

# COMPARISON OF ENGINE PERFORMANCE AND EMISSIONS FOR PETROLEUM DIESEL FUEL, YELLOW GREASE BIODIESEL, AND SOYBEAN OIL BIODIESEL

M. Canakci, J. H. Van Gerpen

**ABSTRACT.** Biodiesel is a non-toxic, biodegradable and renewable alternative fuel that can be used with little or no engine modifications. Biodiesel is currently expensive but would be more cost effective if it could be produced from low-cost oils (restaurant waste, frying oils, animal fats). These low-cost feedstocks are more challenging to process because they contain high levels of free fatty acids. A process for converting these feedstocks to fuel-grade biodiesel has been developed and described previously. The objective of this study was to investigate the effect of the biodiesel produced from high free fatty acid feedstocks on engine performance and emissions. Two different biodiesels were prepared from animal fat-based yellow grease with 9% free fatty acids and from soybean oil. The neat fuels and their 20% blends with No. 2 diesel fuel were studied at steady-state engine operating conditions in a four-cylinder turbocharged diesel engine. Although both biodiesel fuels provided significant reductions in particulates, carbon monoxide, and unburned hydrocarbons, the oxides of nitrogen increased by 11% and 13% for the yellow grease methyl ester and soybean oil methyl ester, respectively. The conversion of the biodiesel fuel's energy to work was equal to that from diesel fuel.

**Keywords.** Alternative fuel, Biodiesel, Diesel engine, Engine emissions, Engine performance, Soybean oil methyl ester.

Vegetable oil esters are receiving increasing attention as a non-toxic, biodegradable, and renewable alternative diesel fuel. These esters have become known as "biodiesel." Many studies have shown that the properties of biodiesel are very close to those of diesel fuel (Chang et al., 1996; Freedman and Pryde, 1982). Therefore, biodiesel can be used in diesel engines with few or no modifications. Biodiesel has a higher cetane number than petroleum diesel fuel, no aromatics, and contains 10% to 11% oxygen by weight. These characteristics of biodiesel reduce the emissions of carbon monoxide (CO), hydrocarbons (HC), and particulate matter (PM) in the exhaust gas compared with diesel fuel (Graboski and McCormick, 1998).

Over the past seven years, considerable research has been conducted to investigate the properties of biodiesel and its performance in engines (Chang and Van Gerpen, 1997; Schumacher and Van Gerpen, 1996; Schmidt and Van Gerpen, 1996; Zhang and Van Gerpen, 1996; Chang et al., 1996; Sharp, 1998; Graboski and McCormick, 1998). Virtually all of this work is based on the methyl ester of soybean oil. Soybean oil was chosen because, in the U.S., soybean oil is the only oil that is available in sufficient

quantity to supply a national market. However, the cost of food-grade soybean oil limits its use to cases of severe shortages of petroleum diesel fuel or emergency. Reducing the cost of the feedstock is necessary for biodiesel to be commercially viable.

One way to reduce the cost of biodiesel is to use less expensive feedstocks. Waste oils and greases from restaurants and rendered animal fats are possible sources of lower cost feedstocks for biodiesel. When the free fatty acid level of these waste oils and fats is less than 15%, the product is known as "yellow grease." If the free fatty acid (FFA) level exceeds 15%, it may be sold at a discount as "brown grease" or blended with low-FFA material to meet the yellow grease specifications. Approximately 1.1 billion kg of waste restaurant fats are collected annually from restaurants and fast-food establishments in the U.S. (Haumann, 1990). The objective of the current study is to investigate the performance and emissions of a diesel engine operating on yellow grease-based biodiesel and compare them to the performance and emissions when the engine is operated on soybean oil-based biodiesel and petroleum-based diesel fuel.

## LITERATURE REVIEW

The problem with processing waste oils is that they usually contain large amounts of free fatty acids that cannot be converted to biodiesel using an alkaline catalyst due to the formation of soaps. The soaps can prevent separation of the biodiesel from glycerin, its co-product. An alternative way is to use acid catalysts, which some researchers have claimed are more tolerant of free fatty acids (Aksoy et al., 1988; Freedman and Pryde, 1982; Liu, 1994). A process developed in a previous study (Canakci and Van Gerpen, 2001a) and implemented in a 190 L/d pilot plant (Canakci and Van

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Gerpen, 2001b) has demonstrated that fuel-quality biodiesel can be produced from yellow and brown grease using an acid catalyst.

Several studies (Engelman et al., 1978; Laguë et al., 1988; Kouremenos et al., 1990; Karaosmanoglu et al., 1992; Cigizoglu et al., 1997) have presented the results of engine tests with waste vegetable oils without transesterification blended with diesel fuel. The best results appear to be with relatively low blends (10% to 20%) in indirect-injection engines. Increases in in-cylinder deposits were noted, although the deposits did not appear to affect performance. Emissions results were mixed; some researchers reported decreases of a specific pollutant, and others reported increases.

Since most modern diesel engines have direct-injection fuel systems, and these engines are more sensitive to fuel spray quality than indirect-injection engines, a fuel with properties that are closer to diesel fuel is needed. Therefore, most recent research has focused on transesterification of the waste vegetable oils before using them in diesel engines. Mittelbach et al. (1992) prepared methyl esters from used frying oil and compared their fuel properties to Austrian standards valid for rapeseed oil methyl ester. The content of the free fatty acids of the oils was between 0.26% and 2.12%. After filtration at 40°C to remove solid particles, the oil was transesterified using an alkaline catalyst. They noted that all specification values could be met by the used vegetable oil esters except for the cold filter plugging point, which in most cases was over -8°C.

