# FUELING DIESEL ENGINES WITH BLENDS OF METHYL ESTER SOYBEAN OIL AND DIESEL FUEL

The authors are Leon G. Schumacher, Assistant Professor, Steven C. Borgelt, Assistant Professor, William G. Hires, Associate Professor, Agricultural Engineering Department, University of Missouri, Columbia, MO 65211; Dwayne Fosseen, President, Fosseen Manufacturing and Development, Radcliff, IA, 50230; and Wendel Goetz, Heavy Duty Engine Testing, ORTECH International, Toronto, Ontario, Canada L5K 1B3.

## ABSTRACT

A 6V92TA Detroit Diesel Corporation diesel engine was fueled on blends of 10, 20, 30, and 40 percent soydiesel/diesel fuel. The engine was tested in an Environmental Protection Agency (EPA) certification test cell. This cell was capable of operating the EPA heavy-duty engine test cycle. A 2000 cfm DPF-CVS dilution tunnel, gaseous bench and particulate bench provided full gaseous and particulate emissions data.

## KEYWORDS

Biodiesel, soydiesel, emissions testing, fuel economy, performance, and exhaust opacity.

## INTRODUCTION

The Clean Air Act of 1990 requires more stringent engine exhaust emission levels in the United States. Of great concern are the particulate matter (PM) emissions. Research conducted during the last 15 years has indicated that vegetable oil derived fuel can be used in a diesel engine to reduce some engine exhaust emission components such as unburned fuel, or total hydrocarbons (THC), carbon monoxide (CO) and PM. Biodiesel, which is esterified vegetable oil, displays properties similar to diesel fuel. However, unlike petroleum diesel, biodiesel contains oxygen, which contributes to lower levels of PM emissions.

Biodiesel's ability to reduce emissions has been recognized by the National SoyDiesel Development Board (NSDB), who has established a program to introduce biodiesel as an alternative fuel. The NSDB realized that economic factors, (market price of biodiesel is 2-3 times that of low sulfur diesel fuel) necessitate the use of blends of biodiesel and low sulfur diesel. The use of 10/90 to 50/50 biodiesel/diesel fuel blends rather than 100% biodiesel reduced fuel costs by 30 to 54 percent (Schumacher et al., 1993). Engine testing with biodiesel/diesel fuel blends revealed reductions in exhaust emissions. This testing also suggested that few changes would be needed in the fuel system when fueling with blends of biodiesel (Schumacher et al., 1992). These factors prompted researchers to determine the engine exhaust emissions trends that could be expected when fueling with biodiesel/soydiesel blends.

## REVIEW OF LITERATURE

Ziejewski et al., (1984), Reece et al., (1993), Scholl et al., (1993), and Schumacher et al., (1992, 1993) reported reductions in smoke density when fueling with soydiesel or biodiesel as compared to #2 diesel. Reece et al., (1993) also noted reductions in smoke density when fueling with a 20% biodiesel/80% #2 diesel blend. Ziejewski fueled with sunflower derived biodiesel and Reece fueled with rapeseed derived biodiesel. Scholl and Schumacher used soybean derived biodiesel. Srinivasa et al., (1991), however, noted increases in smoke density when fueling with karanja based biodiesel.

Marshall (1993), Schumacher et al., (1992), Mittelbach et al., (1985), Mittelbach et al., (1988), and Scholl and Sorenson (1993) noted reductions in hydrocarbons and carbon monoxide. Schumacher and Scholl and Sorenson fueled with soybean derived biodiesel. Mittelbach fueled with rapeseed derived biodiesel in 1985, but used waste cooking oil during the 1988 investigation. Marshall used animal derived fats as his source of biodiesel. Niehaus (1985), however, noted increases in carbon monoxide and hydrocarbon exhaust emissions. Niehaus also noted decreases in oxides of nitrogen exhaust emissions.

Ziejewski et al., (1984), Niehaus et al., (1985), Schumacher et al., (1992), Reece and Peterson (1993), and Marshall (1993) observed reductions in power ranging from one to seven percent. Schumacher observed increased power (three percent) using a 1991 Cummins 5.9L DI turbocharged engine. Increased power was observed by Feldman and Peterson (1992) during a 200 hour EMA test using a 3 cylinder, DI, naturally aspirated diesel engine with the injection timing advanced two degrees.

These findings suggest that trends in engine exhaust emissions exist. Data reviewed usually compared 100 percent biodiesel with 100 percent diesel fuel. Data pertaining to fueling diesel engines with biodiesel/diesel fuel blends was deficient in the literature. Gathering this data became the central focus of this investigation.

