Center for Integrated Manufacturing Studies
ROCHESTER INSTITUTE OF TECHNOLOGY

Final Report

Biodiesel Research

Alternative Fuels & Life-Cycle Engineering Program

November 29, 2006 to November 28, 2011

Prepared for:

U.S. Department of Transportation
Award No. DT0S59-07-G-00049

December 20, 2011

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1. Abstract

This Biodiesel Research portion of the DOT Alternative Fuels Study covers three research areas: an RIT Vehicle Fleet Study; Component Wear Studies; and an Engine Durability Dynamometer Study. All three areas are complementary, and the results of the cumulative study should add to the current understanding of the effects of biodiesel in modern engines used in the transportation industry.

The RIT Fleet Study included the use of two medium-duty diesel vehicles used exclusively on the RIT campus. The two vehicles were used for different purposes, and the operating profiles were significantly different. Fuel economy, emissions and maintenance histories were compared with the engines operating on a range of fuel blends from ULSD to B90 over a four-year period (2007-2010). Fuel economy was monitored over the duration of the study and comparisons were made as to the efficiency of ULSD, B20, B20 with 30% kerosene and B90. Since B90 was only used in the warm summer months, the seasonal variation in fuel use overshadowed changes in fuel efficiency caused by the fuel blend. Since the impact of biodiesel use on CO emissions is well documented, more emphasis was placed on nitrogen emissions, specifically the combined NO and NO_2 species known as NO_x. In the idle test, one vehicle showed increased NO_x and the other showed reduced NO_x The general tendency with both vehicles during the driving test was that increased biodiesel fraction caused increased NO_x. However, vehicle condition and type of use appear to impact NO_x emissions more than fuel blend. Finally, there were no cold fuel problems when using B20 with kerosene (20% biodiesel, 50% ULSD and 30% kerosene) during the winter months in Western New York. Neither the vehicles nor the fueling station had any fuel-related problems over the study period.

Two component studies were performed. One investigated the lubricating properties and oxidation propensity of engine lubricating oil when diluted with biodiesel fuel. The other investigated the changes in lubricating properties of ULSD when mixed with biodiesel. Using a reciprocating wear tester, the first study found that a small amount of biodiesel (2%) in lubricating oil improved the lubricity of the oil. Up to 10% biodiesel dilution continued to improve lubricity. When heated to 300°F during testing, no oxidation was detectable. The second study used a standardized high speed wear tester to compare wear characteristics of parts lubricated in ULSD with various quantities of biodiesel added. In all cases, increased biodiesel quantity reduced wear on the test specimens.

The Engine Dynamometer Testing was run in three parts: a Gage R&R Study, a Fuel Screening Study, and a Durability Study. The Gage R&R Study was performed to document variation in RIT's new engine dynamometer lab and the test engines. Results from that study are summarized in this report. The Fuel Screening Study looked initially at the effect of five fuel blends on exhaust emissions, performance and efficiency. As the biodiesel ratio increased, NO by increased (+4.5%), but the smaller quantity and highly toxic NO_2 decreased (-6%). So too, CO (-17%) and Soot (-81%) decreased with increased biodiesel blends. Fuel*torque and fuel*speed interactions were found significant to CO production as well. With the exception of soot, operating conditions affected the emissions more than the fuel blend. On the dynamometer, for a particular operating condition, efficiency decreased by approximately 6% as the blend increased to B90. Maximum available torque decreased by 8.5% and peak engine power by 17%. The Durability Study focused primarily

on wear and maintenance items but looked at emissions, performance and efficiency with greater resolution. Two identical 6.5L Cummins ISC engines were run on different fuels for 1500 hours each. ULSD and B100 were used as the test fuels. Periodic tear-downs allowed inspection of all typical wear parts to document the aging process. Statistically, no fuel effects on wear items (differences between engines) could be confirmed. Fuel filter problems were persistent throughout all of the B100 operation and completely absent during ULSD testing. Similar results were seen for performance, efficiency and exhaust products as found in the Fuel Screening Study.

2. Introduction

The transportation-related biofuels market is currently dominated by ethanol and biodiesel. Our research has explored both areas in some depth. This report will present the findings of our work with various blends of biodiesel as used in conventional compression-ignition diesel engines.

The market for biodiesel has expanded significantly in the last 10 years. Initially, engine manufacturers and OEMs were cautious about the new fuel, uncertain of the impact on the engine and related warranties. During the time period of our research, however, engine manufacturers have raised the allowable warranty coverage for engines from B5 to as high as B20 in several cases (provided the fuel meets the ASTM D6751 standard).[1] This expansion represents a significant expression of public confidence in the use of biodiesel.

Biodiesel itself is a vehicle fuel produced specifically for use in compression-ignition (CI) engines. Biodiesel is typically produced by the reaction of a vegetable oil or animal fat with an alcohol such as methanol or ethanol in the presence of a catalyst to yield mono-alkyl esters (biodiesel) and glycerin. This reaction is called transesterification. Raw or refined vegetable oil or recycled greases that have not been processed into biodiesel are not biodiesel. Once the biodiesel fuel is produced, it must be separated from the glycerin, catalysts, soaps and any excess alcohol that may remain.[2] These by-products also have value as commodities on their own.

For the fuel to be sold on the commercial market as biodiesel, it must meet the requirements of the ASTM D6751 specification.[3] This specification requires that the product undergo chemical analysis for flash point, methanol, water and sediment, kinematic viscosity, sulfated ash, oxidation stability, sulfur, copper strip corrosion, cetane number, cloud point, acid number, carbon residue, total and free glycerin, phosphorus, reduced pressure distillation temperature, atmospheric equivalent temperature, combined calcium and magnesium, and combined sodium and magnesium. This certification of the fuel is key to ensuring the integrity and consistency of the product and to avoid any adverse effects on the engines. Once the biodiesel fuel is produced, it is commonly blended with petroleum diesel, now known as “Ultra Low Sulfur Diesel” (ULSD) and dispensed to the public by tanker truck or service stations. Common biodiesel blends for winter use are B5, with up to B20 being used in summer or warm weather regions.

Unlike ethanol, which, once produced, has the same chemical properties regardless of the feedstock, biodiesel itself does exhibit different properties depending on the source of the oil used to produce it. The most widely used U.S. feedstock is soybeans, due to its acceptable low temperature properties. However, other oils such as canola, palm and rapeseed are possibilities. In addition, waste grease from food preparation is also usable as a feedstock. The feedstock selection is made by the biodiesel producer, typically using cost as the main selection factor.

One of the main advantages of biodiesel is that it can be used in any compression ignition engine which will accept regular diesel or ULSD without modifications. This allows the biodiesel blends to be sold and used anywhere that currently offers petroleum-based product.

3. Research Areas

At the inception of our program, we performed a literature search to survey the state of the industry and implementation issues with biodiesel. Our initial research led us to focus on the following areas:

- Fuel quality
- Low-temperature properties
- Lubricity
- Water absorption

To gather data on these issues, we embarked on a multi-phase program of investigations. The first phase was deployment of a biodiesel fueling station on the RIT campus. This consisted of an above ground storage tank and dispensing system. This fueling station would be used to service two diesel vehicles on campus with varying blends of biodiesel. The two vehicles were a Ford E350 passenger (shuttle) van and a Chevrolet pickup truck. The second phase of the program was a comprehensive test of two Cummins medium-duty truck engines in the CIMS dynamometer facility on a range of biodiesel blends. The third phase was component studies to determine the impact of biodiesel on engine materials. This took the form of lubricity studies on various fuel blends and wear testing on engine cylinder materials.

4. Research Findings

a. Biodiesel RIT Fleet Study

As part of this DOT project, RIT purchased two new diesel vehicles for the purpose of evaluating biodiesel fuel mixtures. A fueling station was also installed to provide on-site fueling capabilities for the custom biodiesel blends. The diesel vehicles were a passenger van and a pickup truck. The fueling station and the vehicles were deliberately kept outside to evaluate the effects of climate extremes on the fueling station and vehicle performance. Table 1 provides make, model, and engine details for each vehicle. Each vehicle has very different function on the RIT campus. The Chevy Silverado pickup serves as a facilities supervisor’s truck in the summer months and as a plow truck in the winter months. The Ford E350 Econoline Van serves as a shuttle service van all year. It typically operated on a continuous low speed circuit around the RIT campus, a distance of roughly three miles. The van also spent extended periods of time idling – while waiting for or discharging passengers, and in the winter to maintain the cabin warmth and in the summer for air conditioning.

	2007 Chevy Silverado 2500HD	2007 Ford E350 Econoline Van
Engine type	6.6L V8 Duramax Turbo-Diesel	6L Power Stroke Turbodiesel V8
Compression Ratio	16.8:1	17.5:1
Fuel Injection	Common Rail, DI @ 26,000 psi	Electronic Fuel Injection
Transmission	Automatic	Automatic
EGR (Exhaust Gas Recirculation)	Yes	Yes*
Catalytic Converter	Yes	Yes

* The EGR valve for this engine model tended to have carbon buildup problems.

Table 1: RIT Diesel Vehicle Details

Above: Chevrolet Diesel Pickup and Ford F350 Diesel Van

The main objectives for the RIT diesel fleet were:

- Collect data on exhaust emissions for various biodiesel blends (B20 summer, B20 winter blend, B90 summer)
- Monitor vehicle problems including poor starting, leaks, no-starts, fuel filter plugging
- Collect fuel efficiency data for various biodiesel blends (B20 summer, B20 winter blend, B90 summer)
- Monitor fueling station problems including filter plugging, biological growth
- Push the biodiesel blends to high levels during the summer months (B90)
- Compare the effects of biodiesel blends on two very different engine types

The use of only two vehicles means that there is no statistical information that could be obtained from observing large numbers of similar vehicles. The intent was to make close observations of each vehicle and therefore have relatively detailed information on a small sample.

Emissions tests were performed with a commercial *Snap-On Tools* 5 Gas analyzer. This unit takes readings of HC (unburned hydrocarbons), CO (carbon monoxide), CO^2 (carbon dioxide), NOx (nitrous and nitric oxides), and O^2 (oxygen levels). The unit makes conversions to grams/mile from parts per million (ppm) but is not considered to be an accurate conversion and therefore was not reported.

Two different emissions tests were performed. One was a standard low- and high-idle test (normal engine idle for 30 seconds, 2500 rpm for 30 seconds, both with a warm engine). The second test was an on-road test which made use of a loop around the RIT campus. The worst exhaust emissions for any diesel vehicle is during engine transitions, so the road test emissions show the worst case for each engine. The loop included multiple stops, a steady speed period, and a hill which allowed for the collection of real-life readings of each engine during multiple acceleration-deceleration cycles. The loop is three miles and is essentially flat except for the one hill. The loop is shown in Figure 1.

Figure 1: Driving route for on-road emissions testing, RIT campus

Year One (2007)

The initial fuel used was standard ULSD (ultra low sulfur diesel). The project started in the summer so there was no winter blending involved. Emission testing was performed at this point to develop an emission baseline. Immediately after baseline testing the vehicles were switched to B20 and retested for emissions. Operators of the vehicles and the maintenance staff were instructed on keeping careful logs of either operator issues with the vehicles or maintenance issues with the vehicles. Also, an automatic fueling log was generated at the fueling station.

In the fall, the fueling station was switched to B20 and 30% kerosene for the winter months. Again, the vehicles were tested for exhaust emissions with the winter blend.

Year Two (2008)

B20 was used throughout year two with the only changes being the switch to winter blend as the winter months approached.

Year Three (2009)

The summer blend used was B90 to push the vehicles to high biodiesel levels. There was the potential for seal deterioration by biodiesel or lubricating oil problems due to engine piston ring blowby with biodiesel (Peterson, C.L., Hammond, B. L., Reece, D. L., "Engine Performance and Emissions with Methyl and Ethyl Esters of Rapeseed Oil", in Liquid Fuels and Industrial Products from Renewable Resources: Proceedings of the Third Liquid Fuels Conference, American Society of Agricultural Engineers, 1996).

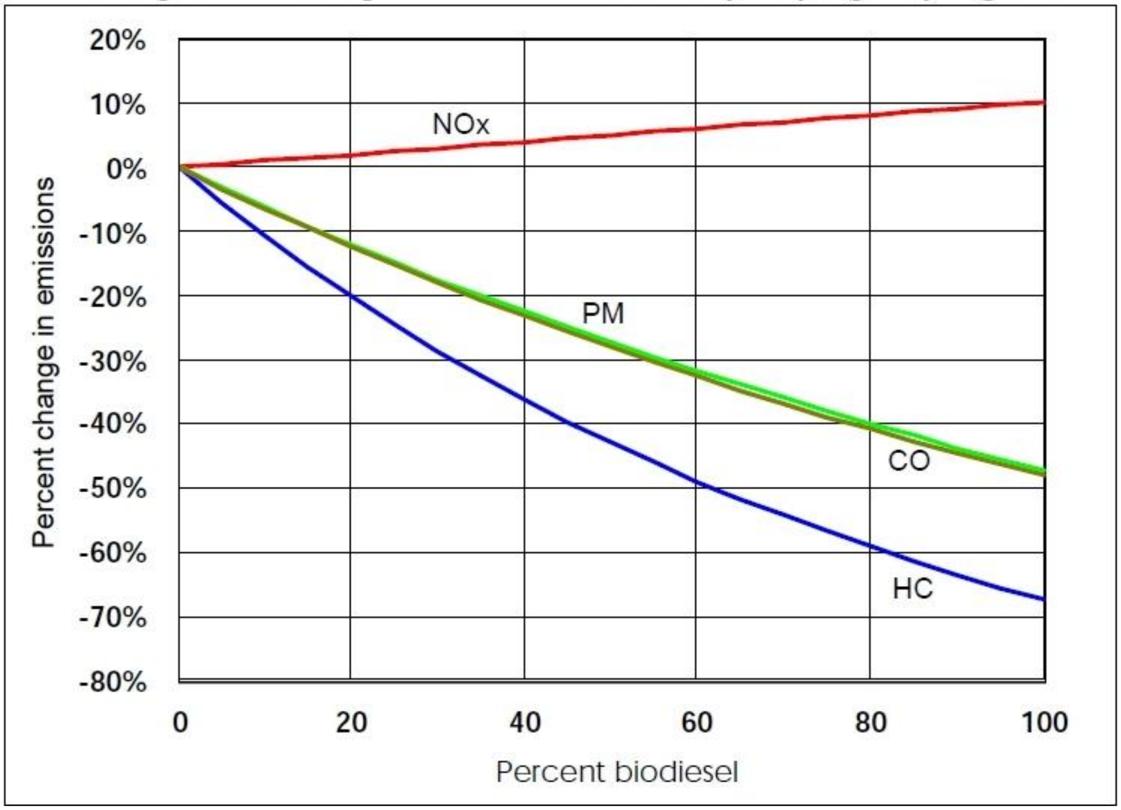
Year Four (2010)

Again B90 was used at the beginning of the summer months. At midsummer, the vehicles were switched back to full ULSD to develop a repeat baseline for emissions tests. This provided a means of evaluating the general changes in vehicle emissions with vehicle age without the confounding factor of biodiesel.

Emissions Test Results

The primary emission of interest for biodiesel testing is NOx (nitrous and nitric oxides). EPA summary information shows that a typical diesel engine produces a gradual reduction in HC, CO, and PM, with an increase in NOx as the percentage of biodiesel increases (Figure ES-A, from A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions, Draft Technical Report, EPA420-P-02-001, October 2002). This report also noted that all the vehicles were heavy duty highway trucks, none had EGR valves, and 98% were 1997 models or earlier. What can be said from this information and other reported NOx emissions is that the NOx emissions are the only ones with the possibility of increasing with increasing concentrations of biodiesel. All other emissions are expected to decrease rather dramatically with increasing biodiesel concentrations.

Figure ES-A
Average emission impacts of biodiesel for heavy-duty highway engines



A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions, Draft Technical Report, EPA420-P-02-001, October 2002).

Emissions tests at RIT consisted of an idle test and a driving test around a known route. Each vehicle was found to have a unique NOx emissions pattern probably related to the type of engine and the control technology associated with the EGR valves (Figure 2 and Figure 3).

