to 32 hp @ 55 mph.
4. Run vehicle at stabilized speed and load until oil temperature reached 192 degrees F.
5. When oil temperature reached 192 degrees F simultaneously start timer, zero fuel measurement scale, and begin storing data from the infra-red exhaust analyzer.
6. Record the amount of fuel in 30 second intervals.
7. At the beginning of the second, third and fourth minutes of testing, conduct a 20 second steady flow opacity test..
8. After 5 minutes of testing record the final readings and reduced the speed and load on the engine.
9. Repeat steps 4-7 two more times for a total of three tests.
10. Repeat steps 1-8 for each fuel mixture in the study.

#### C. Full Throttle Acceleration Testing Steps

1. Record the atmospheric conditions.
2. Connect test fuel tank to the vehicle.
3. Connect infra-red analyzer and opacity meter to the exhaust system and load engine to 15 hp @ 30 mph.
4. Run vehicle at stabilized speed and load until oil temperature reached 192 degrees F.
5. When oil temperature reached 192 degrees F simultaneously open throttle to the wide open position and begin storing data from the infra-red exhaust analyzer and opacity meter.
6. At the end of 20 seconds of full throttle acceleration stop vehicle and record exhaust emissions and opacity levels.
7. Repeat steps 4-6 two more times for a total of three tests.
8. Repeat steps 1-7 for each fuel mixture in the study.

#### **IV. Driveability Testing**

The driveability component of the study focussed on the cold starting characteristics of the test fuels in addition to characteristics during the warm-up period of operation. During the development of the test procedure the researchers found this portion of testing to be largely subjective and difficult to quantify the small differences found in mixtures of very similar composition. As a result four specific fuel mixtures of larger incremental differences were selected for evaluation. The four fuels evaluated were; 100% #2 diesel, 100% biodiesel, a mixture containing 80% #2 diesel and 20% biodiesel, and a mixture containing 90% #2 diesel and 10% ethanol. The test fuels were evaluated in two main areas, cold start and driveability. The test fuels were evaluated in these areas based on their affect on engine/vehicle performance.

Test sessions were held once in the morning and once in the evening separated by at least a ten hour cold soak period. Each fuel was tested for two days for a total of four tests per fuel. The method of purging the fuel system, developed during the emission and fuel efficiency testing, was conducted at the completion of each set of four tests.

During the cold start component of the testing, the vehicle was started after being parked outside Nelson Hall room 104 in ambient temperatures. The length of engine cranking required to start the vehicle was measured. Initial engine RPM and comments on idle quality were also recorded during this phase. Comments on idle quality included; stalling, rough idle, smooth idle, and high idle

Once the vehicle was started, the driveability test was immediately conducted. This involved driving the vehicle on a predetermined route as shown on the map in Figure #3. The route had to meet the criteria of having low volume traffic in addition to having an extended stretch of road for steady state operation. During this portion of the testing vehicle driveability was evaluated and noted. Performance problems that would cause a test fuel to rate low in driveability included; low power, hesitation, rough idle, and stalling.

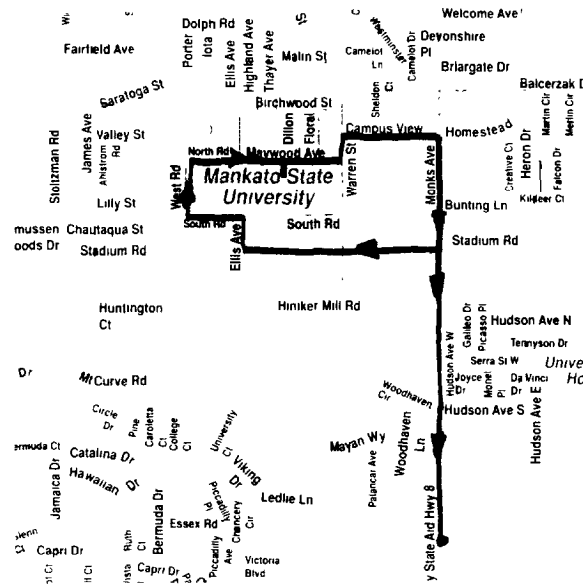


Figure 3

## Driveability Testing Steps

### A. Cold Start Testing Steps

1. The vehicle was parked outside Nelson Hall 104.
2. The vehicle was allowed to cool outside for 10 hours.
3. The engine block heater was turned on 2 hours prior to testing by an automatic timer.
4. Air temperature, relative humidity, barometric pressure, and engine oil temperature were recorded.
5. Turn ignition switch allowing glow plugs to warm for 10 seconds.
6. Start vehicle measuring the length of time from starter motor engagement until the motor starts.
7. Initial engine RPM and comments on idle quality were then recorded.
8. For safety, the engine was turned off briefly to allow removal of the tachometer.
9. The engine was restarted and testing proceeded to the driveability evaluation.