## PURPOSE AND OBJECTIVES

The purpose of this investigation was to determine the effects of fueling a diesel engine with biodiesel/diesel fuel blends. The blends investigated were 100% diesel fuel (#1 & #2), 10% biodiesel/90% diesel, 20% biodiesel/80% diesel, 30% biodiesel/70% diesel, and 40% biodiesel/60% diesel. Specific objectives of this investigation were:

(1) To determine and compare engine power when fueled with diesel and biodiesel/diesel fuel blends.

(2) To determine engine exhaust particulate matter when fueled with diesel and biodiesel/diesel fuel blends.

(3) To determine gaseous engine exhaust emissions associated with the fueling of diesel and biodiesel/diesel fuel blends.

(4) To determine the effects of adjusting timing on oxides of nitrogen emissions when fueling with biodiesel/diesel fuel blends.

(5) To determine the exhaust emissions when the engine exhaust system is equipped with a platinum based catalytic converter while the engine is fueled with biodiesel and diesel fuel blends.

## METHODOLOGY

### Gaseous Emission Analytical Techniques

All tests were conducted in an Environmental Protection Agency (EPA) certification test cell. This cell is capable of operating the EPA heavy-duty engine test cycle. A 2000 cfm DPF-CVS dilution tunnel, gaseous bench and particulate bench provided full gaseous and particulate emissions data.

#### Dilution Tunnel

All gaseous emissions were sampled from a 25.4 cm inside diameter primary dilution tunnel. All tunnel components were fabricated from stainless steel. The engine exhaust was directed from the engine through a 13 cm transfer tube, where it enters the tunnel through a 10.2 cm nozzle facing downstream. Dilution air flowed past the nozzle and mixed with the engine exhaust. Three sample probes located approximately 2.5 meters downstream of the exhaust inlet allowed the extraction of sample gas for analysis.

#### Air Mover

The primary tunnel gas flow was maintained at 51.0 normal cubic meters per minute. A rootes type, high capacity positive displacement blower, driven by a 22 kW electric motor, was used to maintain air flow. Excessive noise, typical of these blowers, was lowered using a Donaldson muffler.

#### Gas Analysis

The gas analysis system was composed of three extractive systems; a Total Hydrocarbon Console, a Main Console, and a Background Hydrocarbon System.

Total hydrocarbons were measured using a Beckman Mode 402 heated analyzer equipped with a Flame Ionization Detector (FID). Sampling was accomplished by probes in the dilution tunnel. The sample was transferred via heated teflon sample lines to the total hydrocarbon console. The main sample filters which protect the gas analyzers from particulate matter were located in a heated compartment (190o C). A heated sample pump extracted the sample from the dilution tunnel and delivered it to the hydrocarbon analyzer.

The main console housed the Carbon Dioxide ($CO_2$), Carbon Monoxide(CO) and heated Oxides of Nitrogen (NO/NOx) analyzers. The sample was extracted from the dilution tunnel, filtered in the total hydrocarbon console and transported to the main console through heated teflon lines. The sample was then apportioned in the main console. Part of the hot sample gas was analyzed by the NO/NOx analyzers; the balance was cooled and dried by a condensation dryer. The cooled sample was then analyzed by the $CO_2$ and CO analyzers.

The following analyzers were used:

* NO/NOx Beckman Model 955 heated chemiluminescent analyzer.

* CO Beckman Model 867 non-dispersive infra-red.

* $CO_2$ Beckman Model 864 non-dispersive infra-red.

* THC Ratfisch Model RS55, heated FID

All gas analyzers and related emissions equipment were calibrated using standard procedures. This included instrument calibration prior to the start and frequently throughout the testing day. Matheson Gas Products "Primary Standard" gases were used for calibration (+/- 1% accuracy).

Engine

A DDC 6V-92TA coach engine was provided by Fosseen Manufacturing and Development (FMD) for the project. This 1991 engine model meets the 1991 EPA Heavy-Duty Diesel Engine Emission Standards. Engine specifications are listed below:

Table 1: Engine Specifications

| | |
|---|---|
| Model: | 6V-92TA DDEC 11 Coach |
| Unit (Serial Number): | 06VF187152 |
| Engine Family: | MDDO552FZL1 |
| Rated: | 277 hp @ 2100 rpm (using D-1 fuel) |
| Peak Torque: | 880 ft.lb @ 1200 rpm |
| Maximum No-Load rpm: | 2225 rpm |
| Min. Idle: | 600 rpm |
| Max. Allowable Backpressure: | 3.0 in. HgT |

Fuel

The soydiesel was analyzed by Cleveland Technical Center, North Kansas City, Missouri. Typical elemental and physical analysis information can be found in Table 2. The density of the soydiesel was .884 kg/l at 21oC (70oF). The diesel test fuel used during the project was either low sulfur #2 diesel fuel, density = .832 kg/l at 21oC (70oF), or Esso Diesel #l, density = .816 kg/l at 21oC (70oF).