The primary purpose of an EGR valve is to recirculate a portion the exhaust gases back into the incoming combustion air supply. The exhaust gases have reduced oxygen content therefore reducing the oxygen content of the combustion chamber. This results in reduced combustion temperatures. High combustion temperatures along with excess oxygen produce higher NOx, so the EGR causes lower combustion temperature and reduced oxygen resulting in less NOx. At lower combustion temperatures there is also likely to be higher particulate (PM) since combustion is less complete. In the RIT vehicle study, particulate could not be measured and therefore could not be verified.

EGR valves are turned on or off based on engine activity. An EGR valve will be closed (no recirculation) during normal idling and during high load. Normal idling uses very little fuel and the engine is running at lower temperatures than during operation, so NOx levels will be low naturally. During high loads the maximum fuel energy is required to achieve maximum power so the EGR valve is closed. During high idle and higher engine rpm's such as cruising speeds, the EGR valve should be open to force the engine combustion to run cooler due to less oxygen and more CO2. This will reduce the NOx levels since NOx formation requires high combustion temperatures and excess oxygen (Labeckas, Gvidonas, Slavinskas, Stasys, *The Effect of Rapeseed Oil Methyl Ester on Direct Injection Diesel Engine Performance and Exhaust Emissions*, Energy Conversion and Management, 47 (2006), pp 1954-1967). Since biodiesel contains more oxygen than ULSD, biodiesel will have a greater tendency to form NOx than ULSD.

The lack of EGR valves in the initial population of vehicles used for the EPA study allows both higher temperatures of combustion as well as allowing excess oxygen for the formation of NOx. Therefore, it is not surprising that the reported NOx levels increased with increasing biodiesel concentrations. A study by McCormick, et. al. did an extensive study on the NOx emissions of newer vehicles (EGR valves) which showed wide variation in NOx emissions when comparing engine types and engine operating conditions (McCormick, R. L., Williams, A., Ireland, J., Brimhall, M., Hayes, R. R., *Effects of Biodiesel Blends on Vehicle Emissions, Fiscal Year 2006 Annual Operating Plan Milestone 10.4*, Prepared under task No. FC06.9400, National Renewable Energy Laboratory, 1617 Cole Blvd., Golden, CO, 80401-3393, Oct. 2006). They found that NOx levels could become higher or lower with the addition of biodiesel to the fuel. So the NOx does not necessarily increase with biodiesel content as previously reported by the EPA study.

Both RIT vehicles have catalytic converters which will affect the CO and NOx tailpipe emissions readings. However, the NOx emissions still vary with the engine load as shown in Figures 2 and 3, idle test results, and Figure 4 driving tests for B90. Note that the truck NOx emissions typically went up slightly during the high idle phase of the idle test regardless of the fuel blend while the van's NOx levels went down dramatically during the high idle phase again regardless of the fuel blend. Also, there was no correlation between fuel blend and NOx levels in the idle test for either vehicle.

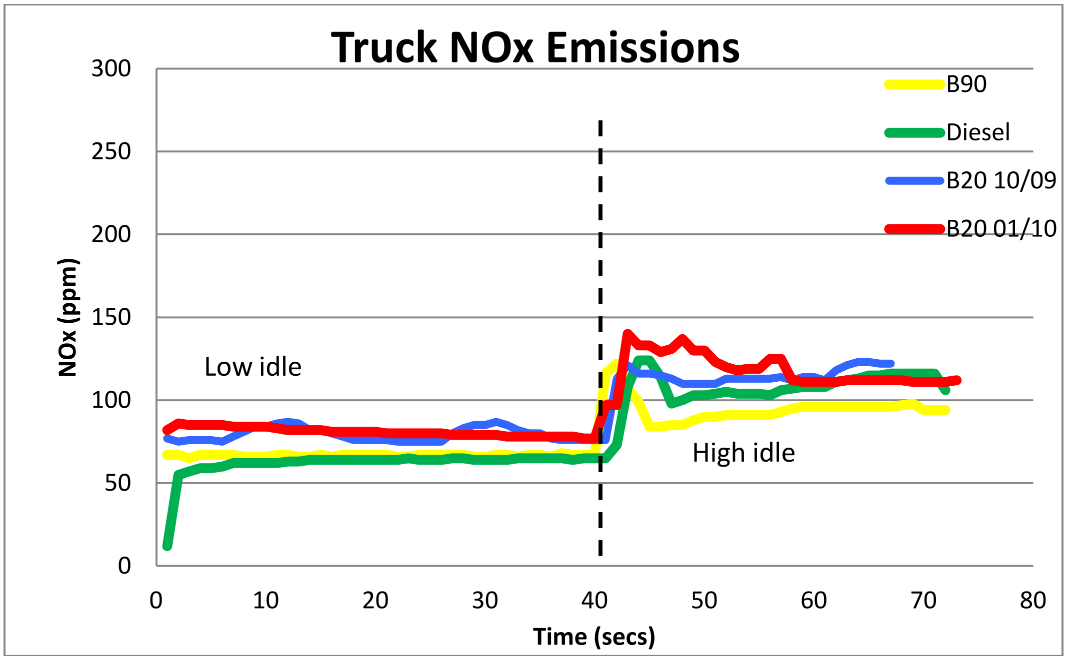


Figure 2 Truck Low-High Idle Tests

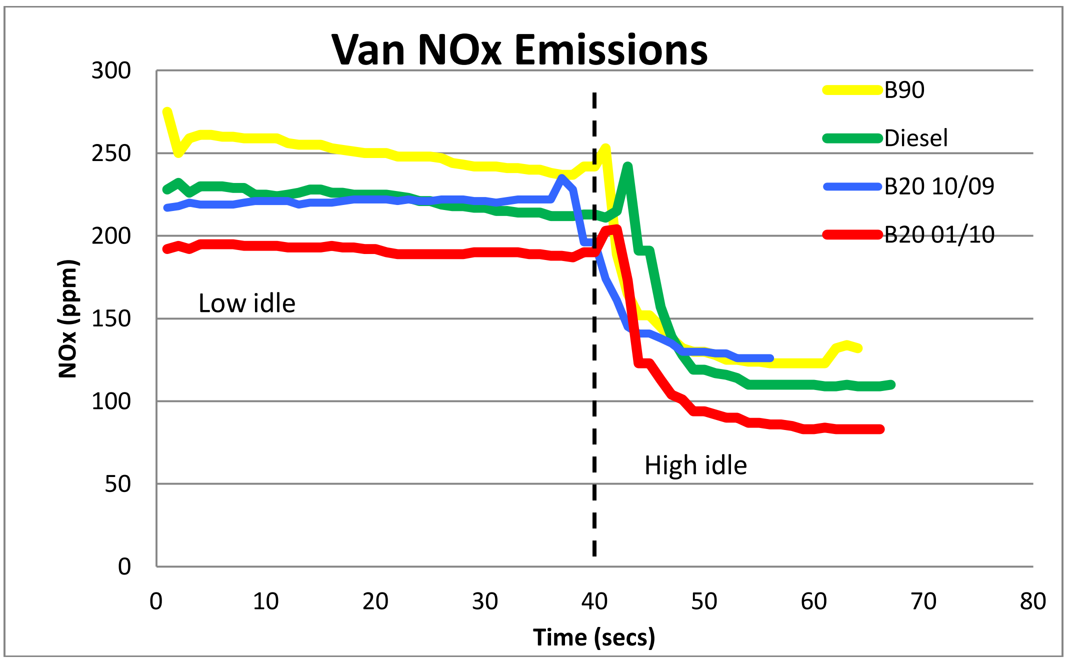


Figure 3 Van Low-High Idle Tests

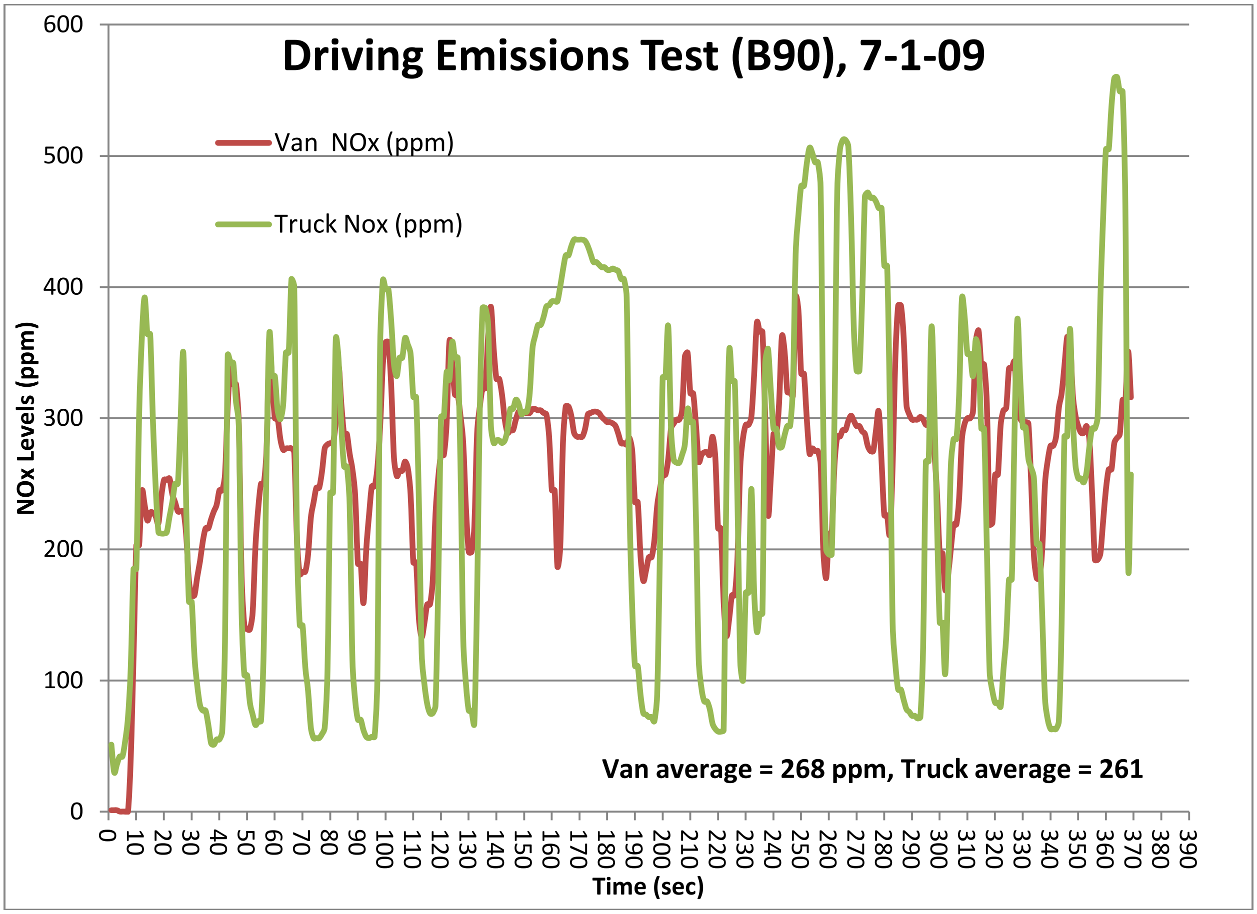


Figure 4: Truck and Van Driving Test B90

The driving test for the two vehicles shows two interesting results. The first result is that the driving results showed a different pattern from that of the idle test. It would be expected from the idle tests that the van would have overall higher NOx emissions in the drive test compared to the truck, since the van had much higher NOx readings than the truck in the idle test. However the overall average NOx emissions for this test showed essentially no difference (Van = 268 ppm, Truck = 261 ppm). The other result is that the truck had much wider swings in NOx production compared to the van. Again this is not what would be predicted from the idle test since the van showed the greatest emissions range based on the engine RPM.

The B90 drive test data is shown in Figure 4, this pattern was repeated for the other fuel blends as shown by one of the B20 driving tests shown in Figure 5. The fact that the two vehicles behave so differently with NOx emissions is a clear reinforcement of the conclusions of McCormick et. al., that the engine type and vehicle operation have a large effect on the NOx emissions.

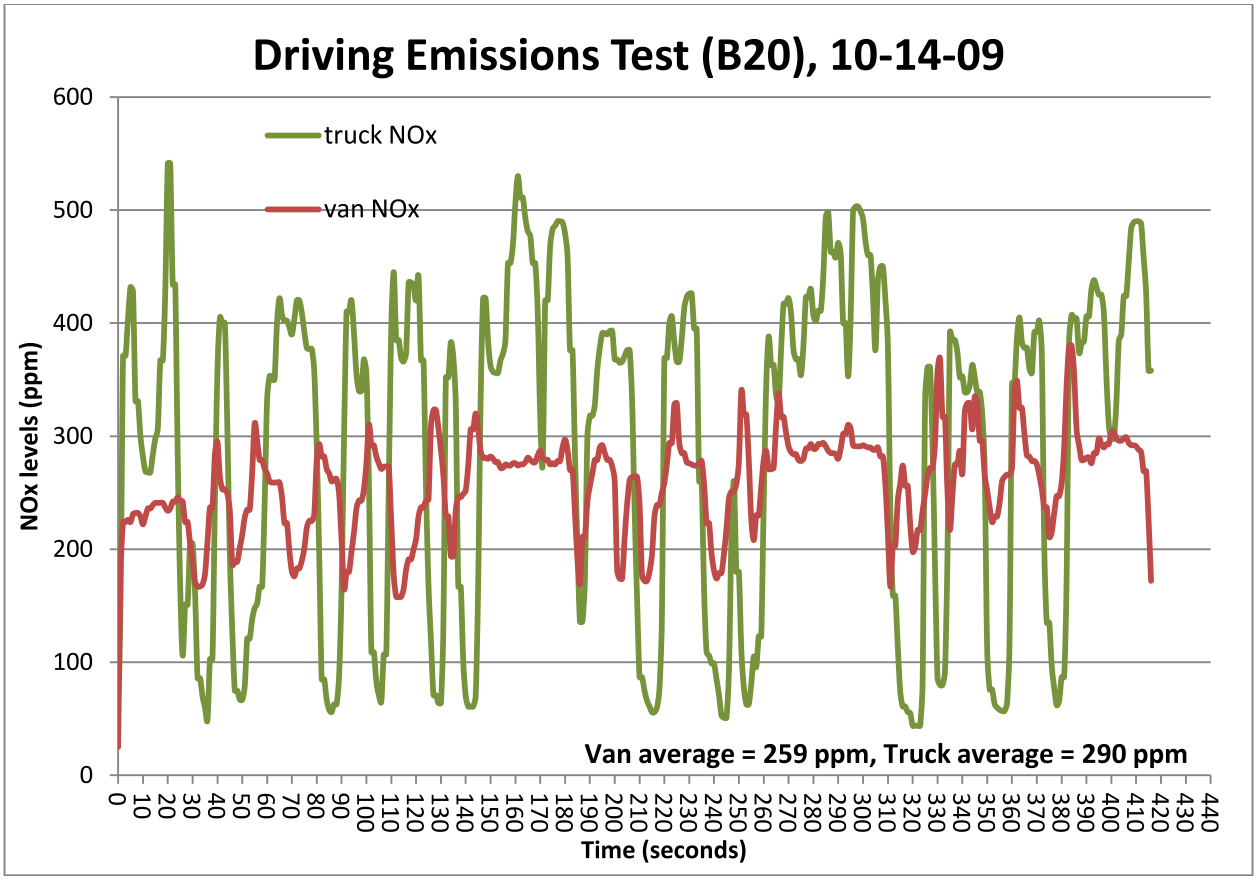


Figure 5: Truck and Van Driving Test B20

The NOx emissions were compared for the biodiesel blends to determine if there was a possible correlation between the NOx levels and the amount of biodiesel in the blend. Figures 6 and 7 show the maximum recorded NOx levels for each of the idle tests. The van had relatively little difference in NOx generation between low and high idle, but the overall average NOx generation was approximately 225 ppm. The truck was relatively consistent in having higher NOx during the high idle portion of the test. The truck's overall average was approximately 105 ppm compared to the van's 225 ppm.