### B. Driveability Testing Steps

1. Back the vehicle out of the parking stall at idle speed.
2. Remain stopped at each stop sign for a period of 2 seconds before accelerating.

3. Accelerate vehicle at a constant rate from each stop.
4. Passenger recorded notes during each section of the course relating to the parameters set up at the start of driveability testing.
5. Return to the parking stall outside of Nelson Hall 104 and plug in the block heater and timer.

## **DATA ANALYSIS**

### **Material Compatibility**

- The material compatibility evaluation consisted of both visual and tactile comparisons of the material samples and also the fuel samples used to soak the components. The metal samples were examined for deposits of rust or corrosion. The fuel samples were inspected for sediment and color changes caused by the breakdown of the fuel line and gasket material. Fuel samples containing test materials were compared with reference samples that did not contain test materials.
- The measurable portion of the material compatibility test (weight, diameter, and thickness measurements) failed to yield significant differences between fuel samples. There was a slight weight gain on parts in all fuel samples, which is believed to be attributable to oily residue left behind from the initial soaking in the fuels. Material thickness and weight data varied widely with no specific trend. This variance is believed to be caused by differences in the consistency of the thickness and diameter of the samples. The researchers attempted to measure each part in the same location every time, however the differences in thickness change was less than the error in the procedure. Variances noted in the weight measurement component of the was believed to come from materials being weighed in various stages of dryness.
- It should be noted that materials used in this test were completely submerged in the fuel samples. Metal samples used in this test were sections removed from a fuel tank. Although some of these samples showed signs of corrosion on one side, it is unknown if the corroded side was the inside of the fuel tank or the outside. In addition, because

materials where completely submerged in fuel, any fuel color changes or sediment buildup results can not be definitively linked to the inside or outside of the hose materials used in this test. However, a reaction did take place with components in some of the fuel samples that did not occur in others.

- The samples of the fuel tank material did react differently to the various mixtures of the test fuels. While 100% concentrations of each of the test fuels exhibited no significant discoloration or corrosion, mixtures of the sample fuels did **cause** adverse effects. Of particular interest is the fact that the largest amount of corrosion occurred in the sample that was immersed in the biodiesel and ethanol mixture. The same level of corrosion was not noted in the 100% samples of each fuel.
- The following table displays the findings of the material compatibility portion of the study. The comments represent a summary of the documentation recorded over the course of **the study**.

### Material Compatibility Fuel Comparison

FUEL TYPE	COMMENTS
#2 Diesel	Fuel significantly darker, no sediment, metal slightly corroded
Biodiesel	Fuel clear, no sediment, metal mildly corroded
Ethanol	Fuel cloudier than other samples. no sediment, metal more corroded than other 100%'s
90B /10B 80B /20B 70B /30B 60B /40B 50B /50B 40B /60B	#2 Diesel / Biodiesel mixtures had no significant change in fuel color. No sediment was found. Metal corrosion varied slightly but with no Increasing or decreasing pattern.
90#2 /10E 80#2 /20E 70#2 /30E 60#2 /40E 50#2 /50E 40#2 /60E	Biodiesel / Ethanol mixtures tended to; <b>increase</b> in darkness, Increase in <b>sediment</b> . and increase in metal corrosion with higher Concentrates of Ethanol. Although no sediment was found in The 100% Bio or 100% Ethanol, there seemed to be some interaction Between Biodiesel / Ethanol fuels causing <b>sediment</b> to form in These mixtures.

- The research conducted found no material compatibility problems with steel braided rubber fuel hose, neoprene hose, **gasket** and seal materials in 100% concentrations of #2 diesel, biodiesel, or ethanol. However, there was more corrosion noted on the fuel tank material immersed in 100% ethanol than on the diesel or biodiesel samples.
- The results of the material compatibility testing of the #2 diesel fuel and biodiesel fuel blends did not indicate any problems with the components **tested**. There were no sediments present in any of the containers, no significant differences in the color of the fuel samples, and no significant difference in the corrosion noted on the metal.
- A noticeable increase in both the amount of sediment and darkened color of the fuel samples was noted as the concentration of ethanol increased in the mixture. In addition, as the concentration of ethanol increased the amount of corrosion of the metal samples also increased.