The density of the fuel was used to mix the biodiesel/diesel blends (at 21oC (70oF)) on a volume basis. A clean, empty, 55 gallon barrel was placed on a scale and the scale was zeroed. Biodiesel was poured in to obtain the required weight. Diesel fuel was added to achieve the total mass desired. The engine was fueled directly from each barrel as needed.

<u>Catalyst</u>

The catalytic converter used for the testing was made available by AC Rochester. It is an oxidation catalyst using platinum as the catalyst.

Table 2: Elemental and physical characteristics of Soydiesel.*

| Soydiesel Characteristic | Value Reported |
|---|---|
| Specific gravity API | 28.5 |
| Viscosity @ 40 C | 4.06 |
| Cloud point | -1o C (30o F) |
| Pour point | -7o C (20o F) |
| Cold filter plugging point | -4o C (24o F) |
| Heat of combustion | 39,465 kJ/kg (17,650 BTU/lb) |
| Flashpoint | 179o C (355o F) |
| Cetane | 45.8 |
| Carbon | 76.50% |
| Hydrogen | 12.50% |
| Oxygen | 11.00% |
| Sulfur | .01% |
| Water | NIL |
| Sediment | NIL |

| | |
|---|---|
| Ash | .01% |

*Note: The soydiesel was analyzed by Cleveland Technical Center, North Kansas City, Missouri.

Testing Procedures

Phase I

The engine was instrumented and engine exhaust emissions testing equipment were calibrated. Engine performance was checked at peak power and peak torque to ensure proper operation. The two-point check was performed throughout the project to maintain a record of engine performance.

EPA procedures (CFR 40, Part 85) were followed to generate an autotorque map (computer generated torque curve at 8 rpm/sec). This information was used to generate data to develop the baseline neat diesel heavy-duty transient cycle. Trial transient cycles were run to optimize dyno-engine control coefficients. Regression analyses was then performed and the results compared to the EPA's test cycle validation criteria. This process statistically compares (in tenths of seconds) how the actual engine speed and torque compare to the requested or reference speed and torque. All criteria were met on neat diesel. Formal baseline emission tests of CO2, CO, NOx, THC and PM were conducted.

The pre-mixed drum of blended fuel was connected to the fuel supply system of the engine. The engine was idled while the return fuel line from the engine drained. The fuel system was purged before the return fuel was redirected to the recirculation tank. Purged fuel was placed in a waste fuel tank.

The engine was operated at 1200 and 2100 rpm at 50% and 100% load for ten minutes. A two point power check was run. The engine was accelerated to rated power (2100 rpm full throttle) and held there until engine oil temperature stabilized (230 to 240oF). Exhaust backpressure was checked and then three logs of measured engine parameters were recorded. The engine was then decelerated to peak torque speed (1200 rpm full throttle). Engine exhaust backpressure and three measures of engine operating parameters were recorded.

One cold start transient test and four hot start transient tests were completed each day. Each set of data was analyzed statistically with regression analysis, and between each test, a 20 minute soak time was allowed. Catalyst testing was performed with the exhaust backpressure (before the catalyst) set to 40 inches of water (3.0 inches Hg) at 2100 rpm/100% load.

Phase II

The same engine and set-up used in the previous program was retained.

The Electronic Control Module (ECM) or DDEC 11 was programmed to shift the beginning of injection (BOI). Detroit Diesel corporation provided two reprogrammed ECM's for testing. In addition, ORTECH, through a previous program, had access to a DDEC monitor that allowed shifting of the complete timing schedule at one-half degree steps. The changes made to the ECM's by DDC, in combination with a shift in the complete schedule, achieved the desired NOx reduction.

## RESULTS

Regression analysis was conducted for each transient cycle to determine if the test was within limits set by the EPA. All tests met the EPA test cycle validation criteria. The weighted averages used to calculate the exhaust emissions values were conducted using the following formula:

Weighted Average = ((1/7 x cold test) + 6/7 x average of 4 hot tests).