From the idle test data it would be expected that the driving test NOx emissions would much higher for the van compared to the truck. Instead, Figure 8 shows that the van had slightly lower average NOx levels than the truck, 222 ppm compared to 236 ppm. As noted earlier, the engine type and engine controls appear to have a much larger effect on NOx emissions than the type of fuel being used. Figures 6-8 show no consistent pattern between the fuel blend and the NOx levels, either with idle testing or drive testing.

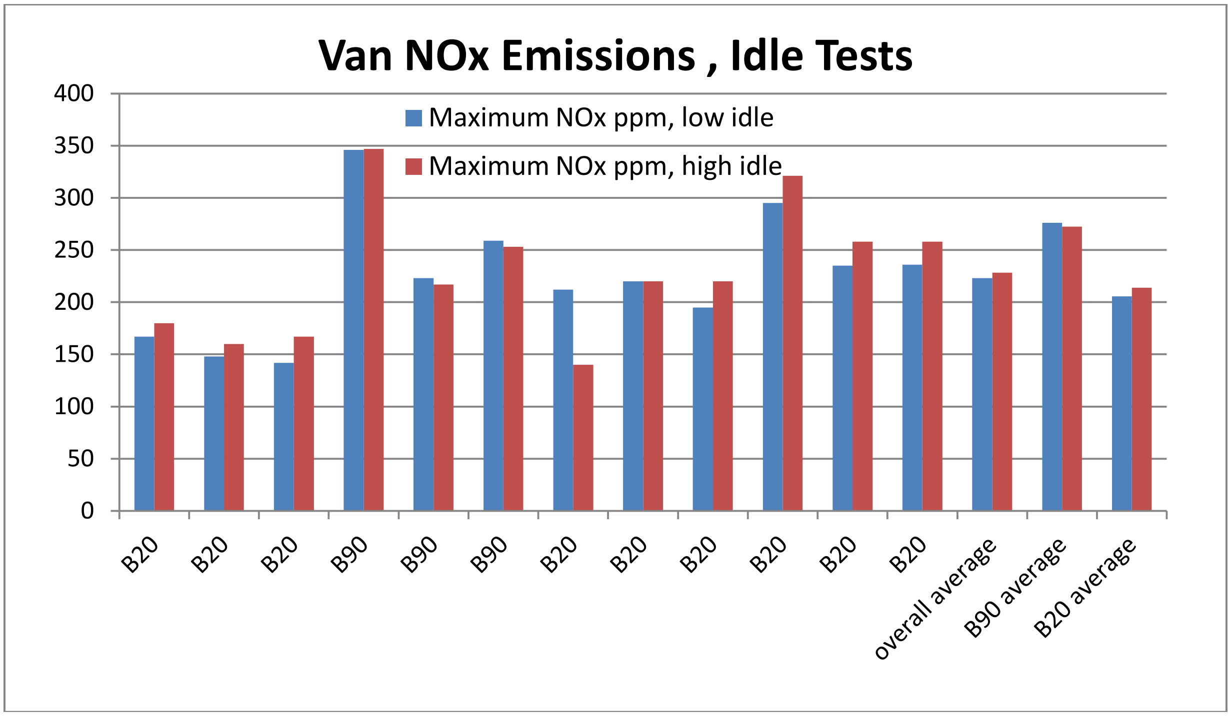


Figure 6: Van, Low and High Idle showing maximum NOx emissions, biodiesel only

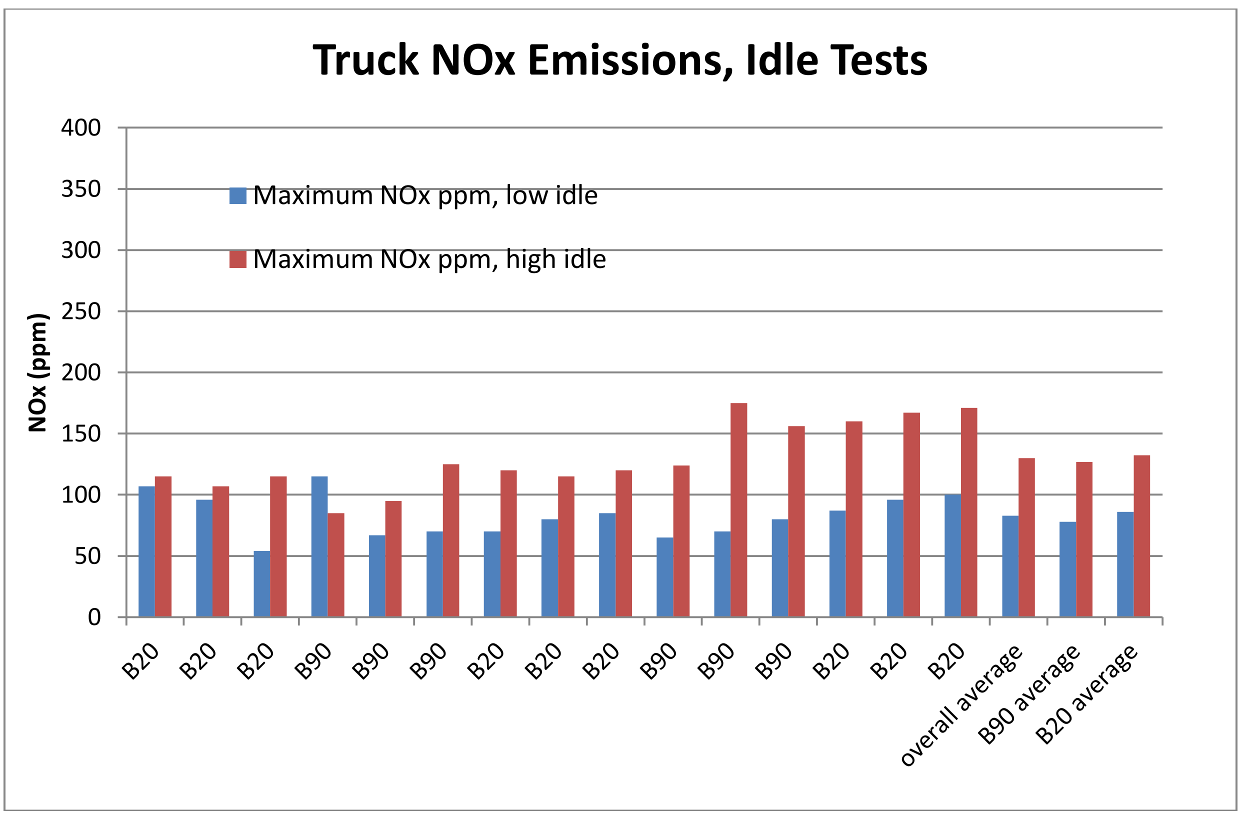


Figure 7: Truck, Low and High Idle showing maximum NOx emissions, biodiesel only

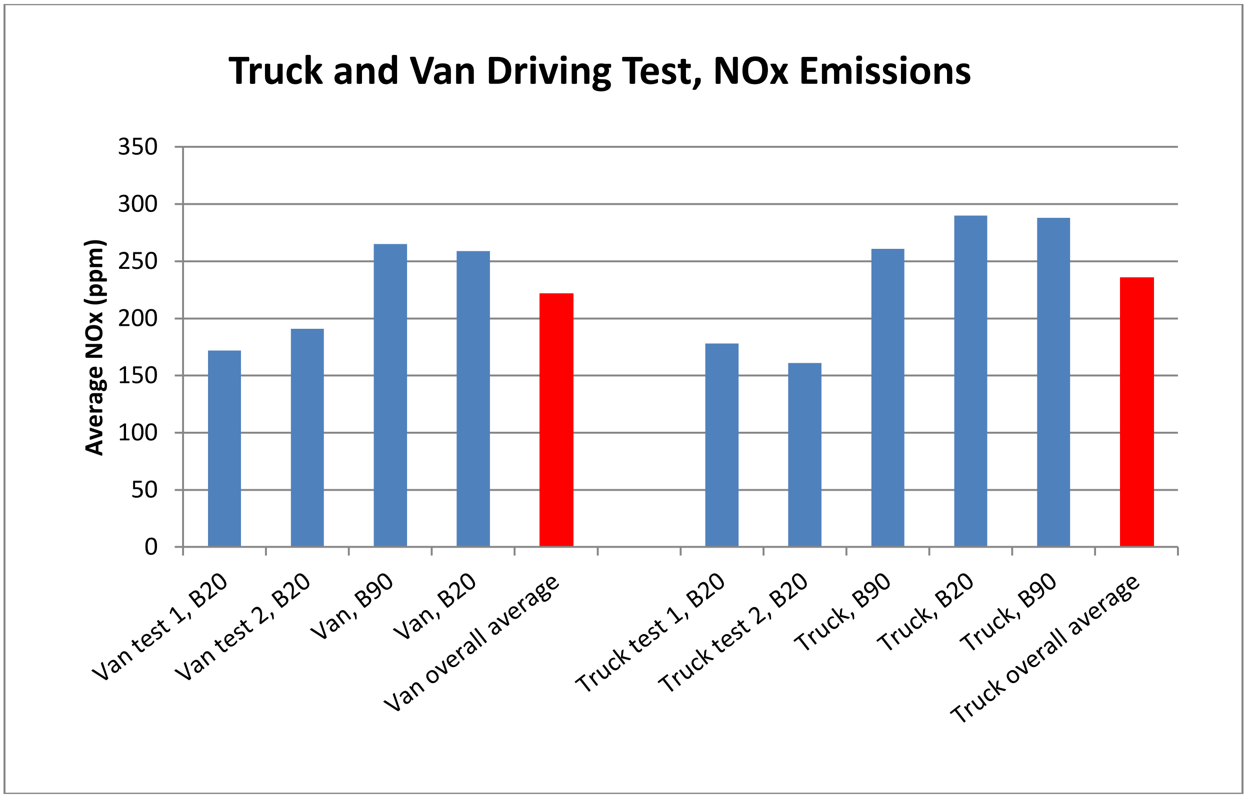


Figure 8: Average NOx emissions for the driving test

Vehicle Performance and Maintenance Results

Vehicle performance includes any reported driving problems or starting problems that could potentially be associated with the use of biodiesel. Potential maintenance issues are fuel system, engine problems or exhaust system problems which again could potentially be associated with the use of biodiesel. Typical problems reported in the literature for biodiesel include:

- Fuel filter plugging, either from low-temperature fuel gelling or from converting an older vehicle over to biodiesel, resulting in fuel system "cleaning" by the biodiesel.
- Hard starting in cold weather due to fuel thickening resulting in injection problems.
- Fuel getting into the lubricating oil typically from the higher viscosity biodiesel blowing by the piston rings.
- Elastomer seal degradation by biodiesel due to its higher solvency. More problematic with older vehicles.
- Fuel picking up water, since biodiesel is slightly more hygroscopic than diesel fuel. Potential fuel line freezing in the colder months.
- Fuel developing biological growth due to the biodegradability of biodiesel and the ability to pick up water. Potential filter plugging and hard starting.

- Fuel oxidation stability, potential performance problems unknown.
- Fuel efficiency, with biodiesel being reported to have loss of efficiency in the form of miles per gallon in proportion to the amount of biodiesel in the blend.

Of particular interest at RIT is the potential for fuel gelling, resulting in either hard starting or failure to start in the winter. Rochester, New York has reasonably long periods of time with below freezing temperatures. These conditions are ideal for causing any kind of diesel fuel to gel, resulting in a no-start condition. Figure 9 is a daily temperature average of the three winters of biodiesel testing. As shown in the figure, the worst low temperature stretch was from 1/3/09 to 2/6/09, with an average daily temperature of 19°F. There were no reported problems with either vehicle or with the fueling station during this time period. The other winters had less severe stretches of cold and also had no reported problems.

When oil changes were made, samples were sent for oil analysis to determine whether there were any unusual problems occurring such as the biodiesel getting past the piston rings or any unusual wear. Table 2 is an overview of either reported abnormal levels for the various oil tests or levels of interest associated with potential biodiesel problems. Of special note are ”fuel in oil” measurements for the truck and the van. The van showed consistently high amounts of fuel in oil readings compared to the truck. Some literature has reported that the higher viscosity of biodiesel results in biodiesel getting past the rings in the engine, resulting in larger amounts of biodiesel getting into the lubricating oil. It would be expected that the vehicles would have larger amounts of fuel getting into the lubricating oil with the higher concentration of biodiesel being used. So the use of B90 should be the worst case for this condition. The results for the van showed that the fuel in oil levels were consistently high – greater than 2% – regardless of the biodiesel concentration. This would indicate a ring bypass problem in the van that cannot be attributed to the presence or amount of biodiesel being used.

One other test result that may be attributed to biodiesel in the engine oil is the high TAN (total acid number) result for the van on 9/20/09. The van consistently had higher levels of engine oil in the lubricating oil. The van was using B90 during that particular test period, so therefore the majority of the fuel in the oil would be biodiesel. Biodiesel oxidation will increase the TAN number, so the high TAN number may be attributable to biodiesel. Again, the amount of fuel in the oil cannot be attributed to the biodiesel but the high TAN number may be caused by the biodiesel blend being high. The other abnormal or high normal readings reported in Table 2 were transient and not explainable based on the fuel blend being used.

After the conclusion of our formal research on the vehicles, we were notified by the RIT maintenance department in April 2011 that the Ford Van required repairs. Upon inspection by the dealer it was found that the head gasket seals had degraded to the point where they needed immediate replacement. Although we were unable to obtain the parts for analysis, we suspect this degradation was due to the use of the higher blend of biodiesel (B90), however, the problem did not appear until many months after the use of biodiesel in these vehicles was discontinued. Nonetheless, this should be a watch item when using higher percentages of biodiesel.

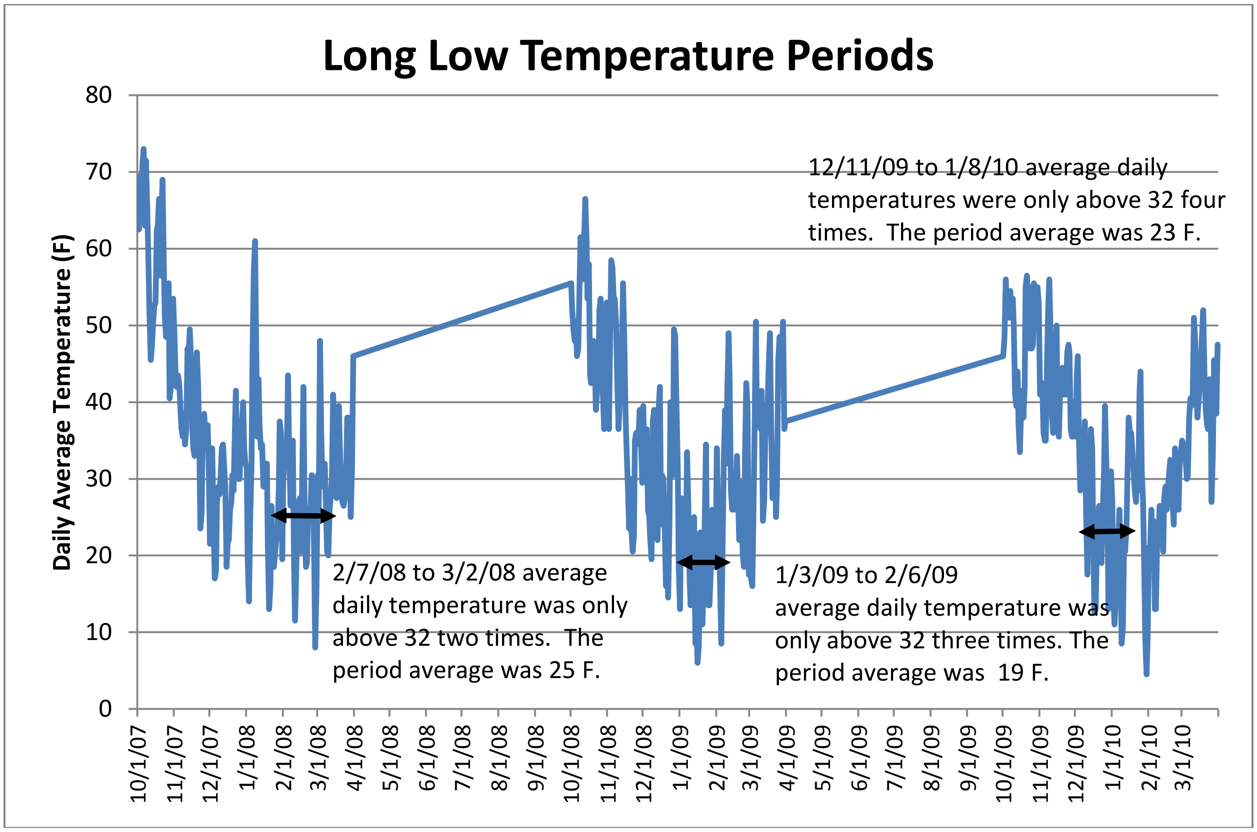


Figure 9: Rochester winters, daily temperature averages

Vehicle	Date	Mileage	Fuel type	Analysis	Flag level	Reported level	Units
Truck	10/14/08	9,000	B20	copper	low abnormal	116	ppm
	10/14/08	9,000	B20	fuel in oil	normal	<1	%
Truck	3/30/09	14,000	B20	copper	normal	32	ppm
	3/30/09	14,000	B20	fuel in oil	normal	0.6	%
Truck	3/28/10	20,118	B20	fuel in oil	normal	0.3	%
Truck	7/27/10	22,709	B90	fuel in oil	normal	1	%
Van	10/15/08	28,000	B20	silicon	high normal	23	ppm
	10/15/08	28,000	B20	fuel in oil	high normal	2.1	%
	10/15/08	28,000	B20	oil oxidation	normal	9	
	10/15/08	28,000	B20	oil nitrates	normal	10	
Van	3/27/09	35,000	B20	silicon	normal	8	ppm
	3/27/09	35,000	B20	fuel in oil	normal	1.7	%
	3/27/09	35,000	B20	oil oxidation	high normal	21	
	3/27/09	35,000	B20	oil nitrates	high normal	20	
Van	7/10/09	42,000	B20 - B90 overlap	fuel in oil	high normal	2.2	%
Van	9/20/09	46,100	B90	TAN (total acid number) of oil	high normal	5.58	
Van	3/29/10	58,060	B20	fuel in oil	high normal	2.7	%
Van	7/27/10	64,836	B90	fuel in oil	high normal	2.2	%