Isigigur-Tuna et al. (1990) prepared 10% and 20% blends (by volume) of methyl ester of used frying oil with No. 2 diesel fuel and found that while the heating value and cetane number were a little lower than for No. 2 diesel fuel, most of the fuel properties of the blends were within the range of those for pure No. 2 diesel fuel.

Mittelbach and Tritthart (1988) prepared methyl esters from used frying oil to investigate the effects of the ester on diesel engine exhaust emissions. They measured slightly lower HC, CO, and particulate emissions but increased NO<sub>x</sub> values when the ester fuel was used. They found higher fuel consumption for the ester when compared with No. 2 diesel fuel due to its lower energy content.

Nye et al. (1983) investigated the esters of used frying oil to determine their effects on engine performance and emissions. The esters of methanol, ethanol, 1-propanol, 2-propanol, 1-butanol, and 2-ethoxyethanol were prepared using sulfuric acid and potassium hydroxide as acid and base catalysts, respectively. They found that all of the acid-catalyzed fuels had low viscosities, but all of the base-catalyzed fuels had higher viscosities, except for the methanol-based fuel, which was the least viscous of all fuels. The authors noted that the viscosity results of the esters correlated with the percentage of ester yield, indicating that some of the fuels probably contained substantial amounts of unreacted and partially reacted oil. In that study, the three fuels with the lowest viscosity (methyl ester prepared with base catalyst, ethyl ester prepared with acid catalyst, and butyl ester prepared with acid catalyst) were tested in half-hour runs in a MWM high-speed diesel engine. No problems were observed with regard to starting at 25°C, smoothness of running, or smokiness of exhaust. They also tested the methyl

and ethyl esters in a Perkins P6 low-speed diesel engine, and no problems were observed in that engine either.

Peterson et al. (1995) compared the engine performance and emissions of ethyl esters produced from waste hydrogenated soybean oil with No. 2 diesel fuel. In this study, two types of engines were used. For the engine performance tests, a direct-injected, four-cylinder John Deere 4239T turbocharged diesel engine was used. The emissions testing was conducted with a 1994 Dodge pickup equipped with a direct-injected, turbocharged and intercooled, 5.9 L Cummins diesel engine. The biodiesel had a higher specific gravity and 1.9 times the viscosity of No. 2 diesel fuel at 40°C. The heat of combustion of the biodiesel was 12% lower than for diesel fuel. The smoke opacity was 71% lower and the engine power was 4.8% lower when the engine was operated with the biodiesel compared with No. 2 diesel fuel. The peak engine torque was reduced 6% and 3.2% at 1700 and 1300 rpm, respectively. There was no significant difference in the thermal efficiencies. Emissions tests showed a 54% decrease in HC, a 46% decrease in CO, a 14.7% decrease in NO<sub>x</sub>, a 0.57% increase in CO<sub>2</sub>, and a 14% increase in PM when biodiesel was used.

Reed et al. (1991) converted waste cooking oils to their methyl and ethyl esters and tested pure biodiesel and a 30% blend of biodiesel in diesel fuel in a diesel-powered bus using a chassis dynamometer. No significant difference in power and performance was observed, except for a visible reduction of smoke on acceleration with the esters of the used oil. They also found that the smoke opacity was reduced to 60% of the diesel value by the 30% blend and to 26% of the diesel value by the pure ester.

All of the researchers appeared to use biodiesel produced from feedstocks with relatively low free fatty acids. The biodiesel was generally prepared using alkaline-catalyzed processes that were similar to those used for high-quality soybean oil or canola oil. None of the researchers used feedstocks with the high free fatty acid level typical of rendered animal fats (10% to 25%).

## EXPERIMENTAL EQUIPMENT

This study was an investigation of the impact of biodiesel prepared from yellow grease on engine performance and exhaust emissions. Comparisons were made to biodiesel from soybean oil and to No. 2 diesel fuel. A John Deere 4276T, four-cylinder, four-stroke, turbocharged diesel engine was used for the testing. The engine was connected to a 112 kW General Electric (Schenectady, N.Y.) model TLC 2544 direct current dynamometer. The combustion system of the diesel engine was a bowl-in-piston, direct-injection, medium-swirl type. The engine was equipped with a rotary-type fuel pump. The basic specifications of the engine are listed in table 1.