### Exhaust Gas Analysis

The results of the exhaust emission testing are broken up into three areas. Table 1 shows the results of steady state operation with a 6 hp load at 30 mph.

### Exhaust Gas Emissions 6hp@30mph

FUEL TYPE	HC(PPM)	Change(%)	CO(%)	Change(%)	NOx(PPM)	Change(%)
<b>100#2</b>	8.50		0.01		123.00	
<b>90#2/10B</b>	15.00	+76.5	0.01		135.00	+9.8
<b>80#2/20B</b>	6.67	-21.5	0.01		134.33	+9.2
<b>70#2/30B</b>	8.00	-5.9	0.01		129.00	+4.9
<b>60#2/40B</b>	2.33	-12.5	0.01		93.33	-24.1
<b>50#2/50B</b>	2.33	-72.5	0.01		125.33	+1.9
<b>40#2/60B</b>	5.33	-37.3	0.01	•	84.00	-31.7
<b>100B</b>	2.43	-71.4	0.01		148.2	+20.5
<b>5E/95B</b>	2.67	-68.6	0.01		142.00	+15.4
<b>10E/90B</b>	4.33	-49.1	0.01		119.00	-3.3
<b>15E/85B</b>	4.33	-49.1%	0.01		100.33	-18.4%

Table 1

- With the exception of one data point, HC emissions were significantly lower with blends of biodiesel and #2 diesel than with 100% #2 diesel. As the concentration of biodiesel in the mixture increased, the HC emissions decreased accordingly. The greatest reduction in HC emissions, 72.5% lower than 100% #2 diesel, was observed at concentrations of 40% and 50 % biodiesel. In addition 100% biodiesel yielded 71.4% lower HC emissions than #2 diesel under these test conditions.
- There was no significant difference noted in CO levels between any of the test fuels.
- Levels of NO<sub>x</sub> emissions were generally higher with concentrations of biodiesel and #2 diesel. The results of the 100% biodiesel had 20.5% higher concentrations of NO<sub>x</sub> than the #2 diesel. However when ethanol was added to the biodiesel, at concentrations of 10% and higher, NO<sub>x</sub> values were lower than #2 diesel.
- Three samples of biodiesel and ethanol were evaluated under these test conditions; 5%E, 10%E, and 15%E. The results indicated that as the concentration of ethanol in the mixture increased, the NO<sub>x</sub> levels decreased by 4.1%, 19.7% and 32.3% respectively.

Table 2 displays the data obtained from testing at a simulated highway cruising speeds. The vehicle had a load of 32 hp at 55 mph.

### Exhaust Gas Emissions 32hp@55mph

FUEL TYPE	HC(PPM)	Change(%)	CO(%)	Change(%)	NOx(PPM)	Change(%)
<b>100#2</b>	13.67		0.01		131.67	
<b>90#2/10B</b>	16.00	+17.0	0.01		125.67	-4.5
<b>80#2/20B</b>	17.67	+29.3	0.02	+100	203.00	+54.2
<b>70#2/30B</b>	12.33	-9.8	0.02	+100	210.00	+59.5
<b>60#2/40B</b>	6.33	-53.7	0.01		148.33	+12.7
<b>50#2/50B</b>	4.33	-68.3	0.01		172.33	+30.9
<b>40#2/60B</b>	9.67	-29.3	0.01		147.33	+11.9
100 B	8.67	-36.6	0.01		230.67	+75.2
<b>5E/95B</b>	7.67	-43.9	0.01		216.33	+64.3
<b>10E/90B</b>	7.00	-48.8	0.01		187.00	+42.0
<b>15E/85B</b>	11.00	-19.5	0.01		162.67	+23.5

Table 2

- Levels of HC recorded were higher than those recorded under the 6 hp @ 32 mph test conditions. The differences between the test fuels levels of HC were very similar. HC levels were generally lower with the greatest decreases noted at the 40% and 50% concentrations of biodiesel.
- With the exception of two data points, there was no significant difference noted in CO levels between any of the test fuels. While there was a 100% increase in CO levels at concentrations of 20% and 30% biodiesel, these results should be disregarded because the levels recorded were at the extreme lower limits of the exhaust gas analyzer.
- Levels of NO<sub>x</sub> emissions followed the same trend as the 6 hp @ 32 mph results, with however much higher differences when compared to #2 diesel. Increases in NO<sub>x</sub> levels were as much as 59.4% higher than #2 diesel under these test conditions.