Table 2: Lubricating Oil Analysis Results

One final method of monitoring vehicle health was with Networkfleet™. This system links to the vehicle computer and monitors system signals. If a system reports a transient change, it is reported via satellite link to designated fleet managers. The Ford van had multiple reports of EGR problems. As previously noted, the EGR valve is critical for controlling NOx emissions. In reviewing service records for this particular engine type, it was found that the EGR problem is common and therefore not associated with biodiesel use but could affect NOx emissions over the life of the vehicle.

> "The EGR valve carbon deposit issue in the 6.0 L has proved common enough to merit some special attention. When the valve clogs, it requires replacement, which has often been done under the powertrain warranty. However, it has been discovered that extended idle times are the cause of the carbon buildup, as diesel engines have low combustion efficiency at idle speeds. Ford has since resolved the issue via updated programming for the powertrain control module."

en.wikipedia.org/wiki/Ford_Power_Stroke_engine

After the EGR valve was replaced on the van, an additional emissions test was run. Figure 10 shows the dramatic drop in the NOx emissions after the EGR valve was replaced. Based on this change, and the lack of difference in the NOx emissions for the various fuel blends shown in Figure 3, the conclusion is that for specific engine types the NOx levels are more strongly affected by engine EGR health than fuel type.

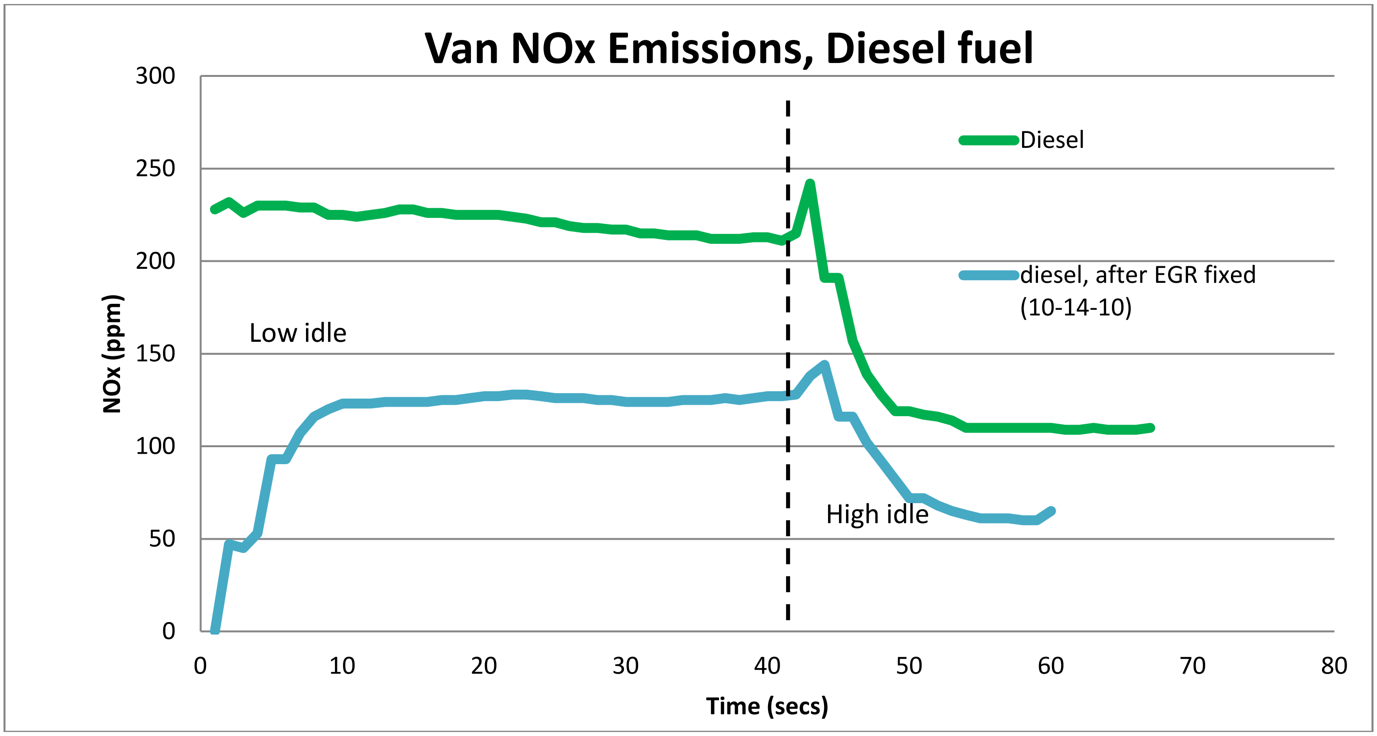
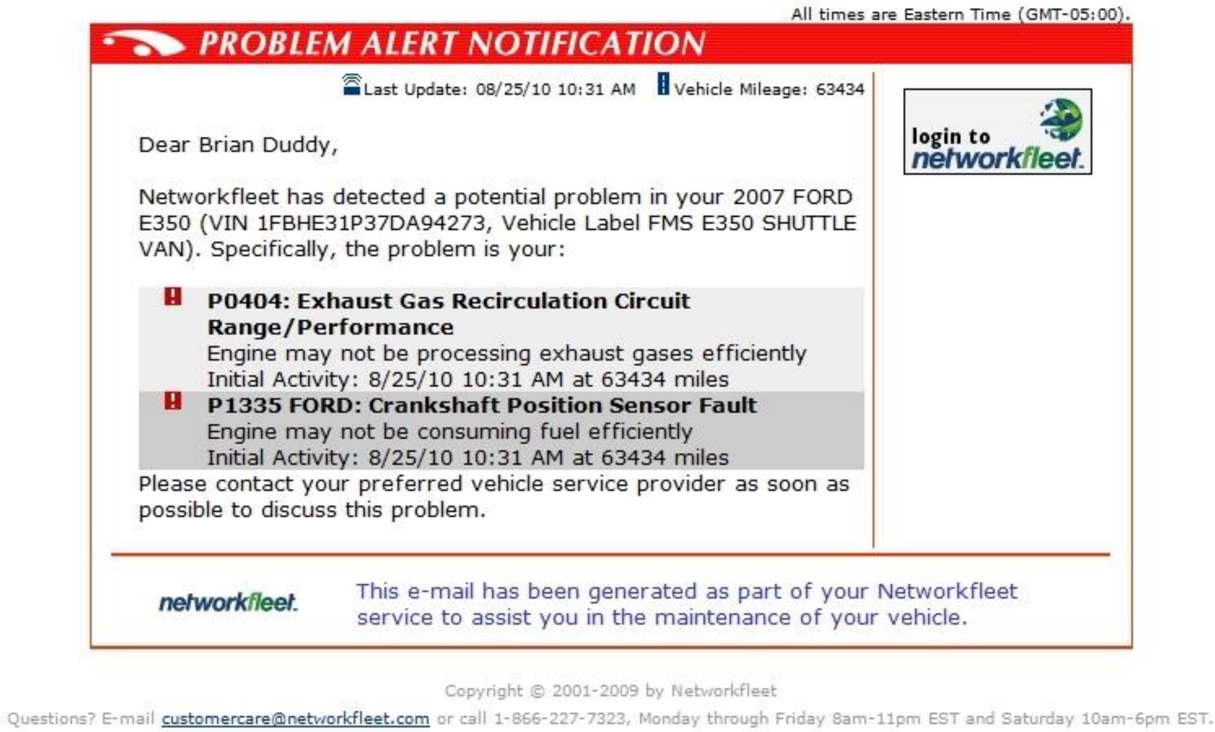


Figure 10: Van NOx emissions with diesel fuel, before and after EGR replacement



All times are Eastern Time (GMT-05:00).

PROBLEM ALERT NOTIFICATION

Last Update: 08/25/10 10:31 AM Vehicle Mileage: 63434

login to networkfleet.

Dear Brian Duddy,

Networkfleet has detected a potential problem in your 2007 FORD E350 (VIN 1FBHE31P37DA94273, Vehicle Label FMS E350 SHUTTLE VAN). Specifically, the problem is your:

P0404: Exhaust Gas Recirculation Circuit Range/Performance
Engine may not be processing exhaust gases efficiently
Initial Activity: 8/25/10 10:31 AM at 63434 miles

P1335 FORD: Crankshaft Position Sensor Fault
Engine may not be consuming fuel efficiently
Initial Activity: 8/25/10 10:31 AM at 63434 miles

Please contact your preferred vehicle service provider as soon as possible to discuss this problem.

networkfleet. This e-mail has been generated as part of your Networkfleet service to assist you in the maintenance of your vehicle.

Copyright © 2001-2009 by Networkfleet

Questions? E-mail customercare@networkfleet.com or call 1-866-227-7323, Monday through Friday 8am-11pm EST and Saturday 10am-6pm EST.

Figure 11: Sample Networkfleet report, in this case EGR and crankcase position sensor problems on the RIT van

Vehicle Fuel Efficiency

The literature results indicated that the biodiesel fuels would have lower miles per gallon than the use of straight ULSD. This information was based on:

Engine dynamometer tests:

(Peterson, C.L., Thompson, J. C., Lowe, G. A., Taberski, J. S., Mann, P. T., Chase, C. L., *Quality Fuel Production and Support of the Over-the-road Operational Demonstration*, BioEnergy '98: Expanding BioEnergy Partnerships, 972-981) with a reported fuel efficiency loss of 6.5% using B50.

One report using an engine dynamometer showed that fuel economy dropped by 2.9% using B20 soy-based biodiesel compared to ULSD certification diesel. All testing was done on a 2002 Cummins ISB engine (with EGR) for that study (Williams, A., McCormick, R. L., Hayes, R., Ireland, J., Biodiesel Effects on Diesel Particle Filter Performance, National Renewable Energy Laboratory, Milestone report NREL/TP-540-39606, March 2006).

Unreferenced test methods:

(*2004 Biodiesel Handling and Use Guidelines*, U.S. Department of Energy, Energy Efficiency and Renewable Energy, DOE/Go-102004-1999 Revised November 2004). The energy content value provided by the DOE article is about an 8% reduction in B100 biodiesel compared to No.2 diesel. This equates to approximately a 1-2% decrease in fuel efficiency for B20. These values are based on 129,050 BTU's per gallon for No. 2 diesel oil and 118,170 BTU's per gallon for B100 biodiesel. The difference in energy content is approximately 8%.

There were four fuel types used over the RIT study period:

- No. 2 ULSD (straight diesel)
- B20, ULSD blend
- B20, 30% kerosene, 50% ULSD winter blend
- B90, ULSD blend

Based on the typical energy content of each blend, fuel efficiency was calculated based on that energy content. The ULSD energy content was normalized at 100% against each blend to compare the energy content values. Reported energy content for the various components and blends is shown in Table 3.

Neat fuel (100%) or Blend	Neat fuel BTU/gallon	Blend BTU/gallon	Normalized Efficiency (ULSD=100%)	Expected reduction in MPG	Source of data
ULSD	129,050		100%	0%	2004 Biodiesel Handling and Use Guidelines, D.O.E.
B100 (soy-based)	118,170		92%	8%	2004 Biodiesel Handling and Use Guidelines, D.O.E.
Kerosene	125,800		97%	3%	Aviation Turbine Fuel Performance [pdf]. Chevron Products Company, 2000
B20, 80% ULSD		126,874	98%	2%	
B20, 30% kerosene, 50% ULSD (winter blend)		125,899	98%	2%	
B90, 10% ULSD		119,258	92%	8%	

Table 3: Energy content of Neat and Blended Fuels with Expected MPG Losses

The van and truck used at RIT for biodiesel testing made use of operator logs to determine the vehicle mileage at each fueling interval. Unfortunately, the vehicles were not always completely refilled at each fueling interval, so the miles per gallon (MPG) values had to be averaged over the extended periods of specified fuel types. The highs and lows of individual MPG calculations were also removed to eliminate mileage misreads and missed refills.

Truck, Fuel type	Average MPG in fuel groups	Variation from ULSD (+ better than ULSD, - worse than ULSD)
B20, summer	13.64	21%
B20 winter blend, 30% kerosene	10.38	-8%
B90, summer	13.43	19%
B20 winter blend, 30% kerosene	11.98	6%
ULSD	11.27	0%
Van, Fuel type		
B90	12.03	12%
B20, winter	11.87	11%
B20, summer	11.67	9%
B20, winter	11.62	9%
B20, winter	11.54	8%
B20, winter	11.47	7%
B90	11.33	6%
B20 winter blend, 30% kerosene	10.57	-1%
ULSD	10.71	0%

Table 4: Vehicle Fuel Blend Efficiency compared to ULSD

Based on the data for fuel mileage, Table 4 suggests that the biodiesel blends have better overall MPG than straight diesel. This is contradictory to the actual energy content of the various fuel types. Figures 12 and 13 show the variation in the MPG data for the truck and van. These figures show the wide statistical variation in the MPG data and the fact that each fuel blend has a large overlap for MPG readings. Therefore, no conclusions can be made concerning the fuel efficiency for each fuel blend, contrary to the expected decrease in fuel efficiency with higher concentrations of biodiesel based on energy content. It should also be noted that each of these vehicles can have unusual driving patterns which can strongly affect fuel usage. The truck is routinely used as a plow truck in the winter which entails multiple stops and starts. The van will have long periods of idling while waiting for passenger pickup.