Table 1. Specifications of John Deere 4276T diesel engine.

|                       |                      |
|-----------------------|----------------------|
| Bore                  | 106.5 mm             |
| Stroke                | 127.0 mm             |
| Connecting rod length | 202.9 mm             |
| Compression ratio     | 16.8:1               |
| Maximum power         | 57.1 kW at 2100 rpm  |
| Peak torque           | 305.0 Nm at 1300 rpm |

The yellow grease methyl ester (YGME) and the soybean oil methyl ester (SME) were tested as pure fuels and as 20% blends with No. 2 diesel fuel. The No. 2 diesel fuel was

**Table 2. The physical and chemical properties of No. 2 diesel fuel, soybean oil methyl ester, and yellow grease methyl ester.**

| Test Property                                     | No. 2 Diesel Fuel                                    | Soybean Oil Methyl Ester  | Yellow Grease Methyl Ester  |
|---|--|---|---|
| Carbon (% mass)                                   | 86.70 <sup>[a]</sup>                                 | 77.10 <sup>[b]</sup>  | 76.46 <sup>[b]</sup>  |
| Hydrogen (% mass)                                 | 12.71 <sup>[a]</sup>                                 | 11.81 <sup>[b]</sup>  | 12.25 <sup>[b]</sup>  |
| Oxygen (% mass)                                   | —  | 10.97 <sup>[b]</sup>  | 11.29 <sup>[b]</sup>  |
| C/H ratio   | 6.82   | 6.53  | 6.24  |
| Sulfur (% mass)                                   | 0.041 <sup>[a]</sup>                                 | <0.005 <sup>[a]</sup>   | <0.005 <sup>[a]</sup>   |
| Typical formula                                   | C <sub>14.09</sub> H <sub>24.78</sub> <sup>[b]</sup> | C <sub>18.74</sub> H <sub>34.43</sub> O <sub>2</sub> <sup>[b]</sup> | C <sub>18.06</sub> H <sub>34.72</sub> O <sub>2</sub> <sup>[b]</sup> |
| Average molecular weight                          | 193.89 <sup>[c]</sup>                                | 291.62 <sup>[b]</sup>   | 283.52 <sup>[b]</sup>   |
| Cetane number (ASTM D613)                         | 42.6 <sup>[a]</sup>                                  | 51.5 <sup>[a]</sup>   | 62.6 <sup>[a]</sup>   |
| Gross heat of combustion (kJ/kg)                  | 45,339 <sup>[a]</sup>                                | 39,871 <sup>[a]</sup>   | 39,817 <sup>[a]</sup>   |
| Net heat of combustion (kJ/kg)                    | 42,640 <sup>[a]</sup>                                | 37,388 <sup>[a]</sup>   | 37,144 <sup>[a]</sup>   |
| Specific gravity (at 21°C)                        | 0.8537 <sup>[d]</sup>                                | 0.8814 <sup>[d]</sup>   | 0.8728 <sup>[d]</sup>   |
| Kinematic viscosity (at 40°C, mm <sup>2</sup> /s) | 2.8271 <sup>[d]</sup>                                | 4.2691 <sup>[d]</sup>   | 5.1643 <sup>[d]</sup>   |
| Total glycerin (%)                                | —  | 0.028 <sup>[e]</sup>  | 0.129 <sup>[e]</sup>  |
| Free glycerin (%)                                 | —  | 0.000 <sup>[e]</sup>  | 0.015 <sup>[e]</sup>  |
| Distillation (ASTM D86, °C) <sup>[a]</sup>        |  |   |   |
| Initial boiling point                             | 178  | —   | —   |
| 5%  | 200  | —   | —   |
| 10%   | 212  | —   | —   |
| 20%   | 227  | —   | —   |
| 30%   | 239  | —   | —   |
| 40%   | 250  | —   | —   |
| 50%   | 261  | —   | —   |
| 60%   | 272  | —   | —   |
| 70%   | 284  | —   | —   |
| 80%   | 298  | —   | —   |
| 90%   | 317  | —   | —   |
| 95%   | 332  | —   | —   |
| End point   | 345  | —   | —   |
| Recovery (%)                                      | 98.0   | —   | —   |
| Residue (%)                                       | 1.9  | —   | —   |
| Loss (%)  | 0.1  | —   | —   |

<sup>[a]</sup> Measured by Phoenix Chemical Laboratory, Chicago, Ill.

<sup>[b]</sup> Calculated from the fatty acid distribution.

<sup>[c]</sup> Calculated using Method 375–86, Universal Oil Products, Des Plaines, Ill.

<sup>[d]</sup> Done in Department of Mechanical Engineering, Iowa State University, Ames, Iowa.

<sup>[e]</sup> Measured by Williams Laboratory Services, Kansas City, Kansas.

purchased from a local commercial supplier. The SME and YGME were prepared in the pilot plant located at the Biomass Energy Conversion Center of the Iowa Energy Center in Nevada, Iowa. This pilot plant is described in a separate paper (Canakci and Van Gerpen, 2001b). The properties and composition of the fuels are presented in tables 2 and 3.

The blends were tested at full load (100%) at the engine's peak torque condition, which is 1400 rpm and 258 N–m. This condition was chosen because it is the point of minimum air/fuel ratio and maximum smoke. This provides the best conditions for discerning any differences between the fuels. The fueling rate of the engine was adjusted to hold this torque level for all fuels. The tests were performed at steady-state conditions. The fuels were tested in random order, and each fueling was repeated three times. The results of the three replications were averaged and reported. The following instruments were used for the measurements of the engine exhaust emissions:

- Model 755R O<sub>2</sub> monitor, Rosemount Analytical, La Habra, Cal.
- Model 880A non-dispersive infrared CO analyzer, Rosemount Analytical.
- Model 880A non-dispersive infrared CO<sub>2</sub> analyzer, Rosemount Analytical.
- Model VE7, flame ionization detector (FID), HC analyzer, J.U.M. Engineering, Munich, Germany.
- Model 955 chemiluminescent NO/NO<sub>x</sub> analyzer, Beckman Industrial Corp. (currently Rosemount Analytical, La Habra, Cal.). The NO<sub>x</sub> measurements were corrected for humidity following the procedure recommended by the Society of Automotive Engineers (SAE, 1993).
- Model ETD02050 smoke meter, Robert Bosch GmbH, Stuttgart, Germany.