- Ethanol added to biodiesel yielded the same effect on NO<sub>x</sub> emissions at this test point as observed in testing at lower loads. The addition of ethanol to biodiesel reduced NO<sub>x</sub> emissions from levels obtained at 100% biodiesel. As the concentration of ethanol in the mixture increased, the NO<sub>x</sub> levels decreased by 6.2%, 18.9% and 29.5% respectively.

The exhaust gas emission results measured under wide open throttle acceleration starting at 25 hp and 35 mph are presented in Table 3.

### Exhaust Gas Emissions At WOT Acceleration

FUEL TYPE	HC(PPM)	Change(%)	CO(%)	Change(%)	NO <sub>x</sub> (PPM)	Change(%)
<b>100#2</b>	57.67		0.40		134.00	
<b>90#2/10B</b>	18.67	-61.6	0.33	-17.5	133.33	-0.5
<b>80#2/20B</b>	13.33	-76.9	0.33	-17.5	146.33	+9.2
<b>70#2/30B</b>	9.00	-84.4	0.34	-15.0	152.00	+13.4
<b>60#2/40B</b>	10.00	-82.7	0.21	-47.5	127.00	-5.2
<b>50#2/50B</b>	9.67	-83.2	0.28	-30.0	154.67	+15.4
<b>40#2/60B</b>	9.54	-83.4	0.27	-32.5	162.43	+21.2
100 B	6.67	-88.4	0.12	-70.0	219.00	+63.4
<b>5E/95B</b>	7.00	-87.9	0.06	-85.0	157.33	+17.4
<b>10E/90B</b>	6.33	-89.0	0.05	-87.5	155.67	+16.2
<b>15E/85B</b>	5.00	-91.3	0.04	-90.0	127.33	-4.9

Table 3

- HC levels under WOT acceleration were significantly lower across the board with all concentrations of biodiesel. Levels ranging from 67.6% to 88.4% lower than #2 diesel were noted. Further reductions were observed with the addition of ethanol to biodiesel with the greatest reduction of 91.3% reported at a concentration of 15% ethanol and 85% biodiesel.
- The WOT acceleration testing results yielded the largest variations of CO. As the concentrations of biodiesel increased, CO decreased from a starting point of 17.5% at the 90% #2 and 10% biodiesel blend to a 90% reduction at the 15% ethanol and 85% biodiesel blend.

- Levels of NO<sub>x</sub> emissions followed the same trend as the two preceding test conditions, the higher the concentration of biodiesel, the higher the NO<sub>x</sub> levels.
- Ethanol added to biodiesel yielded the same effect on NO<sub>x</sub> emissions at this test point as observed in previous testing. The addition of ethanol to biodiesel reduced NO<sub>x</sub> emissions from levels obtained at 100% biodiesel. As the concentration of ethanol in the mixture increased, the NO<sub>x</sub> levels decreased by 28.2 %, 28.9% and 41.9% respectively.

### Opacity

It was found that for steady-state testing of opacity levels of the different concentrations of #2 diesel and biodiesel, the opacity varied greatly in a random pattern. Many steady-state tests were within the 0 - 1% opacity range which is the very low end of the scale. Acceleration testing, which is the operating condition that produces the most significant amount of particulate material, produced opacity readings well within the accuracy range of the equipment used in the study. The results of the particulate emission testing are displayed in Table 4.

### Opacity Levels

FUEL TYPE	6 hp @ 30 mph	32 hp @ 55 mph	Acceleration	Change (%)
<b>100#2</b>	<b>123</b>	<b>1.03</b>	<b>5543</b>	
<b>90#2/10B</b>	<b>1.12</b>	<b>0.61</b>	<b>44.47</b>	<b>-19.8</b>
<b>80#2/20B</b>	<b>4.7</b>	<b>2.61</b>	<b>40.69</b>	<b>-26.6</b>
<b>70#2/30B</b>	<b>135</b>	<b>1.41</b>	<b>36.25</b>	<b>-34.6</b>
<b>60#2/40B</b>	<b>0.38</b>	<b>0.41</b>	<b>41.65</b>	<b>-24.9</b>
<b>50#2/50B</b>	<b>7.00</b>	<b>5.22</b>	<b>4035</b>	<b>-27.2</b>
<b>40#2/60B</b>	<b>023</b>	<b>1.84</b>	<b>3656</b>	<b>-34.0</b>
<b>100B</b>	<b>1.42</b>	<b>2.01</b>	<b>22.75</b>	<b>-58.9</b>
<b>5E/95B</b>	<b>11</b>	<b>1.90</b>	<b>19.07</b>	<b>-65.6</b>
<b>10E/90B</b>	<b>1.37</b>	<b>0.64</b>	<b>12.91</b>	<b>-76.7</b>
<b>15E/85B</b>	<b>0.69</b>	<b>0.65</b>	<b>10.39</b>	<b>-81.3</b>