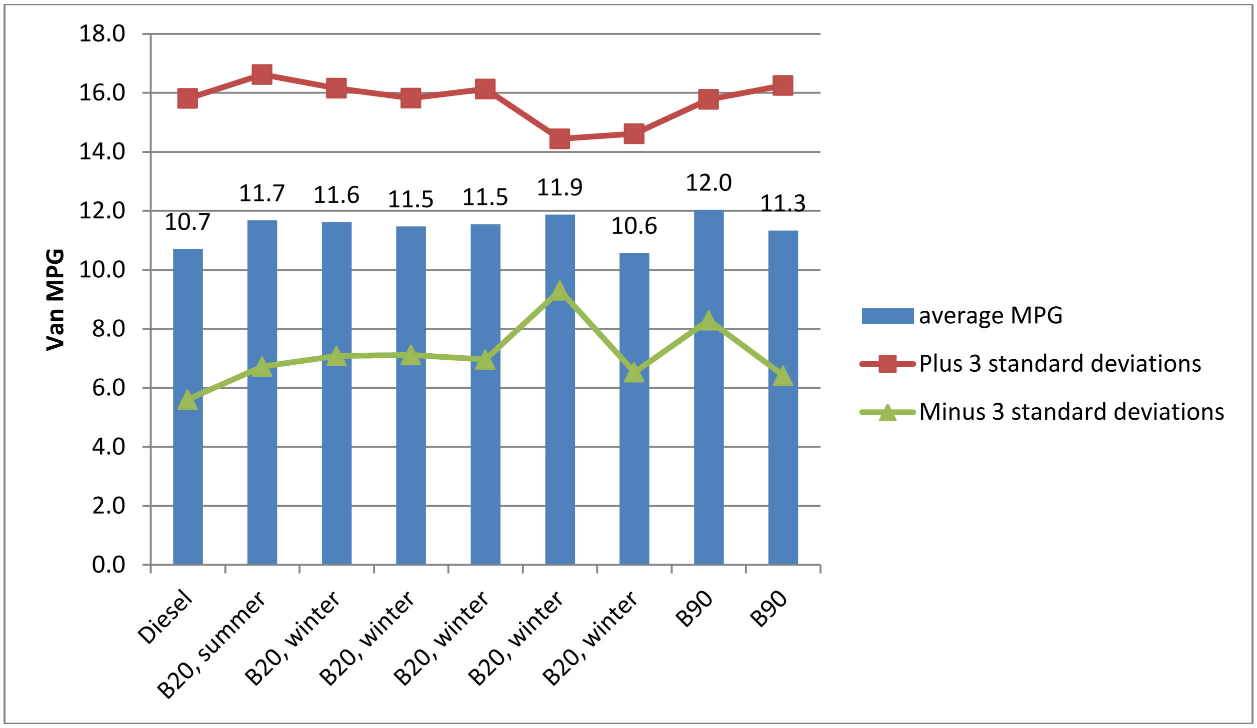


Figure 12: Van MPG data for each fuel blend and statistical variation

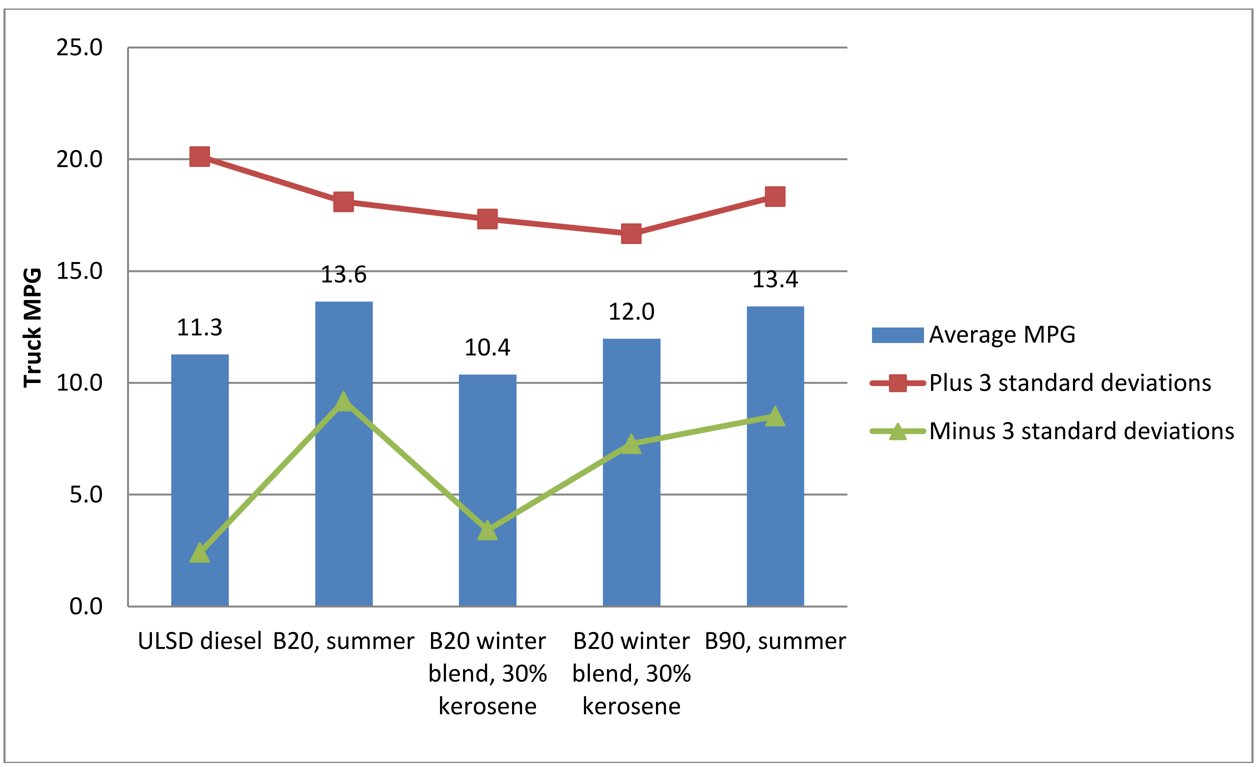


Figure 13: Truck MPG data for each fuel blend and statistical variation

Fueling Station Performance and Maintenance Results

Biodiesel made from soy oil has a typical cloud point of 28°F based on the ASTM test D2500. Typical ULSD has a typical cloud point of 3-4°F (Donald A. Heck, Jordan Thaeler, Steve Howell and Joshua A. Hayes, *Quantification of the Cold Flow Properties of Biodiesels Blended with ULSD*, 2009). Cloud point is a measure of the beginning of solids formation in oil. As such, it is an indicator of the temperature at which a fuel will start to gel, causing filter plugging, fuel line plugging, or fuel injector plugging. Due to the higher temperature cloud point of soy-based biodiesel compared to petroleum-based fuel there was the potential of filter plugging problems associated with both the vehicles and with the fueling station at RIT. The fuel blend was altered during the winter months to reduce the potential of fuel gelling by switching from the summer B20 to a winter B20 with 30% kerosene. This method of reducing gelling in the winter is used for ULSD as well. Since the B20 is considered the high end of the normal biodiesel blends for on-road use, it was considered somewhat risky to stay with B20 in the Rochester area during the winter. For this reason, the RIT vehicles and the fueling station were continued on the B20 during the winters to determine what problems might be encountered due to the potential of fuel gelling. Vehicles were left outside, and the fueling station is outside and has no tank heating. Figures 14a and b show the fueling station.

The winters of B20 testing were 2007-2008, 2008-2009, and 2009-2010. Figure 9 show the daily temperature averages for these three winters. Of interest for potential problems are the winter periods with long stretches of low temperature. Each winter had at least one period of below freezing temperatures that lasted more than a week. As noted previously in regards to vehicle performance, the worst winter cold stretch was from 1/3/09 to 2/6/09 with an overall average temperature of 19°F. The fueling station did not experience any fueling problems during that period of time even though the tank is above ground and unheated.

Figures 14a and 14b, RIT Biodiesel Station

Biodiesel Fleet Study Summary

The Biodiesel Fleet Study was a four-year observation of two light-duty diesel trucks operated on the RIT campus using four different fuels. ULSD was used as a baseline fuel. B20 with 30% kerosene was used in the winter months, and B20 and B90 were used in the summer. Fuel use was logged, emissions were measured periodically, and vehicle and fuel station problems were monitored over the life of the program.

Emissions including oxides of nitrogen were the primary focus of the exhaust products portion of the study. NO and NO_2 (collectively measured as NO_x were logged and compared between vehicles and between fuel blends. Two apparent trends emerged from the data: NO_x was reduced with increased biodiesel in the Chevrolet Pick-up Truck (increased in the Ford Van) during the idle tests, and NO_x increased with increased biodiesel during the driving tests. The variation in the NO_x measurements was large, and one of the vehicles had a malfunctioning EGR valve during much of the testing, so the conclusions may not be real. The data does show that vehicle condition and operating parameters have greater influence on NO_x emissions than fuel formulation.

The Higher Heating Value (HHV), which is a good measure of available energy in a fuel, is lower for biodiesel than ULSD so reduced efficiency is normally expected with increased biodiesel content. The raw data from the Biodiesel Fleet Study suggests otherwise; the general trend was that higher biodiesel content offered increased efficiency. It should be noted that the measurement variation of fuel mileage was greater than the differences between fuel content effect. It should also be noted that B90 was used only during warm summer months, while B20 was used mostly in the winter, but occasionally in the summer. The seasonal effect could be strong, especially since one of the trucks was used as a snowplow in the winter. One would suspect that the improved efficiency seen with increased biodiesel is likely caused by some other effect, such as vehicle use changes or cold, slippery conditions of winter in western New York. Again, vehicle condition and use parameters affect fuel efficiency more than the biodiesel content of the fuel.

Using the schedule of running B20 winter blend (20% biodiesel, 50% ULSD and 30% kerosene) during winter months and B90 during summer months caused no noticeable maintenance problems with either vehicle. The Ford Van experienced an EGR valve problem, but the problem cannot be linked to biodiesel use. It may have been malfunctioning before this study began. Likewise, RIT's campus fueling station experienced no problems or additional maintenance issues during the study.

b. Biodiesel Component Studies

The second major phase of our biodiesel investigation was two separate efforts to identify the impact of biodiesel on engine materials and components. These efforts involved a component wear study to determine the impact of biodiesel mixing with engine oil in the crankcase and a study of the impact of biodiesel on the lubrication properties of fuel.

Wear Testing of the Effect of Biodiesel Dilution in Engine Oil

Background

Not all of the diesel fuel injected to the cylinder of an engine is expended during the combustion process. Inevitably, some works its way past the piston rings and into the crankcase where it "dilutes" or mixes with the engine's lubricating oil (fuel dilution). While the heat in the crankcase will evaporate traditional petroleum diesel fuel because it has a higher heat of vaporization, the biodiesel does not evaporate as readily. This creates potential engine problems because the biodiesel fuel dilution could potentially decrease the viscosity and lubricity engine oil, it can also alter the performance of anti-wear additives added to the oil.

The heating value of the biodiesel is approximately 10% less than petroleum diesel, which results in a higher brake-specific fuel consumption (BSFC).[4] The biodiesel combustion increases NOx emissions because of advancing phenomenon of injection start due to the physical properties of the biodiesel. The hydrocarbon and CO emissions tend to decrease because of the oxygen content and the higher cetane number of the biodiesel will enable more complete combustion.[5]

Engine lubricating oil function is to develop a hydrostatic lubricating film between sliding surfaces, protect components from corrosion and reduce the total amount of friction and wear of the engine. Wear of engine parts is the main limiter of the life of an engine. When biodiesel is combusted in an engine it accumulates in the crankcase, and unlike petroleum-based diesel it does not evaporate but instead results in higher volumes of fuel diluting the oil in the crankcase. The reason biodiesel accumulates in the engine crankcase is biodiesel has a higher viscosity, surface tension, and specific gravity, and compared to petroleum-based diesel it does not atomize as well during fuel injection; for this reason it forms fuel larger droplets compared to petroleum diesel. These larger droplets are not completely combusted during the combustion cycle, and some of the fuel that is not combusted sticks to the cylinder walls where it is scraped into the crankcase by the piston rings.[6]

The effect of biodiesel on engine wear has been investigated using both laboratory testing and engine tests, but the results are mixed and inconclusive. One collaborative research effort by Cummins and Chevron concluded that when engine oil is diluted with biodiesel, oxidation of the engine oil occurs, which, in turn, reduces the lubrication properties of the engine oil, thus increasing the wear on critical engine components.[7] Hefei University of Technology performed a study using the high-frequency reciprocating test rig to analyze the effects of a mixture of diesel and biodiesel. This study determined that biodiesel dilution caused increased engine wear. One potential reason for the increased wear was that biodiesel lacked certain anti-corrosion properties in comparison to diesel.[8]

Another study performed by Cummins, Inc.,[9] showed that engines running with B100 had an increased amount of fuel dilution in the engine oil and an increased amount of engine wear. They concluded that biodiesel fuel can lead to increased engine wear because of the interaction of oxidized biodiesel compounds and the wear additives in the engine oil. Polaris Laboratories, in a 2008 technical bulletin,[10] also stated that biodiesel dilution in the engine oil increases engine wear. They concluded that the polar constituents in the biodiesel attract the wear additives in the engine oil, thus reducing the amount of additives available to protect the engine components and increasing wear rates.

In contrast, other studies have shown that biodiesel additions to engine oil does not cause increased engine wear. Fraer et al.,[11] ran both a 1993 Ford cargo van and a 1996 Mack truck on a 20% biodiesel blend (B20). They found no difference in wear between the vehicles run on 100% petroleum diesel and those run with B20. An MIT study ran 100% biodiesel in 5.9L 6 cylinder ISB 300 Cummins diesel engine for 1000 hours[12]. Their results showed that engines running on 100% biodiesel did not show any increased amount of wear or required any more maintenance compared to the same engine running petroleum-based diesel.

Agarwal[13] and Wadumesthrige[14] ran laboratory bench friction and wear tests to evaluate the effects of the biodiesel additions on the lubrication properties of the engine oil. Agarwal's pin-on-disk testing showed that the pin-on-disk specimens using a 20% biodiesel blend showed less damage and wear on both the pin and the disk than the pin and disks run using the engine oil without the biodiesel additions. These results confirmed the additional lubricity of the biodiesel. Wadumestbrige's studies using a High-Frequency Reciprocating Rig (HFRR) showed that the biodiesel additions up to 2 volume % significantly improved the lubricity of ultralow sulfur diesel fuel (ULSD). However, further additions above 2% did not decrease the lubricity of the ultralow sulfur diesel fuel. The authors attributed the improved lubricity to improved boundary film formation.

Agarwal[15] also studied the effect of using a 20% biodiesel blend on engine wear by running two single-cylinder engines, one with 100% petroleum diesel, and one with the 20% biodiesel blend for 512 hours. The wear measurements after testing showed that wear of the components for the engine that ran the biodiesel blend was 30% less than the same parts for the engine that ran the 100% petroleum diesel. These results was also confirmed with oil analyses which showed that the oil from 20% biodiesel fuel engine contains a significantly lower amount of amount of iron and aluminum wear particles than that from the 100% petroleum diesel fueled engine. This study again demonstrated that the improved lubrication properties of the biodiesel reduced the wear of the moving parts in the single cylinder engine.

Haseeb[16] performed a literature review and summarized the work performed to date on the compatibility of biodiesel with automotive components. The review found that short-term laboratory studies have shown that biodiesel reduces wear and friction. However, it was also stated that oxidation of biodiesel at higher test temperatures will adversely affect its triboligical properties. The conclusions from laboratory testing and on road data suggest that lower biodiesel blend do not increase the wear of iron engine components. However, the effect of higher blends 50-100% is not known and that more data is required to determine the effect of higher biodiesel blends on the wear of engine components. For this reason, the objective of this testing was to determine the effect of high levels of biodiesel dilution (5 and 10 volume %) in engine oil on the wear of a piston ring running against a cast iron cylinder liner in an accelerated wear test. These biodiesel dilution concentrations will occur when running B50 to B100 blends.

Experimental Test Setup

All testing was performed on a reciprocating wear tester developed and constructed by the Center for Integrated Manufacturing Studies (CIMS). Figures 1 and 2 show the test configuration. The test configuration consisted of an oscillating cast iron specimen that ran against a stationary piston ring. This was fabricated to represent the motion of the ring against the inside of the cylinder wall.

Figure 1. Stationary Piston Ring Test Fixture.