Calibration of each analyzer was performed before each test.

## RESULTS AND DISCUSSION

### ENGINE EFFICIENCY

In order to understand the effect of the biodiesel on engine efficiency, the brake specific fuel consumption (BSFC) and thermal efficiency of the engine were measured at full load (258 N–m) and at an engine speed of 1400 rpm. The engine load and speed were kept constant for all of the test fuels.

The BSFC and the percentage change in the BSFC from the baseline diesel fuel are listed in table 4. As seen in the table, the methyl esters have higher BSFCs than the No. 2 diesel fuel. The increase in BSFC is understandable since the methyl esters have heating values that are about 12% less than for No. 2 diesel fuel. These results are similar to those

**Table 3. Fatty acid composition of the feedstocks and esters.**

| Product                    | Carbon Chain (%) <sup>[a]</sup> |       |       |       |       |       |       |       |       |       | Unknown Components | Sat. (%) |
|----------------------------|---------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------------------|----------|
|                            | C14:0                           | C15:0 | C16:0 | C16:1 | C17:0 | C18:0 | C18:1 | C18:2 | C18:3 | C20:0 |                    |          |
| Soybean oil                | <0.10                           | <0.10 | 10.58 | <0.10 | 0.11  | 4.76  | 22.52 | 52.34 | 8.19  | 0.36  | 0.48               | 16.29    |
| Soybean oil methyl ester   | <0.10                           | <0.10 | 10.56 | <0.10 | 0.11  | 4.74  | 22.51 | 52.39 | 8.22  | 0.36  | 0.44               | 16.26    |
| Yellow grease              | 2.43                            | 0.37  | 23.24 | 3.79  | 1.00  | 12.96 | 44.32 | 6.97  | 0.67  | 0.14  | 1.11               | 39.76    |
| Yellow grease methyl ester | 2.42                            | 0.36  | 22.77 | 3.84  | 0.95  | 12.03 | 44.98 | 7.80  | 0.79  | 0.14  | 1.24               | 38.67    |

<sup>[a]</sup> Measured by Woodson–Tenent Laboratories, Inc., Des Moines, Iowa.

**Table 4. Average values and percent changes in BSFC and thermal efficiency.**

| Fuel Type    | BSFC (g/kW-hr) | % Change in BSFC | Thermal Efficiency (%) | % Change in Thermal Efficiency |
|--------------|----------------|------------------|------------------------|--------------------------------|
| No. 2 Diesel | 228.42 (c)     | —                | 36.96 (a)              | —                              |
| 20% SME      | 234.55 (b)     | 2.69             | 36.90 (a)              | -0.16                          |
| 20% YGME     | 234.29 (b)     | 2.57             | 36.99 (a)              | 0.07                           |
| SME          | 259.33 (a)     | 13.53            | 37.13 (a)              | 0.45                           |
| YGME         | 260.94 (a)     | 14.24            | 37.14 (a)              | 0.49                           |

of Monyem (1998) and McDonald et al. (1995), who fueled diesel engines with soybean oil methyl ester and No. 2 diesel fuel. In those studies, a 13% to 14% increase in BSFC for the methyl esters was found. Ali (1995) found a 12% to 14% increase in BSFC for beef tallow methyl ester.

A statistical analysis technique called “Tukey grouping” was performed on the data to determine whether the differences observed between the fuels are statistically significant at the 95% confidence level (Ott, 1993; Barnes, 1994). The letters in parentheses in table 4 show the Tukey grouping analysis for the BSFC. If the variables in the Tukey grouping have the same letter, then the differences between those variables are not statistically significant. There was no significant difference between the BSFC of the engine operating on SME and YGME, or between the 20% blend of SME and the 20% blend of YGME. However, both biodiesels and their blends have a significant effect on the BSFC compared with the No. 2 diesel fuel.

The brake thermal efficiencies of the engine when operating on the different fuels and blends are also shown in table 4. Brake thermal efficiency is defined as the actual brake work per cycle divided by the amount of fuel chemical energy as indicated by the fuel’s lower heating value. As the table shows, the thermal efficiency of the SME, YGME, and their blends were almost the same as for No. 2 diesel fuel. This means that the engine converts the chemical energy of the fuel to mechanical energy with the same efficiency for all the fuels used in the test. This was confirmed by the Tukey grouping test, which indicates that there is no significant difference between any of the fuels.

Monyem (1998), Chang and Van Gerpen (1997), and Yahya (1988) fueled a John Deere 4276T four-cylinder, four-stroke, turbocharged direct-injection diesel engine with biodiesel fuels and No. 2 diesel fuel. They also found that the thermal efficiency of the biodiesel and their blends were the same as with No. 2 diesel fuel.