The averaged test results are summarized in Table 3. This table describes the test description, in terms of fuel blend used and the work done by the engine over the transient cycle (horsepower-hour). Particulate matter (PM) is expressed as total and soluble particulates. Brake specific fuel consumption, carbon monoxide (CO), carbon dioxide (CO2), oxides of nitrogen (NOx) and total hydrocarbon (THC) are expressed as required by EPA.

Table 3. Biodiesel emissions data for a 6V92 TA Detroit Diesel Engine fueled with blends of biodiesel and diesel fuel.

| Diesel Blend Agent | Biodiesel Percent | Work Hp-hr | Grams/brakehorsepower-hour | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | BSFC | PM | CO2 | CO | NOx | THC |
| **Phase 1** | | | | | | | | |
| #1 | 0 | 18.94 | .49 | .197 | 654 | 1.51 | 4.23 | .72 |
| #1 | 10 | 18.92 | .49 | .186 | 657 | 1.43 | 4.38 | .63 |
| #1 | 20 | 18.85 | .50 | .175 | 657 | 1.32 | 4.46 | .56 |
| #1 | 30 | 19.03 | .50 | .173 | 685 | 1.14 | 4.80 | .54 |
| #1 | 40 | 19.05 | .50 | .162 | 684 | 1.07 | 4.86 | .43 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Phase II** | | | | | | | | |
| #1 | 0 | 19.11 | | .199 | 686 | 1.29 | 4.42 | .70 |
| #2 | 0 | 20.88 | | .276 | 667 | 1.67 | 4.40 | .42 |
| #2 LSD | 0 | 20.92 | | .261 | 664 | 1.67 | 4.46 | .45 |
| #2 LSD | 20a | 20.72 | | .216 | 676 | 1.50 | 4.25 | .38 |
| #2 LSD | 20b | 20.76 | | .191 | 671 | .45 | 4.32 | .12 |

a. w/ Modified Electronic Control Module (ECM) & 3 degree timing adjustment

b. w/ Platinum catalyst, modified ECM & 3 degree timing adjustment

## DISCUSSION - Phase I

Engine Performance

The following observations were based on the data collected during this investigation:

a. Peak torque was not affected by the addition of up to 40% biodiesel; however, a slight drop at rated speed was noticed at the 40% level.

b. A steady drop in exhaust gas temperature was observed for both the rated and peak torque condition, indicating a shift in the peak pressure point toward top dead center, resulting from an increasingly shorter ignition delay. The lower exhaust gas temperature was a result of increased heat transfer into the coolant.

c. The reduced ignition delay and increased peak pressure and temperature contributed to the increased oxides of nitrogen. This was most pronounced at peak torque, which generated the highest peak pressures and temperatures.

d. Fuel consumption on a mass basis was very similar for all blends tested.

Emissions

Emissions results follow trends established by previous research. Increased levels of biodiesel increase NOx while reducing PM. Proportionally, PM reduction was slightly more than the increase in NOx, on a percentage basis. The decrease in PM was contributed to the oxygen in the fuel. The reduction in CO and THC was linear with the addition of biodiesel for the blends tested. These reductions indicate more complete combustion of the fuel. The presence of oxygen in the fuel was thought to promote complete combustion.

The BSFC and $CO_2$ did not change appreciably, and fuel consumption increased only minimally over the test cycle.

Fueling with biodiesel reduced PM emissions. This reduction applied primarily to the solid or carbon fraction which cannot be removed by an oxidation catalyst. A particulate trap is normally required to remove the solid component from the exhaust. The soyate induced reduction in solid PM provides an opportunity to further decrease PM using an oxidation catalyst which can oxidize the soluble fraction stemming from engine lubricant.

The 20% blend represented a good compromise between increased NOx and reduction of all other emissions. This biodiesel/diesel fuel blend was recommended for testing during Phase II.

## DISCUSSION - Phase II

As indicated in Table 3, the switch to #2 diesel from #1 results in an increase in the total work done over the EPA transient cycle (19.11 versus 20.85 HP-hr).

The optimization of NOx required several steps. The following observations were made:

a. The changes made to the ECM's by DDC, in combination with a shift in the complete injection timing schedule, achieved the desired goal of NOx reduction.

b. A change in fuel from #1 to #2 diesel resulted in an increase in particulate matter; however, NOx did not seem to be affected.

c. The percent changes in emissions are reported in Table 4.

d. The desired reductions in NOx were achieved without sacrificing reductions of the other emissions.

e. The catalyst was effective in reducing CO, THC, and PM.