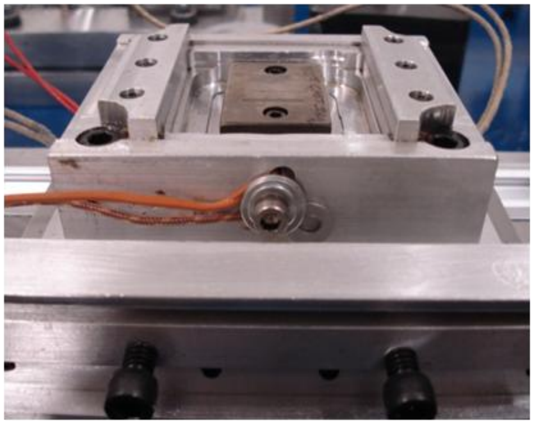


Figure 2. Cast Iron Sample Fixture and Oil Bath

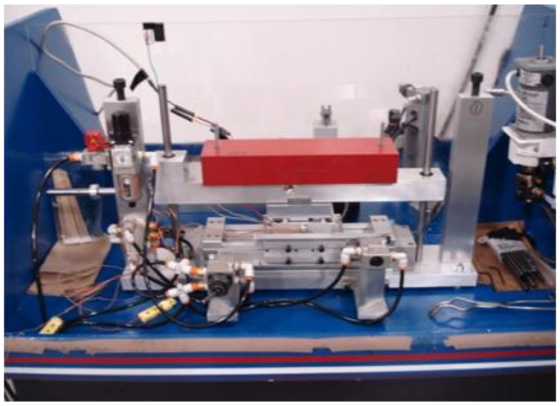


Figure 3. Fully Assembled Reciprocating Test Rig.

The fully assembled test rig with the weights (red blocks) placed on top of the piston ring sample is shown in Figure 3.

The test conditions used in this study were:

- 40 pound load on piston ring,
- 15 mm stroke length, and
- Oscillating frequency of 3 Hz.
- Oil temperature was 300°F.

During the reciprocating test, the cylinder liner sample was completely immersed in the oil bath. This setup enabled both hydrostatic lubrication between the piston ring and oscillating cylinder liner samples and a continuous mixing of the oil and fuel. All tests were run for 24 hours after a five-minute break-in period. Each test used new or unused motor oil and biodiesel. Table 1 lists the test parameters used.

Test Parameters	
Oil Temperature:	300 ±1°F
Frequency:	3 Hz
Test Time:	24 hours
Run-in Time:	5 Minutes
Stroke:	15 mm
Load:	40 lbs
Oil Types Used:	15W40 – Valvoline (New)
Fuel Type:	B100 – Griffith Energy

Table 1. Test Parameters

The test matrix used is shown in Table 2. In general, two biodiesel dilutions were evaluated: 5 and 10 volume %. The control used undiluted engine oil.

Test Matrix		
Oil Dilution with B100 (% by vol. per 20mL)	Oil Type (New Valvoline)	Number of Tests
0%	15W40	3
5%	15W40	3
10%	15W40	3

Table 2. Test Matrix

The average oil temperatures during operation of a Cummins ISC 240 engine range between 200°F and 220°F. A test temperature of 300°F was chosen because it is higher than the engine normal operating temperature, which should accelerate the test but is below the flashpoint and will not ignite the blend. In addition, at this temperature oxidation of the biodiesel in the engine oil should occur.

Griffith Energy B100 biodiesel fuel was used to dilute new Valvoline 15W-40 Fleet Plus engine oil. The control was 100% pure 15W-40 oil, not diluted with biodiesel. The B100 biodiesel was used to dilute the new 15W-40 oil to 5% and 10% concentrations by volume (per 20ml). The test matrix shown in Table 2 shows that each oil dilution concentration was repeated three times. The properties of the Valvoline 15W-40 Fleet plus oil is listed in Table 3.

Typical Properties	**15W-40**
Gravity, degree API	29.5
Specific Gravity, 15 C	0.879
Viscosity @ 40 C, cSt	117
Viscosity @ 100 C, cSt	15.2
Viscosity Index	135
CCS Viscosity, cP	6600@-20
HTHS Viscosity, cP	4.2
Borderline Pumping Viscosity	Pass
Pour Point, deg. C	-30
Total Base Number (D-2896)	10
Sulfated Ash, %	**1.0**

Table 3. Properties of Valvoline 15W-40 "Fleet Plus" Engine Oil

Prior to testing, all the gray cast iron samples were surface-ground flat using the same machining parameters so that they possessed similar surface finishes. The hard chrome-plated piston rings, Cummins part number 4089624, were cut into nine equal-length segments (approximately one inch each) to fit into the fixture mold in the test fixture.

Results

Three methods were used to quantify the amount of wear that occurred during the 24-hour reciprocating test:

1. **Material/Weight removal**- The cast iron samples were weighed before and after each test. Then, using the measured change in weight and the theoretical density of cast iron, the approximate volume of material removed was calculated.

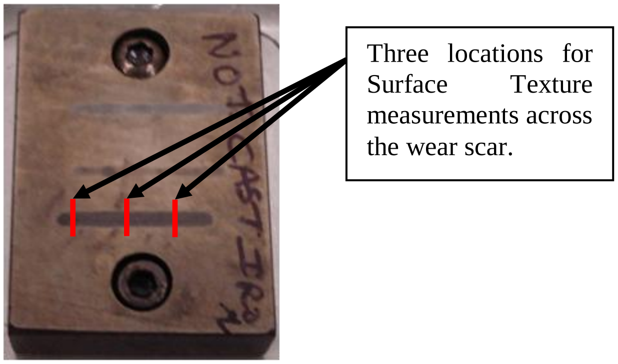


Figure 4. Surface Texture Measurement Locations

2. **Scar Depth/Width-** A Talysurf[17] surface texture measuring apparatus will be used to measure the depth and width of each wear scar in three locations. From these measurements a volume for the wear scar will be calculated.
3. **Optical Analysis of Wear Scars** – Microscope photographs of each sample were taken an analyzed to detect any trends or wear patterns.

Material Removal Due to Wear

The average amount of material removed from the cast iron samples for each biodiesel/engine oil blend is shown in Figure 5 and listed in Table 3. Prior to weighing, all samples were ultrasonically cleaned to remove any wear debris and lubrication. The relationship of wear to weight is that the lowest amount of wear occurs when the least amount of material is removed.

The weight removal results were inconclusive because the amount of material removed was extremely small. One potential reason for these results was the accuracy of the scale used to measure the weight loss was not great enough to determine small differences in the amount of material removed.

Average Value	% Biodiesel		
	0%	5%	10%
Weight removed (mg)	6.1	7.9	4.9
Standard Deviation	2.7	0.4	5.1

Table 3. Average Weight Loss vs. Biodiesel Composition

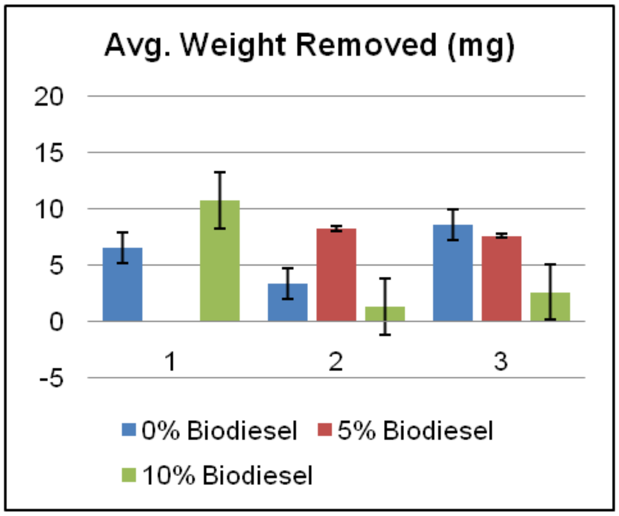


Figure 5. Weight loss Versus Biodiesel Composition

Wear Scar Depth and Width

The profile, depth, and width were determined in three locations for each wear scar using a Talysurf surface texture measuring apparatus. A sample profile from the Talysurf surface texture measuring apparatus is shown in Figure 6. The depth of the wear scar was determined by measuring the distance from the zero line on the plot (small arrow) to the bottom of the trace. Conversely, the width of the scar can be calculated from the distance the line is below the zero line (large arrow). It is interesting to note that the reason the plot is above the zero line both before and after the wear scar test is because the piston ring was not flat, but instead had a slight curvature; i.e., it “plowed” material along the edges of the wear zone. The “plowing” and redeposition of the material along the edges of the wear scar is another potential reason for the variability of the weight measurements.

From the each of the three profile traces for each biodiesel concentration in the engine oil the

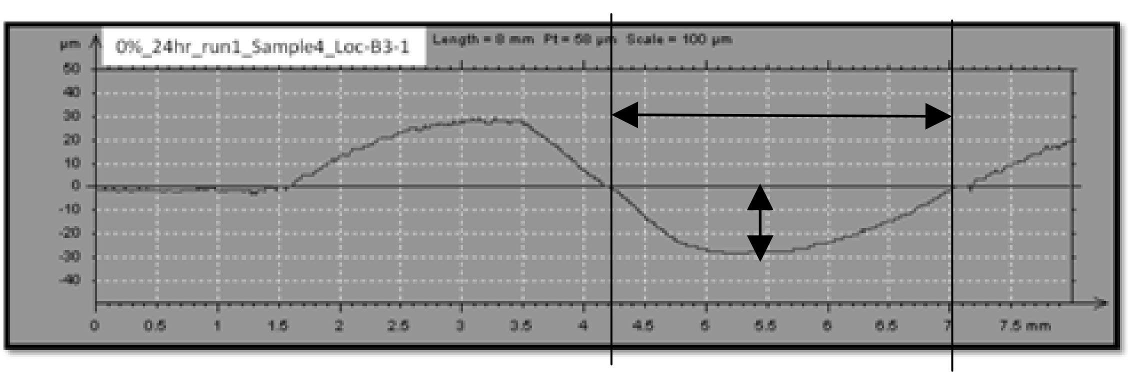


Figure 6. Sample Talysurf Chart Used to Determine Scar Depth and Width

average wear scar depths and widths (average of three tests) for each biodiesel concentration, shown in Figure 7, were determined. Figure 7 shows that increasing biodiesel dilution in the engine oil reduced both the depth and width of the wear scar that developed. While the average scar depth for the 0% biodiesel was 31 um, the wear scar depth for the 5% and 10% biodiesel samples were less than ½ the depth of the wear scar for the 0% biodiesel, or 19 and 16um, respectively. The biodiesel additions to the engine oil also reduced the width of the wear scar. Increasing the biodiesel concentration from 0% to 10% reduced the average wear scar width from 2.8 to 2.3 mm. The width of the wear scar is controlled in part by length and radius of the piston ring. As the wear scar becomes deeper it should also become wider as an increased amount of the piston ring is in contact with the cast iron.

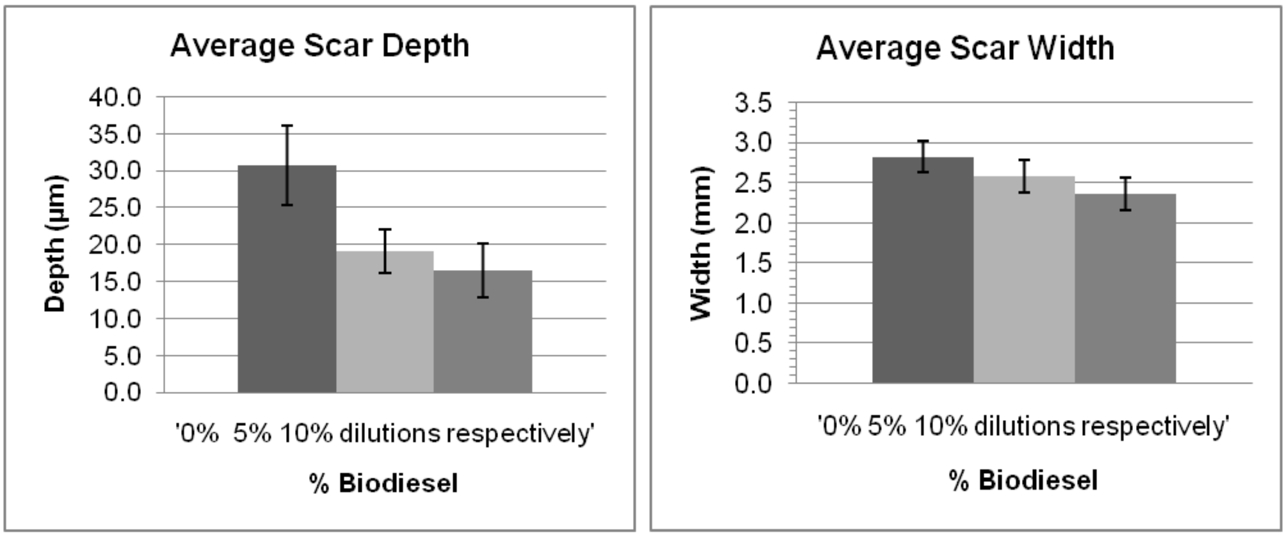


Figure 7. Average depths and widths for 0, 5 and 10 Volume % Biodiesel Concentrations

The profile traces after testing were used to calculate the wear volume using a geometric model method.[18] These results are shown in Figure 8. Figure 8 shows that increasing the biodiesel dilution in the engine oil from 0 to 10 volume % reduced the volume of the wear scar that developed by 52%. The 5 volume % biodiesel dilution reduced the wear scar volume after testing by 40%, compared to the wear scar that developed using the same engine oil without any biodiesel additions. The wear scar data shows that biodiesel additions to the engine oil will reduce the amount of wear. This effect is apparent even with a five volume % biodiesel dilution.

Optical Microscope Analysis of Wear Scars

Optical photomicrographs of the wear scars that developed on the cast iron after the reciprocating wear testing are shown in Figures 8, 9, and 10. These optical photomicrographs show that the wear mode for all three samples, irrespective of the amount of biodiesel dilution in the engine oil, was abrasive wear. However, these photomicrographs also show that as the biodiesel content of the engine oil increased, the severity of the abrasive wear decreased. This is consistent with the wear scar profile trace results.

It is also interesting to note that as the biodiesel content of the engine oil increases the scratches on the wear surface also decreased. These scratches were caused by wear debris being trapped between the piston ring and cylinder liner. Reducing the amount of wear debris or wear will reduce the number of scratches that develop. For this reason, the 10 volume % biodiesel engine oil had the lower number of scratches in the wear scar.