**ENGINE EMISSIONS**

The exhaust emissions were compared for YGME, SME, 20% YGME blend, 20% SME blend, and No. 2 diesel fuel at the load of 258 N-m and the engine speed of 1400 rpm. The

exhaust emissions measured were carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), unburned hydrocarbons (HC), oxides of nitrogen (NO<sub>x</sub>), and the Bosch smoke number (SN). All results were converted to a brake specific basis (g/kW-hr) except for the SN. The numerical values for the emission measurements and the results of the Tukey grouping test to determine statistical significance are provided in table 5.

**Comparison of CO Emissions**

The brake specific CO exhaust emissions are shown in figure 1. For all of the methyl esters and blends, the CO emissions were less than for the No. 2 diesel fuel. Compared to No. 2 diesel fuel, the CO emissions of the SME and YGME were reduced by 18.2% and 17.8%, respectively. These reductions were found to be statistically significant, although the reductions observed for the 20% blends were only borderline significant. There were no statistically significant differences between the two neat biodiesels or between the two blends. Monyem (1998) and Yahya (1988) also found that biodiesel and their blends lowered CO emissions. In their studies, they found 15.7% and 15.8% reductions in CO emissions compared to No. 2 diesel fuel, respectively, when the engine was fueled with neat biodiesel from soybean oil.

**Comparison of CO<sub>2</sub> Emissions**

The brake specific CO<sub>2</sub> exhaust levels are shown in figure 2. The CO<sub>2</sub> emissions for the methyl esters were only slightly higher than for the No. 2 diesel fuel. Compared to No. 2 diesel fuel, the CO<sub>2</sub> emissions of the SME and YGME were increased by 1.8% and 1.2%, respectively, and the changes in CO<sub>2</sub> for the 20% blends were even smaller. None of these changes were found to be statistically significant.

**Comparison of Unburned HC Emissions**

The brake specific HC exhaust emissions are shown in figure 3. For all of the methyl esters and blends, the HC emissions were less than for the No. 2 diesel fuel. Compared with No. 2 diesel fuel, the highest HC reduction was found for YGME, which was 46.3%, while the SME reduction was 42.5%. The HC emissions of the 20% blends of SME and YGME were decreased by 3.1% and 2.3%, respectively. The differences between the methyl esters from different feedstocks are much less than the differences between the esters and No. 2 diesel fuel.

Monyem (1998) and Chang and Van Gerpen (1997) also found significant HC reduction when biodiesel was used in the diesel engine. The Tukey test results show that there is a significant difference between the neat biodiesel fuels and No. 2 diesel fuel (table 5). However, the HC of the 20% blends of the biodiesels showed results that were statistically similar to those of No. 2 diesel fuel.

**Table 5. Average values and percent changes in the engine emissions with Tukey grouping statistical results.**

| Fuel Type    | BSCO (g/kW-hr) | % Change in CO | BSCO <sub>2</sub> (g/kW-hr) | % Change in CO <sub>2</sub> | BSHC (g/kW-hr) | % Change in HC | BSNO <sub>x</sub> (g/kW-hr) | % Change in NO <sub>x</sub> | SN       | % Change in SN |
|--------------|----------------|----------------|-----------------------------|-----------------------------|----------------|----------------|-----------------------------|-----------------------------|----------|----------------|
| No. 2 diesel | 0.56 (a)       | —              | 803.0 (a)                   | —                           | 0.50 (a)       | —              | 18.8 (a)                    | —                           | 1.06 (a) | —              |
| 20% SME      | 0.52 (a)       | -7.5           | 802.7 (a)                   | -0.04                       | 0.49 (a)       | -3.1           | 19.1 (a)                    | 1.5                         | 0.89 (a) | -15.8          |
| 20% YGME     | 0.51 (ba)      | -7.0           | 802.6 (a)                   | -0.06                       | 0.49 (a)       | -2.3           | 19.0 (a)                    | 1.1                         | 0.88 (a) | -16.8          |
| SME          | 0.46 (c)       | -18.2          | 817.4 (a)                   | 1.8                         | 0.29 (b)       | -42.5          | 21.3 (b)                    | 13.1                        | 0.41 (b) | -61.1          |
| YGME         | 0.45 (c)       | -17.8          | 812.3 (a)                   | 1.2                         | 0.27 (b)       | -46.3          | 21.0 (b)                    | 11.6                        | 0.38 (b) | -64.2          |

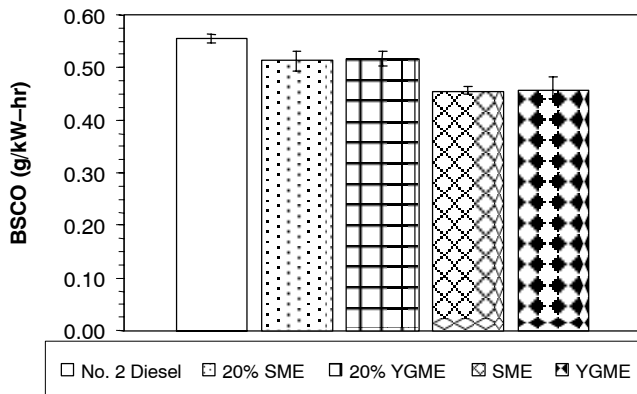


Figure 1. Comparison of brake specific carbon monoxide emissions (values shown are the average of three measurements, and the error bars show the spread between the maximum and minimum points).