Table 4. Percent changes in emissions for a 6V92 TA DDC diesel engine that is fueled with a 20/80 biodiesel/diesel fuel blend.

| Baseline<br><br>Blend #2 Diesel | | 20/80 Blend, ECM2<br><br>-30 Shift in BOI | 20/80 Blend, ECM2<br><br>-30 Shift, Plat. Cat. |
|---|---|---|---|
| $CO_2$ | 100% | +1.8% | +1.0 |
| CO | 100 | -9.8 | -72.8 |

| | | | |
|---|---|---|---|
| NOx | 100 | -4.6 | -3.1 |
| THC | 100 | -14.5 | -73.2 |
| PM | 100 | -17.2 | -26.8 |

## CONCLUSIONS

Fueling with biodiesel/diesel fuel blends effectively reduced particulate matter, unburned hydrocarbons, and carbon monoxide while increasing oxides of nitrogen emissions. The optimum blend of biodiesel and diesel fuel, based on the trade-off of PM decrease and NOx increase, was a 20/80 biodiesel/diesel fuel blend.

Increased NOx emissions can be reduced by retarding engine timing while subsequently maintaining emission reductions associated with fueling a diesel engine with a 20/80 biodiesel/diesel fuel blend. The retarded timing lengthened the ignition delay time. This reduced the peak pressure and temperature that enhance the formation of NOx emissions.

## RECOMMENDATIONS

The Environmental Protection agency has mandated that the level of oxides of nitrogen emissions be equal to or less than the emissions produced by the engine if fueled on reference diesel fuel. Economic conditions concerning the use of biodiesel as a transportation fuel dictate that the fuel should be used as a blend in a diesel engine. As such the following recommendations were made:

1. Engine optimization strategies should be developed that fully take advantage of the physical and chemical makeup of biodiesel.

2. Additional tests should be conducted to evaluate other catalytic converters, and the durability of these devices should be documented over time.

## BIBLIOGRAPHY

Feldman, M. E. and Peterson, C. L. (1992). Fuel injector timing and pressure optimization on a DI diesel engine for operation on biodiesel. Liquid Fuels From Renewable Resources- Proceedings of an Alternative Energy Conference. Nashville, TN.

Marshall, W. F. (1993). Effects of methyl esters of tallow and grease on exhaust emissions and performance of a Cummins L10 engine. Itt Research Institute, National Institute for Petroleum and Energy Research, Bartlesville, OK. (Report prepared for Fats and Proteins Research Foundation, Inc, Ft. Myers, Beach, FL)

Mittelbach, M. P., Tritthart, P, and Junek, H. (1985). Diesel fuel derived from vegetable oils, II: emission tests using rape oil methyl ester. Energy Agriculture. 4: 208-215.

Mittelbach, M. P., Tritthart, P. (1988). Diesel fuel derived from vegetable oils, III. Emissions tests using methyl esters of use frying oil. Journal of the American Oil Chemists' Society. 65(7): 1185-1187.

Niehaus, R. A., Goering, C. E. Savage, L. D., and Sorenson, S. C. (1985). Cracked soybean oil as a fuel for a diesel engine. ASAE Paper No. 85-1560. ASAE, St. Joseph, MI.

Reece, D. L. and Peterson, C. L. (1993). A report on the Idaho on-road vehicle test with RME and neat rapeseed oil as an alternative to diesel fuel. ASE Paper No. 93-5018. ASAE, St. Joseph, MI.

Scholl, K. w. and Sorenson, S. C. (1993). Combustion of a soybean oil methyl ester in a direct injection diesel engine. SAE paper NO. 930934. SAE, Warrendale, PA.

Schumacher, L. G, Hires, W. G, and Borgelt, S. C. (1992). Fueling a diesel engine with methyl-ester soybean oil. Liquid Fuels From Renewable Resources- Proceedings of an Alternative Energy Conference. Nashville, TN.

Schumacher, L. G., Borgelt, S. C., Hires, W. G. and Humphrey, J. K. (1993). Biodiesel on the road- A report from Missouri. ASAE paper No. 93-5017. ASAE, St. Joseph, MI.

Schumacher, L. G., Borgelt, S. C., and Hires, W. G. (1993). Soydiesel/Biodiesel Blend Research. ASAE paper No. 93-6523. ASAE, St. Joseph, MI.

Srinivasa, R. P. and Gopalakrishnan, K. V. (1991). Vegetable oils and their methylesters as fuels for diesel engines. Indian Journal of Technology. 29: 292-297.

Ziejewski, M., Kaufman, K. R., Schwab, A. W, and Pryde, E. H. (1984). Diesel engine evaluation of an nonionic sunflower oil-aqueous ethanol microemulsion. Journal of the American Oil Chemists Society. 61 (10): 1620-1626.