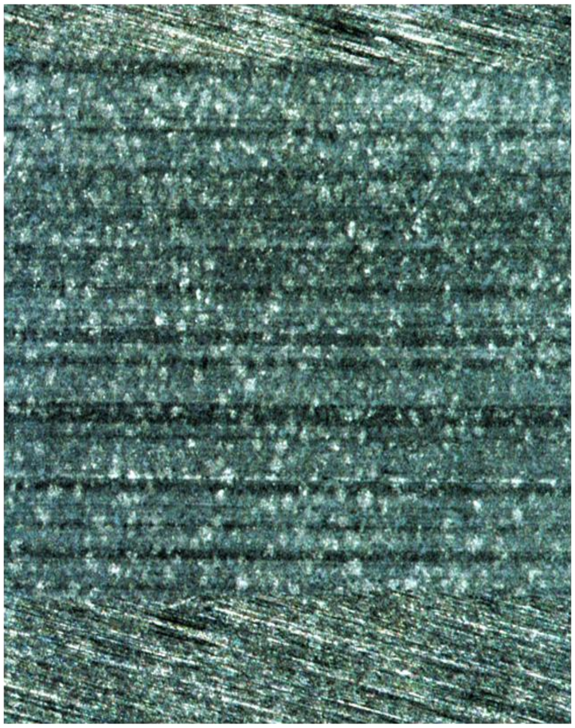


Figure 8.
Wear Surface – 0 % Biodiesel Dilution

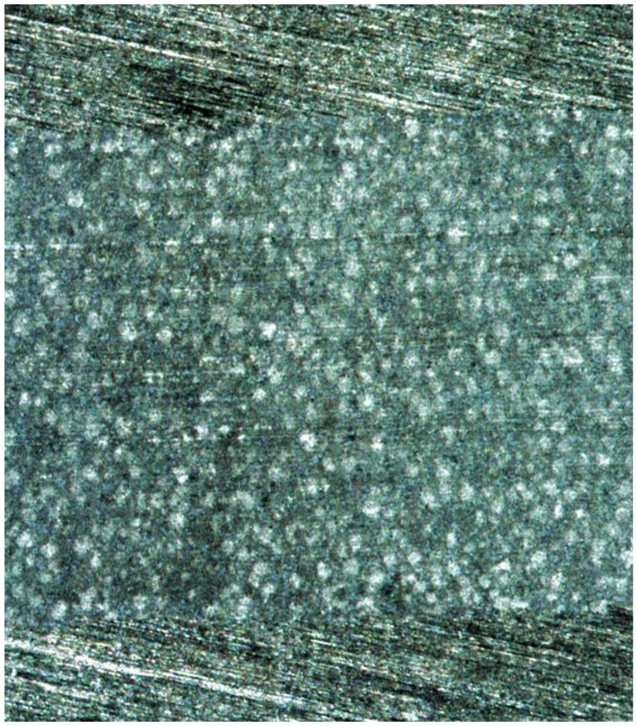


Figure 9.
Wear Surface – 5 Volume % Biodiesel Dilution

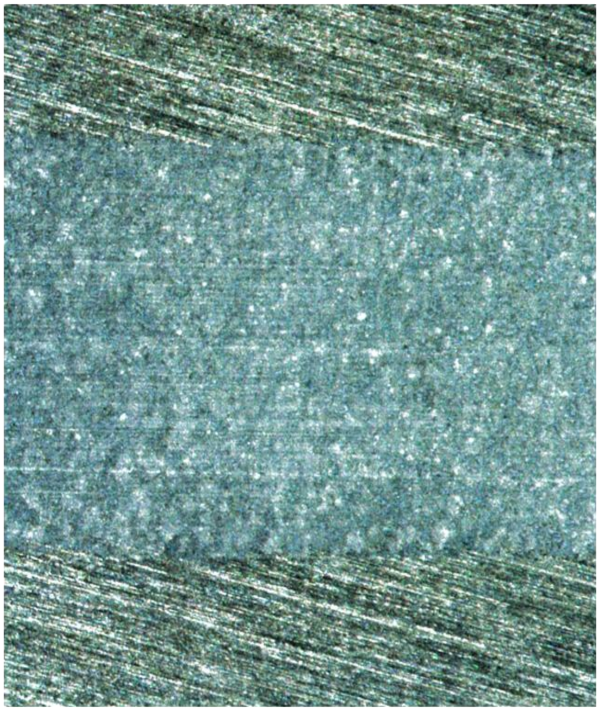


Figure 10.
Wear Scar – 10 Volume % Biodiesel Dilution

Summary of Component Wear Study

It has been postulated that biodiesel additions to engine oil would result in an increase of engine wear because it will dilute the engine oil, reducing its viscosity, and preventing it from developing a hydrostatic lubrication film between the ring and liner. Instead, this study showed that the opposite occurred and that increasing biodiesel content in the engine oil to 10 volume % decreased the amount of wear that occurred in the simulated piston ring/cylinder liner testing. The improved lubricating properties of the biodiesel more than offset any decrease in viscosity of the engine oil.

Another postulation was that biodiesel oxidation will occur at elevated temperatures and the products of this oxidation will interact with the wear additives present in the engine oil, increasing the amount of engine wear. All the testing in this study was performed at 300°F, a temperature significantly higher than a normal engine operating temperatures, and the biodiesel additions up to 10 volume % to the engine oil *reduced* the amount of wear that occurred during the friction and wear testing. Thus, at 300°F the biodiesel did not oxidize and cause an increased amount of wear.

The results of the simulated piston ring, cylinder liner testing showed that biodiesel dilution in the engine oil should not increase the engine wear. Instead this testing showed that biodiesel dilution up to 10 volume % should reduce engine wear.

Lubricity Improvement Using Biodiesel Fuel as an Additive to Ultra-Low-Sulfur Diesel Fuel

Background

The lubricity properties of a diesel fuel play an important role in obtaining long-lasting engine performance. Fuel pumps and high-pressure injection systems depend solely on the lubrication of the fuel to prevent wear. Within the last several years, a push for cleaner burning diesel fuel has resulted in EPA regulations requiring reduced sulfur content. Although ULSD fuel decreases sulfur emissions, the hydrogen treatment used to remove the sulfur also severely diminishes the natural lubricity of the fuel. In reaction to this problem, the fuel industry added a lubricity requirement to the *Standard Specification for Diesel Fuel Oils* (ASTM D975-07b).[19] This lubricity requirement specified both the test method[20] and the test lubricity limit (wear scar maximum of 520 microns). The lubricity test is called the High Frequency Reciprocating Rig (HFRR) and is summarized below from the ASTM description. In brief, the better a fuel lubricates in the HFRR test, the less wear is seen on the test ball.

Other research[21,22] describes tests involving various combinations of diesel fuel and biodiesel fuel using the HFRR test. These studies found that there was a significant loss of lubricity when a diesel fuel supply is converted from LSD to ULSD (refer to Figure 1). These studies also found that biodiesel has high lubricity compared to unmodified ULSD. They found that low additions of biodiesel to ULSD, between 1% and 2%, were able to show a marked improvement in lubricity. Unfortunately, overall research data tended to be less comprehensive in testing the various diesel blends such as summer blends vs. winter blends, or a full range of biodiesel dilutions in ULSD fuel. This study answers the lubricity questions regarding these blends.

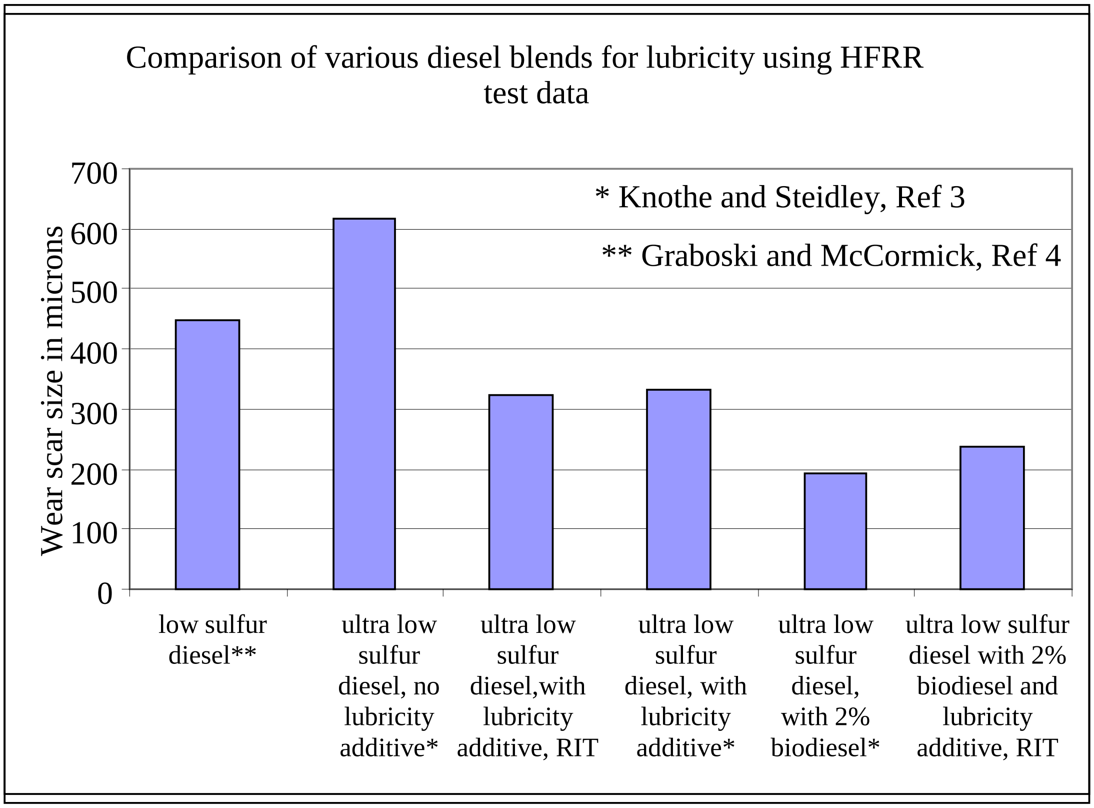


Figure 1. Overview of lubricity changes with fuel changes.

Experimental HFRR Test Apparatus and Setup

The standard method of measuring lubricity of a diesel fuel is ASTM D6079-97 using the HFRR equipment.[23] The basic test measures the wear which has occurred between two lubricated surfaces which are rubbed rapidly against each other. The test method specifies testing fuel at either 25ºC or 60ºC, but the 60ºC test is the prescribed method for the ASTM D975 diesel fuel specifications. However, the 60ºC requirement also makes the equipment much more difficult to build. It is not clear from the ASTM specification why 60ºC was specified. It can only be surmised that the viscosity of the oil was considered as a possible lubricity factor and that higher temperatures would reduce the oil viscosity enough, diminishing the lubricity to provide a "worst-case" test. The HFRR equipment built at RIT was designed for 25ºC tests only. Our lubricity testing is not intended to be a rigorous pass/fail test for the ASTM D975 diesel fuel specifications.

NOTE: The ASTM specification describes the repeatability (within a single lab, single machine) as 62 microns at 25ºC and 95% confidence and the reproducibility (between lab comparison) as 127 microns at 25ºC and 95% confidence. Therefore, the test variation is relatively large, both with repeated machine testing and between machine testing.

The HFRR is a machine designed to reciprocate a hardened E-52100 non-rotating steel ball loaded with 200 grams of mass against a polished annealed E-52100 steel plate. The plate is submerged under a layer of test fuel (approximately 0.635 cm depth) at a temperature of 25°C. The ASTM test method is very precise and requires a 1 mm stroke-length oscillating at a frequency of 50 Hz for 75 minutes. After the test, the ball is removed from the apparatus, cleaned, and the resulting wear scar is photographed under a microscope using 100X magnification. Results are recorded and compared. The smaller the wear scar size, the better the lubricity properties of that particular fuel.

After locating and pricing out several laboratory facilities that provide HFRR testing, and after receiving quotes to purchase a HFRR machine, RIT decided that it was more cost effective to design and construct a unit in-house. With the exception of the heating system, as previously mentioned, the RIT staff replicated the test requirements:

- 6 mm ball of 52100 hardened steel
- Annealed, polished 52100 steel test plate
- 200 g ball load
- 75 minute test duration
- 1 mm stroke length
- 50 Hz oscillation frequency

The RIT HFRR is a unique design consisting of a linear pneumatic vibrator attached to a sliding table that holds the test plate in a shallow bath of fuel (refer to Figures 2 and 3). The sliding table is mounted to a stationary base via vibration dampers that allow for motion adjustability. An arm is attached to this same stationary base and contains a linear ball bearing that freely suspends the ball holder in the z-direction above the sliding table while resisting movement in the x and y planes. The freely suspended specimen holder weighing 200 grams provides the required load when lowered onto the plate. Adjustment of the air pressure provides a frequency near 50 Hz. The results obtained using the RIT designed HFRR for various biodiesel and ULSD blends are very close those listed in the previously cited literature.

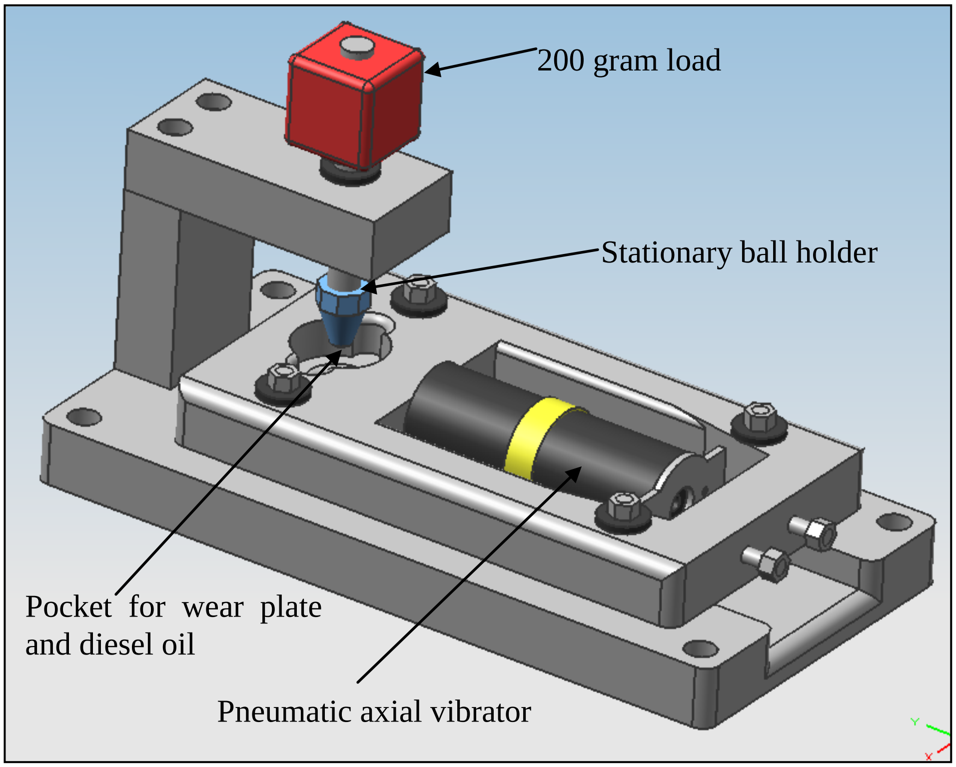


Figure 2. CAD drawing of HFRR design concept.

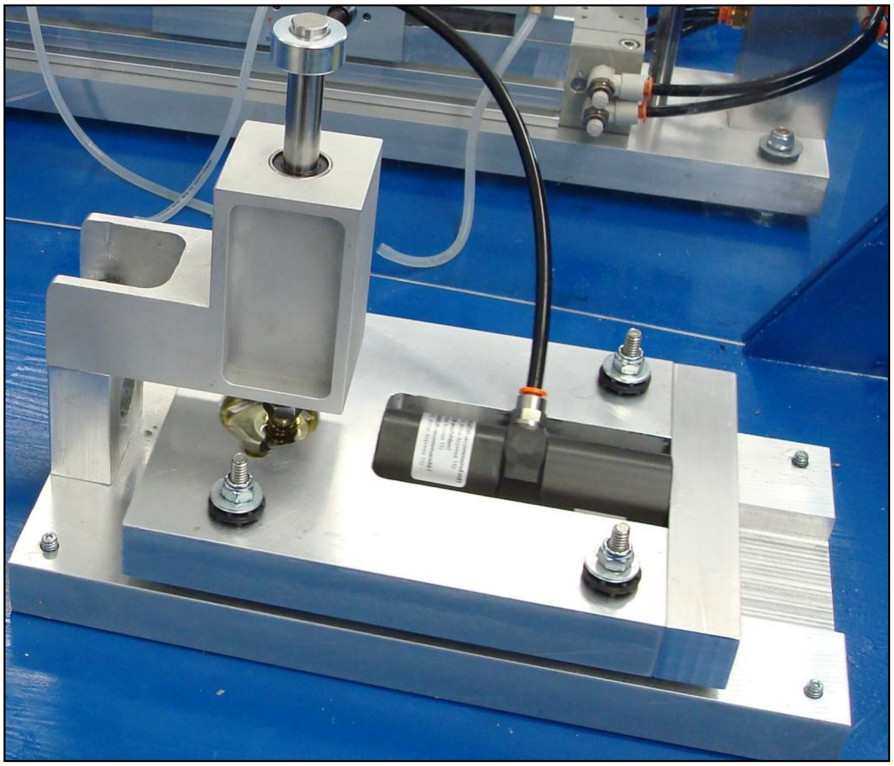


Figure 3. HFRR fixture as-built at RIT.

Test Procedure and Results

After designing, building, and tuning the HFRR, various biodiesel blends were tested both for comparison to data in the literature as well as for repeatability. ULSD was provided by a local diesel supplier with an additive (proprietary) to meet U.S. lubricity requirements. This ULSD was used as the baseline fuel for the lubricity comparison. This same USLD was then blended into the following combinations: B2 (2% biodiesel), B5, B10, B20, B40, B60, B80, and B100, respectively. All fuels were run twice. A clean ball and plate were used for each test. After the 75 minute test duration, as specified in the test method, the test ball was cleaned with alcohol to remove remaining biodiesel, and photographs were taken using 100 x magnification. Representative photos of the wear scars are shown in Figure 4. Scars were measured along the longest and shortest axes (X and Y, respectively), as shown in Table 1.