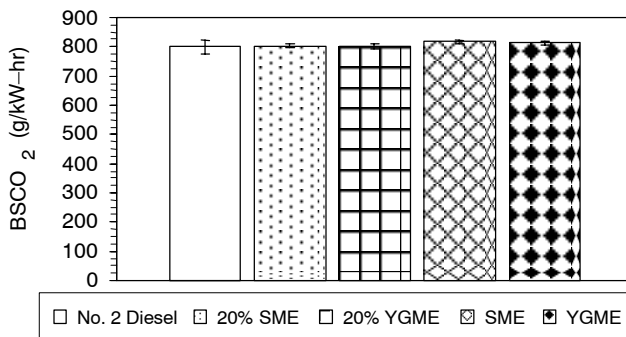


Figure 2. Comparison of brake specific carbon dioxide emissions (values shown are the average of three measurements, and the error bars show the spread between the maximum and minimum points).

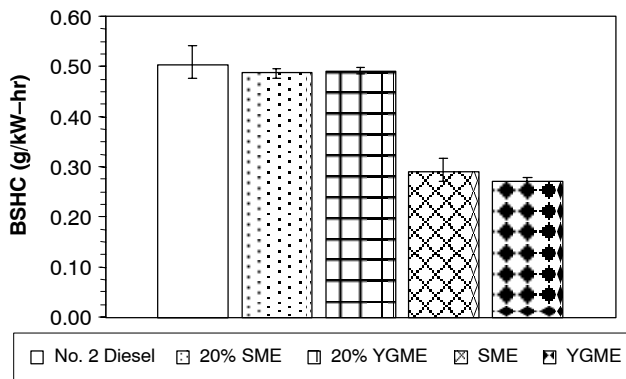


Figure 3. Comparison of brake specific hydrocarbon emissions (values shown are the average of three measurements, and the error bars show the spread between the maximum and minimum points).

### Comparison of NO<sub>x</sub> Emissions

The brake specific NO<sub>x</sub> exhaust emissions are shown in figure 4. The NO<sub>x</sub> emissions were higher for all of the methyl esters than for No. 2 diesel fuel. Compared with No. 2 diesel fuel, the NO<sub>x</sub> emissions of the SME and YGME were increased by 13.1% and 11.6%, respectively. The NO<sub>x</sub> increase in the emissions may be associated with the oxygen content of the methyl esters, since the fuel oxygen may provide additional oxygen for NO<sub>x</sub> formation. However, the overall equivalence ratios for the methyl ester fuels were very similar to No. 2 diesel fuel. The impact of the fuel's physical

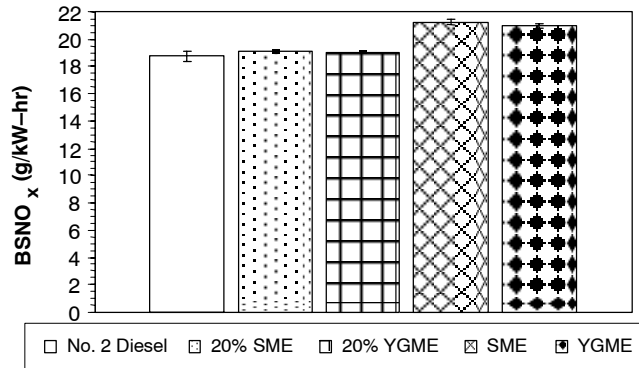


Figure 4. Comparison of the brake specific oxides of nitrogen (values shown are the average of three measurements, and the error bars show the spread between the maximum and minimum points).

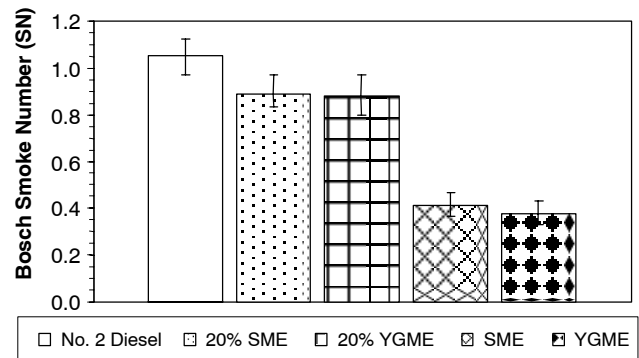


Figure 5. Comparison of the Bosch smoke numbers (values shown are the average of three measurements, and the error bars show the spread between the maximum and minimum points).

properties on the engine's injection timing, which will be discussed later, is not fully understood, but this may also play a role in the higher NO<sub>x</sub> emissions. An even more important mechanism is likely to be the timing advance that results when rotary-style fuel injection pumps deliver the higher fuel volume needed for biodiesel to provide the same power level as No. 2 diesel fuel.

Mittelbach and Tritthart (1988) measured the exhaust emissions from a diesel engine fueled with used frying oil methyl ester, and they found increased NO<sub>x</sub> emissions compared to No. 2 diesel fuel. Rickeard and Thompson (1993) and Monyem (1998) also mentioned that the NO<sub>x</sub> emission increased for biodiesel fuels.