Table 4

- Opacity levels during WOT acceleration were significantly lower when biodiesel was mixed with #2 diesel. The reductions ranged from a 19.8% drop with 10% biodiesel to 34% with a 60% biodiesel blend.
- The opacity levels were further reduced with the addition of ethanol to biodiesel. A mixture of 15% ethanol and 85% biodiesel yielded an 81.3% reduction of particulate material when compared to #2 diesel. This same mixture had a 54.3% lower level of particulate material than 100% biodiesel.

### Fuel Economy

- The increasing concentrations of the biodiesel caused a decrease in fuel economy. Although the standard deviation of the fuel economy numbers may indicate no change whatsoever.

### **Steady State 30 mph Fuel Economy Data**

FUEL TYPE	SG	BTU/Gallon	MPG 30MPH	Change (%)	BTU/MILE	Change (%)
<b>100#2</b>	0.8450	138575	37.083		3736.89	
<b>100B</b>	0.8850	130350	32.780	-11.6	3976.51	6.4
<b>90#2/10B</b>	0.8600	137735	35.642	-3.9	3864.40	3.4
<b>80#2/20B</b>	0.8605	136923	34.626	-6.6	3954.34	5.8
<b>70#2/30B</b>	0.8615	136112	35.845	-3.3	3797.24	1.6
<b>60#2/40B</b>	0.8690	135301	35.770	-3.5	3782.53	1.2
<b>50#2/50B</b>	0.8680	134490	33.650	-9.3	3996.73	6.9
<b>40#2/60B</b>	0.8685	133679	36.302	-2.1	3682.41	-1.5
<b>5E/95B</b>	0.8658	127813	31.974	-13.8	3997.40	7.0
<b>10E/90B</b>	0.8615	125193	32.301	-12.9	3875.82	3.7
<b>15E/85B</b>	0.8550	122573	31.784	-14.3	3856.44	3.2

BTU/gal #2 diesel = 138575    BTU/gal biodiesel = 130350    BTU/gal ethanol = 78829

Table 5

## Steady State 55 mph Fuel Economy Data

FUEL TYPE	S G	BTU/Gallon	MPG 55MPH	Change (%)	BTU/MILE	Change (%)
<b>100#2</b>	0 8450	138575	13.81		10034.40	
<b>100B</b>	0 8850	130350	12.82	-7.1	10167.70	13
<b>90#2/10B</b>	0.8600	137735	13.435	-2.7	10251.95	2.2
<b>80#2/20B</b>	0.8605	136923	13.301	-3.7	10294.19	2.6
<b>70#2/30B</b>	0 8615	<b>136112</b>	13.663	-1.1	9962.09	-0.7
<b>60#2/40B</b>	0 8690	135301	13.318	-3.6	10159.26	1.2
<b>50#2/50B</b>	0.8680	134490	13 422	-2.8	10020.12	-0.14
<b>40#2/60B</b>	0.8685	133679	<b>12 938</b>	-6.3	10332.27	2 9
<b>5E/95B</b>	0 8658	127813	12.045	-12.7	10611.29	2.8
<b>10E/90B</b>	0 8615	125193	12.072	-12.6	10370 53	3.3
<b>15E/85B</b>	0 8550	122573	11 884	-13.9	10314.11	2.8

BTU/gal #2 diesel = 138575    BTU/gal biodiesel = 130350    BTU/gal ethanol = 78829

Table 6

### Cold Start and Driveability

It was found that the test vehicle starting and idle quality varied depending on the fuel sample used. It was also found that test vehicle performed similarly in driveability on 3 of the 4 fuel samples. Environmental conditions, primarily temperature, varied widely during this section of testing. Since each of the four fuel samples had tests that were made while the temperature remained between 12 • 16 degrees Fahrenheit, those test were used as the primary basis for evaluation and comparison.