### Comparison of Bosch Smoke Numbers (SN)

The Bosch smoke number (SN) data are shown in figure 5. For all of the methyl esters and the blends, the SNs were less than for the No. 2 diesel fuel. The SNs of No. 2 diesel fuel, SME, and YGME were 1.06, 0.41, and 0.38, respectively. The smoke levels of the methyl esters and their blends were significantly lower than that of No. 2 diesel fuel. However, almost no difference was observed in the SNs between the two methyl esters and between the two blends.

Schumacher et al. (1992) fueled a Dodge pickup with soybean oil methyl ester and found a large reduction (86%) in SN when using neat biodiesel. Monyem (1998) found a 56.9% reduction in SN when fueling the engine with soybean oil methyl ester, confirming the results of this study.

**Table 6. Combustion characteristics of the fuels.**

| Fuel         | Start of Fuel Injection (°BTDC) | Start of Combustion (°BTDC) | Ignition Delay (°) |
|--------------|---------------------------------|-----------------------------|--------------------|
| No. 2 Diesel | 13.50 (a)                       | 7.42 (a)                    | 6.09 (a)           |
| 20% SME      | 14.40 (b)                       | 8.33 (b)                    | 6.07 (a)           |
| 20% YGME     | 14.60 (b a)                     | 8.50 (b)                    | 6.10 (a)           |
| SME          | 16.18 (c)                       | 10.83 (c)                   | 5.34 (b)           |
| YGME         | 17.05 (c)                       | 11.58 (d)                   | 5.46 (b)           |

**COMBUSTION CHARACTERISTICS OF THE FUELS TESTED**

This section will discuss the combustion characteristics of the fuels used in the engine tests. First, the timing for the start of fuel injection will be compared. Second, a comparison of the start of combustion and the fuel burning rate will be presented. Finally, the ignition delay will be discussed for the different fuels.

The injection line pressure and start of fuel injection are affected by changes in fuel properties, such as the compressibility and speed of sound. The start of injection will also change due to fuel-induced changes in the fuel injection pump. Rotary fuel injection pumps of the type used on this engine typically have a fixed end of injection timing. When additional quantities of fuel are injected, the timing for the start of injection occurs earlier (Heisler, 1995). Since it was necessary to inject 13% to 14% more biodiesel to provide the same torque as with diesel fuel, the injection timing was advanced between one and two degrees. Although not tested here, in-line injection pumps may also have their timing affected by load, depending on the plunger helix design.

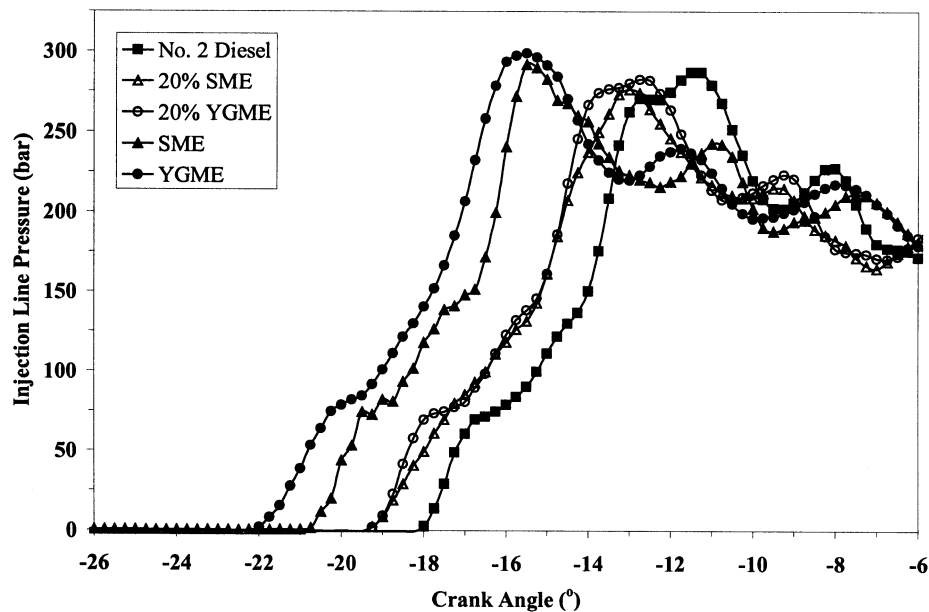
The measured start of fuel injection for each fuel is shown in table 6. For the neat methyl esters, the start of fuel injection timings were earlier than for the No. 2 diesel fuel. The SME and YGME fuels injected about 2.68° and 3.55° earlier than No. 2 diesel fuel, respectively. The start of fuel injection is usually taken as the time when the injector needle lifts off its seat. Since a needle lift sensor was not available for this study, the timing at which the fuel injection line pressure reached

the injector nozzle opening pressure (20.7 MPa) was taken as the start of injection.

Figure 6 shows the injection line pressures for the fuels. Each fuel has a different injection line pressure since the fuels' physical properties were different and different quantities of fuel were injected. The timing advance with the biodiesel fuels is clearly visible.

For this study, the start of combustion was defined as the point at which the first change in slope occurred in the heat release rate. The heat release rates for the different fuels were calculated from the measured cylinder pressure data using the method developed by Krieger and Borman (1966). The start of combustion timings for the fuels are listed in table 6. The start of combustion is the cumulative effect of differences in the start of injection and changes in the ignition delay period. For the neat methyl esters, the start of combustion timings were earlier than for the No. 2 diesel fuel, and this is confirmed by the heat release rate profiles shown in figure 7. The SME and YGME fuels started to burn about 3.4° and 4.2° earlier than No. 2 diesel fuel, respectively. The low-level oscillations in the heat release curves are caused by acoustic resonances in the combustion chamber and do not reflect actual combustion variations.

The ignition delay in a diesel engine is defined as the time between the start of fuel injection and the start of combustion. The physical and chemical properties of the fuels will affect the ignition delay period, and researchers have stressed that chemical properties are much more important than physical properties (Heywood, 1988; Andree and Pachernegg, 1969; Galvincevski et al., 1984). The ignition quality of a fuel is usually characterized by its cetane number. Higher cetane number generally means shorter ignition delay. The cetane numbers of the tested fuels are listed in table 2. The cetane numbers for No. 2 diesel fuel, SME, and YGME were 42.6, 51.5, and 62.6, respectively. The difference between the SME and YGME was expected because, as both Freedman and Bagby (1990) and Van Gerpen (1996) have pointed out,

**Figure 6. Injection line pressures of the fuels.**

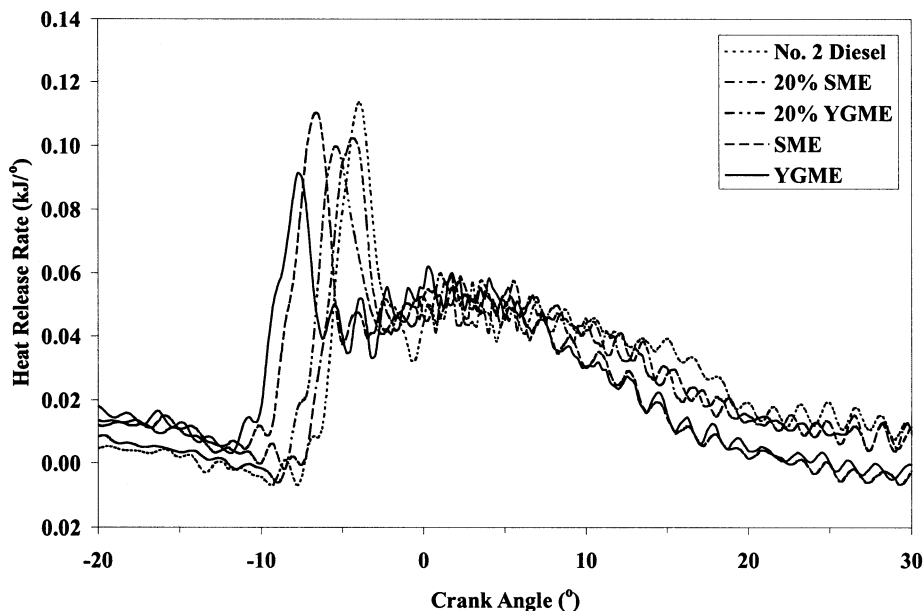


Figure 7. Heat release rate profiles of the fuels.

saturated esters have higher cetane numbers than unsaturated esters, and the YGME is more saturated than the SME.

Table 6 lists the ignition delay data for the fuels. For the neat methyl esters, the ignition delays were shorter than for the No. 2 diesel fuel. The SME and YGME had about  $0.75^\circ$  and  $0.63^\circ$  shorter ignition delays than No. 2 diesel fuel, respectively. Although the cetane number of the YGME was almost 10 points higher than that of the SME, the effect on the ignition delay was not significant. However, the difference between the ignition delay for the two biodiesels and No. 2 diesel fuel was significant. Monyem (1998) also found  $0.6^\circ$  shorter ignition delay when fueling the engine with soybean oil methyl ester compared with No. 2 diesel fuel.

## CONCLUSIONS

The objective of this study was to compare the performance and emissions of a diesel engine fueled with biodiesel from a high-FFA feedstock with biodiesel from soybean oil and with No. 2 diesel fuel. The following conclusions can be drawn from the results of this study:

- Both of the methyl esters and their blends gave nearly identical thermal efficiencies with No. 2 diesel fuel. The BSFCs for the esters were higher than for diesel fuel. The increases in the BSFCs were 13.5% and 14.2% for the neat SME and YGME, respectively. The higher BSFCs for the neat esters may be attributed to their lower heating values. The heating values of the methyl esters are about 12% less than for No. 2 diesel fuel.
- The neat SME and YGME produced statistically significant reductions in the CO, HC, and smoke emissions compared with No. 2 diesel fuel. However, in none of the cases studied were there statistically significant differences between the emissions of SME and YGME.
- The neat methyl esters had higher  $\text{NO}_x$  emissions than the No. 2 diesel fuel. The increase in  $\text{NO}_x$  was 13.1% with SME and 11.6% with YGME.

- The start of fuel injection for the SME and YGME fuels occurred  $2.7^\circ$  and  $3.6^\circ$  earlier than No. 2 diesel fuel, respectively. This was probably due to a combination of the different physical properties of the fuels and fuel quantity-related changes in the injection pump timing. The ignition delay periods for the neat methyl esters were shorter than for No. 2 diesel fuel. The combination of earlier injection timing and shorter ignition delay caused the SME and YGME fuels to ignite about  $3.41^\circ$  and  $4.16^\circ$  earlier than No. 2 diesel fuel, respectively.

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