Best results for starting and idle where obtained using standard #2 diesel fuel. The 90% #2 diesel mixed with 10% ethanol performed almost as well as 100% #2 diesel. The mixture of 80% #2 diesel and 20% biodiesel averaged a longer length of crank time but performed as well as the other fuel samples in driveability tests where the temperature remained above the point at which the fuel thickens beyond use. During two of the 80#2 / 20B tests the temperature was sufficiently low to cause the fuel thicken. The thick 80#2 / 20B fuel caused the vehicle to stall twice during the driveability evaluation section, The 100% biodiesel performed the worst during this section of testing. The vehicle failed to start when fueled with 100% biodiesel on all four test days. This can attributed to the temperature during those days being low enough to cause the biodiesel to solidify.

A short test was performed to compare a variety fuel samples thickness at low temperatures. The fuel samples were place in a freezer and allowed to cool to +8 degrees Fahrenheit. Samples containing biodiesel in higher then 20% concentrations where found to range from thick to solidified. A samples of 100% #2 diesel was clear and had no sign of thickening.

Description of terminology used:

- Excellent indicated a better then average of better than expected result
- Good indicates an average or expected result
- High refers to an idle speed over 700 RPM
- Rough refers to a poor idle
- Smooth refers to an acceptable idle
- Other descriptions are used in place of a term where detail was justifiable

Units of measure used:

- Fahrenheit for temperature
- Inches of Mercury for barometric pressure
- Percentage for relative humidity
- Seconds for crank time
- Revolutions per minute for initial RPM

### 80% #2 DIESEL / 20% BIODIESEL

#### Test 1

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
16	27	29.08	83.5%	15	610

START • Good

IDLE • Smooth

DRIVEABILITY • Good

#### Test 2

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
4	23	28.74	57.5%	10	700

START • Ran briefly then died • Restarted with long crank time

IDLE • Rough and high

DRIVEABILITY • Low Power. hesitation, engine stalled part way through drive test,  
unable to restart to continue due to temperature below pour point

**Test 3**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
18	30	28.70	64.0%	4	610

START • Good

IDLE • Smooth

DRIVEABILITY • Good

**Test 4**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
-2	17	28.89	68.0%	11	725

START • Long Crank time

IDLE • Rough and high

DRIVEABILITY • Low power. hesitation. engine stalled, unable to restart, fuel too thick

**100% #2 DIESEL****Test 1**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
12	28	28.89	66.0%	2	650

START • Good

IDLE • Smooth

DRIVEABILITY • Good

**Test 2**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
22	31	28.70	65.0%	0.5	595

START • Excellent, short crank time

IDLE • Smooth

DRIVEABILITY • Good

**Test 3**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
22	31	28.60	77.0%	0.5	600

START • Excellent. short crank time

IDLE • Smooth

DRIVEABILITY • Good

**Test 4**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
12	25	28.70	75.0%	3	715

START • Good

IDLE • High and smooth

DRIVEABILITY • Good

**100% BIODIESEL****Test 1**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
10	30	28.70	76.0%	Failed	

START • Unable to keep engine running because fuel was frozen at 10 degrees Fahrenheit

IDLE • NA

DRIVEABILITY • NA

**Test 2**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank(Sec)	Initial RPM
12	32	28.82	75.0%	Failed	

START • Unable to keep engine running because fuel was frozen at 12 degrees Fahrenheit

IDLE • NA

DRIVEABILITY • NA

**Test 3**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
8	29	28.75	76.0%	Failed	

START • Unable to keep engine running because fuel was frozen at 8 degrees Fahrenheit

IDLE • NA

DRIVEABILITY • NA

**Test 4**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
10	30	28.70	76.0%	Failed	

START • Unable to keep engine running because fuel was frozen at 10 degrees Fahrenheit

IDLE • NA

DRIVEABILITY • NA

**90% #2 DIESEL / 10% ETHANOL****Test 1**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
38	46	28.26	77.5%	0.5	630

START • Good

IDLE • Good

DRIVEABILITY • Good

**Test 2**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
39	45	28.89	76.0%	1	615

START • Good

IDLE • Good

DRIVEABILITY • Good

**Test 3**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
17	24	28.68	83.0%	2.5	725

START • Stalled and had to be restarted

IDLE • High

DRIVEABILITY • Good

**Test 4**

Air Temp.	Oil Temp.	Baro. Press.	Rel. Hum.	Crank (Sec)	Initial RPM
16	24	28.72	79.0%	2	715

START • Good

IDLE • High

DRIVEABILITY • Good

## CONCLUSIONS

- In reviewing the compatibility test data there was no compatibility problems identified with fuel system components and concentrations of biodiesel and #2 diesel. Based on this research, biodiesel appears to be compatible with the components of the fuel system of a diesel vehicle up to 100% biodiesel.
- Color changes in the ethanol-biodiesel mixtures and the #2 diesel-biodiesel mixtures seem to be a reaction between the fuels and not with the parts added in the fuel. This can **be** concluded since the mixtures with no parts added are also changing color.
- The addition of ethanol to mixtures of biodiesel and #2 diesel fuel appear to have a reaction with fuel system components. As the concentration of ethanol was increased, the amount of sediment in the container increased. However, the sediment appeared to be from the braided material used to protect the outside of the fuel line from abrasion.
- During steady state conditions at 30 mph and 55 mph there was no change in CO emissions. However, under wide open throttle conditions CO reductions of up to 47.5% were recorded on biodiesel blends and up to 90% reductions recorded on blends including ethanol.
- Levels of HC emissions were lower with blends of biodiesel with the exception of three data points. The three points were at low concentrations of biodiesel. The largest reductions in HC emissions were observed during wide open throttle conditions.
- Levels of NO<sub>x</sub> emissions generally increased with concentrations of biodiesel and #2 diesel. However, as the concentration of ethanol in the mixture increased the levels of NO<sub>x</sub> decreased.
- **Steady state** operating conditions identified no significant reductions in particulate emissions. Wide open throttle acceleration testing, which are the conditions that produce the largest amount of particulate emissions, yielded data that identified significant reductions in particulate materials as levels of biodiesel were increased. In

addition particulate emissions were further reduced as the concentration of ethanol in the mixture was increased. A blend of 15% ethanol and 85% biodiesel reduced particulate emissions by 81% over #2 diesel fuel.

- Mixtures of biodiesel and #2 diesel fuel resulted in a lower fuel economy measured in mpg than #2 diesel. This is due in part to the lower energy density of biodiesel as compared to #2 diesel. The addition of ethanol to biodiesel further reduced the fuel economy as measured in mpg.
- Mixtures of biodiesel and #2 diesel fuel resulted in lower fuel **efficiency** when evaluated by comparing the amount of energy in BTUs used to travel a mile. Steady state operation at 55 mph resulted in approximately 2-3% more energy required to travel one mile.
- The driveability of the test vehicle when running 100% #2 diesel, 80% #2 diesel mixed with 20% biodiesel, and 90% #2 diesel mixed with 10% ethanol remained equal with no significant difference when above the temperature at which fuel samples begin to solidify. Based on test results, 80% #2 diesel mixed with 20% biodiesel began to thicken at a temperature near 8 degrees Fahrenheit. The 100% biodiesel fuel mixture was tested at a temperature no higher than 12 degrees Fahrenheit. Therefore, it can be assumed the point at which 100% biodiesel thickens is between 12 • 32 degrees Fahrenheit.

## **RECOMMENDATIONS**

1. A vehicle with limited miles should be used to conduct tests in order to eliminate any possible variables associated with diesel engines and motor vehicles with high mileage.
2. A vehicle with a manual transmission should be used in order to eliminate the horsepower losses and variability associated with automatic transmissions.
3. A constant volume sampler type device should be used to dilute the exhaust gas emissions in order to more accurately measure opacity with less variability.

4. Biodiesel made from different products should be experimentally compared in order to accurately determine the advantages of biodiesel fuels.
5. The biodiesel should be run in diesel two-stroke engines in order to experimentally compare the cleanliness of biodiesel over #2 diesel in a diesel engine with higher emission production.
6. Additional testing should be done on material compatibility that would more closely simulate the actual conditions inside a diesel fuel system. One possibly way to more closely simulate a diesel fuel system would be to construct a apparatus using a pump, filter, and fuel hoses that would continuously circulate a fuel sample. The filter, fuel sample, and inside surface of the hoses could then be evaluated to better determine the material compatibility of the sample.
7. The fuel samples should be run in long term driveability test which would more closely simulate actual vehicle usage in a wide variety of conditions over a greater span of mileage to more accurately evaluate driveability differences.