The results show a dramatic initial decrease in the wear scar size (i.e., large lubricity increase) with small additions of biodiesel followed by a very slight decline in the wear scar size as larger percentages of biodiesel are added (refer to Figure 5). This data correlates well with previous research[24,25], as shown by Figure 6.

Bio Blends	Test 1	Test 1	Test 2	Test 2	Test 1 and 2 combined
	HFRR scar X, microns	HFRR scar Y, microns	HFRR scar X, microns	HFRR scar Y, microns	Scar Averages
ULSD with lubricity additive	338	282	371	300	323
B2	262	203	269	211	236
B5	246	198	251	206	225
B10	251	191	251	191	221
B20	239	191	254	188	218
B40	234	160	236	175	201
B60	221	155	224	150	187
B80	213	142	229	145	182
Biodiesel alone	201	147	208	157	178
B5* Monroe County, winter blend	269	193	272	196	232
B20** RIT, winter blend	257	188	257	193	224

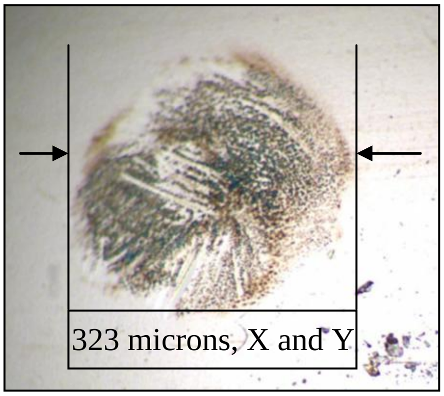
Table 1. Results of RIT HFRR lubricity testing.

* The Monroe County (NY) winter blend was 5% biodiesel, 30% kerosene, and 65% ULSD. RIT partnered with the Monroe County Fleet Center in Rochester, NY, to obtain additional information on the use of biodiesel. Monroe County has used biodiesel in various concentrations for several years and is providing both vehicle information and fuel test samples to RIT as part of this DOT Alternative Fuels project.

** The RIT winter blend was 20% biodiesel, 30% kerosene, and 50% ULSD. RIT went to 20% biodiesel compared to Monroe County to push the limits of what was typically used in the area during the winter months.

Winter Blend Test Results

Figure 5 also shows the lubricity values for two different biodiesel winter blends. Winter blends in upstate New York typically contain large percentages of kerosene to prevent gelling of diesel fuel at low temperatures. The addition of kerosene is even more important for biodiesel blends, because the gel-point temperatures are higher than for petroleum-based diesel fuel.[26] Because kerosene has a lower viscosity than diesel fuel, it is possible that the lubricity will be reduced. The RIT test results (refer to Figure 5) are significant because they show that the presence or absence of kerosene does not change the lubricity.



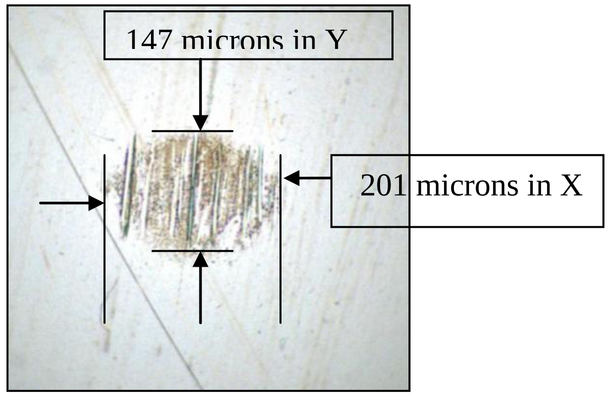


Figure 4. RIT HFRR tests: ULSD with lubricity additive (323 micron average wear scar on left), 100% soy biodiesel (174 micron average wear scar on right).

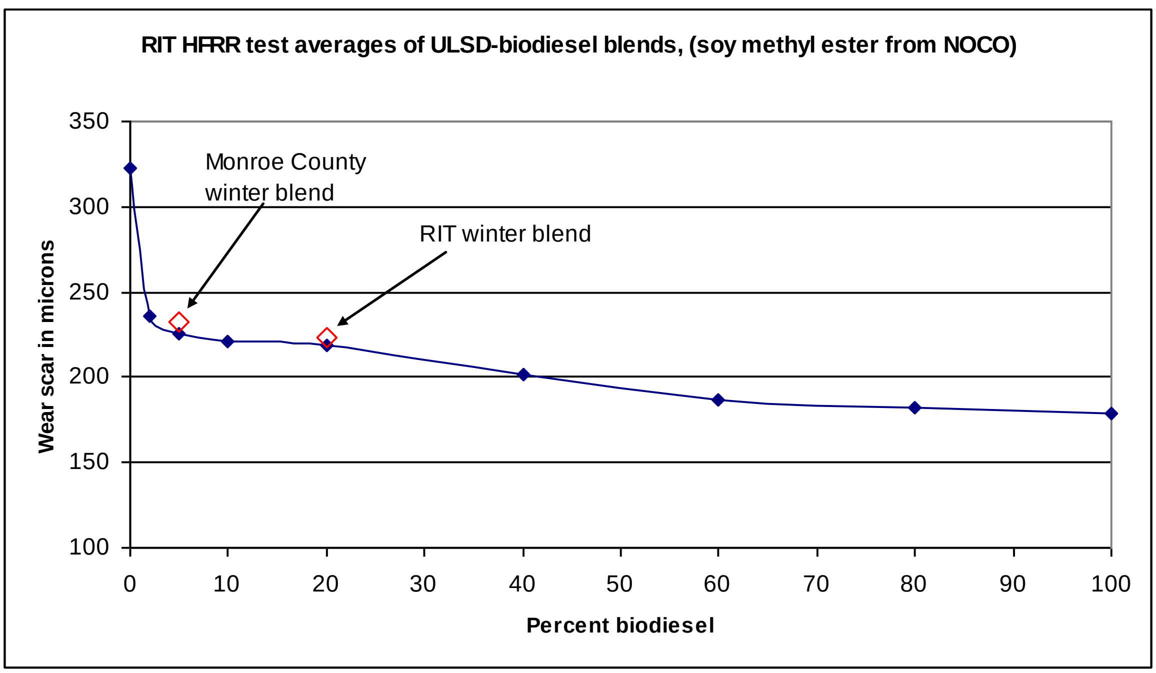


Figure 5. RIT HFRR results running blends from 0% biodiesel to 100% biodiesel.

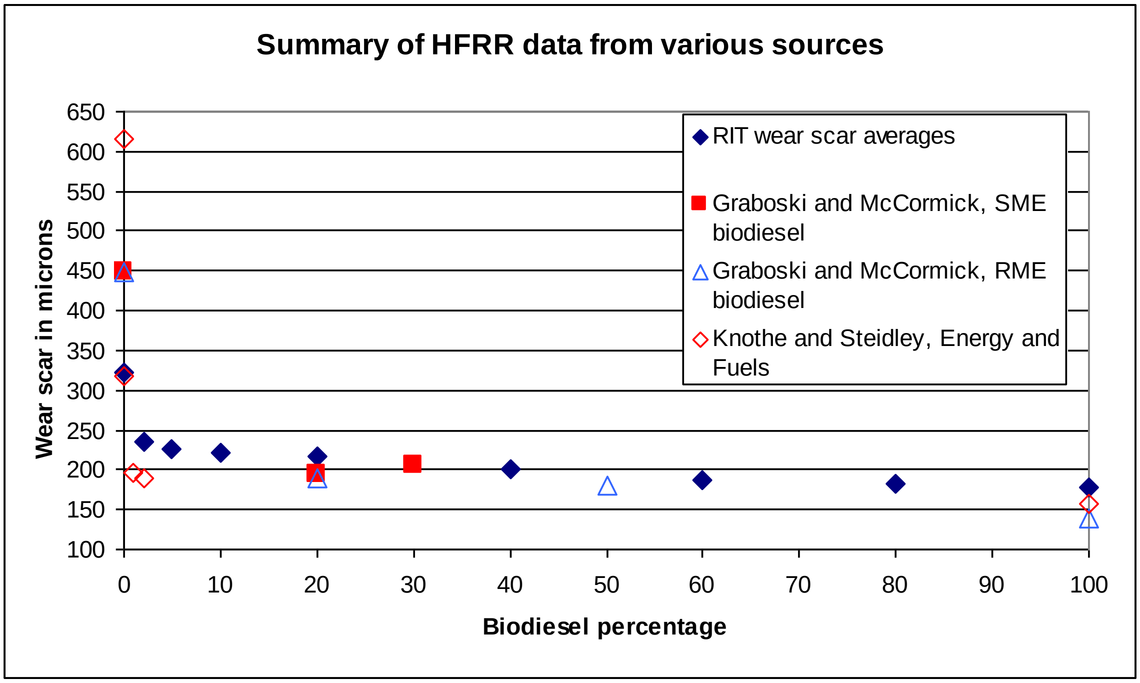


Figure 6. Comparison of other research data against RIT HFRR data.

Note: The maximum wear scar size allowed in the ASTM D975 test method is 520 microns.

Figure 6 shows the HFRR data of biodiesel blends and unblended diesel from references 3 and 4, together with the RIT data. The figure demonstrates that there is good correlation between the reported data and the RIT lubricity data.

Summary

Data from the HFRR fixture built by RIT shows good correlation of the lubricity data against data found in the literature. Our data reaffirms the lubricity improvement that small amounts of biodiesel make to ULSD fuel. This improvement is also evident for ULSD which already has lubricity additives. The addition of small amounts of biodiesel to ULSD is potentially able to reduce diesel engine friction and wear, thus improving engine efficiency as well as engine longevity.

This study also demonstrates that winter blends with significant amounts of kerosene have similar levels of lubricity with biodiesel added as summer blends with no kerosene.

Lubricity Testing References

1. ASTM International, ASTM D975-07b *Standard Specification for Diesel Fuel Oils*, West Conshohocken, PA. 2007.

2. ASTM International, ASTM D6079 - 04e1*Standard Test Method for Evaluating Lubricity of Diesel Fuels*, West Conshohocken, PA. 2004.
3. Knothe, G., and Steidley, K. R., "Lubricity of Components of Biodiesel and Petrodiesel. The Origin of Biodiesel Lubricity," *Energy and Fuels,* 2005, Vol. 19, No. 3, pp. 1192-1200.
4. Graboski, M. S., and McCormick, R. L., "Combustion of Fat and Vegetable Oil Derived Fuels in Diesel Engines," *Progress in Energy and Combustion Science*, Vol. 24, No. 2, 1998, pp. 125-164.

c. –Medium-Duty Truck Engine Dynamometer Study

The final phase of the biodiesel research program was an extensive laboratory test of a medium-duty truck engine. This phase was further broken down into three distinct tasks: a repeatability study of the test equipment; a fuel screening test to determine the impact of various biodiesel blends and finally a long-term durability study. The first section of this report describes the first task of biodiesel testing, a reproducibility and repeatability study of the test equipment. Later sections will document the results of performance and durability testing. We recorded performance, efficiency, exhaust emissions and engine operating parameters while looking for the influence of biodiesel on these responses. Finally, we looked for durability effects which are any of the long-term problems that cause an owner to replace or rebuild an engine. They include engine component wear, build up of combustion products, fuel system problems and maintenance items such as lubricating oil degradation.

Goals of the Medium-Duty Truck Study

For this final phase of biodiesel research, we identified the following goals:

- Measure the effects of high-blend-ratio biodiesel to mineral diesel fuels on engine durability. This is the primary goal of the project. Engine durability includes three main areas: wear, deposit formation and lubricating oil life. Wear includes the fuel system, combustion chamber components and the rotating assembly. Deposit formation is primarily the areas that contact the fuel and the combustion products. Oil life considers dilution caused changes in lubricity and viscosity.
- Measure the effects of high-blend-ratio biodiesel fuels on operating efficiency and exhaust emissions. Engine efficiency is important as it directly affects the operating cost. Currently, biodiesel is more expensive than petroleum diesel. Fleet managers will be interested in the true cost of switching to biodiesel blends before making that sort of commitment. Exhaust emissions measurement may help in understanding the causes and mechanisms of emissions production. At the very least, these measurements will add to the research community database of biodiesel emissions production. We will compare the changes between neat diesel and biodiesel blends to data from other researchers.
- Determine if there are optimum fuel blends for various operating conditions. Load and speed conditions are known to affect efficiency and the production of exhaust gas products like NOx and CO. It is possible that an interaction between load, speed and fuel blend exists also. If so, there may be blends that produce improved emissions profiles for different operating conditions.

We constructed our test program to achieve these goals.

Gage Reproducibility and Repeatability Study of Dynamometer Equipment

Our objective for this first task was to quantify measurement error, identify the error sources and quantify the minimum measureable differences in performance and exhaust emissions.

Background

CIMS constructed an engine dynamometer laboratory for this overall medium-duty truck engine project. We converted existing lab space with modifications to the HVAC, floor, walls and addition of a control room. We purchased an engine dynamometer with control system, two Cummins 8.3L diesel engines, a five-gas exhaust analyzer and an automated fuel mixing system.

Our initial series of tests were constant-torque runs while sweeping the engine's operating speed range. The results of these tests included large variation in exhaust temperature and in all measured emissions products. An analysis of variance (ANOVA) of the results identified run to run variation and operator-to-operator variation as significant factors.

After the disappointing results of the initial runs, we developed a simplified experiment based on a Taguchi L-18 Design of Experiments (DOE). The new experiment included nine simplified test runs consisting of constant torque, constant speed operation. Each run lasted 10 minutes. Calculated means, standard deviations and 95% confidence intervals revealed better results but variations were still high.

We ran a few long tests – up to four hours – and discovered a periodic variation in emissions levels over time. Furthermore, the oscillations were dependent on engine operating conditions and varied in both character and frequency. We refined the tests further, extending the run time and defining an acceptable measurement window for each run. Analysis of the trimmed data eliminated the operator and run variation and provided a 99% regression fit.

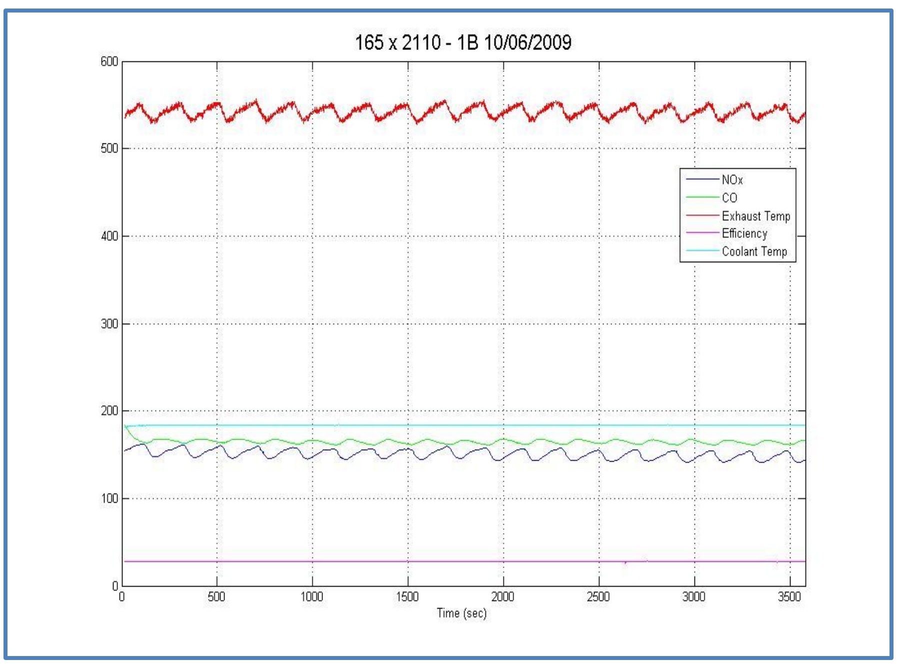


Figure 1 - Continuously varying exhaust temperature and emissions levels typical of high speed, low load operation.

Figure 1 and Figure 2 show two types of exhaust temperature and emissions variation experienced with RIT's combination of dynamometer and test engine. Final test data was for the continuously varying variation (Figure 1) was selected by capturing exactly two or more complete waveforms. For the damped variation of Figure 2, data collection was started after the responses reached steady state operation.

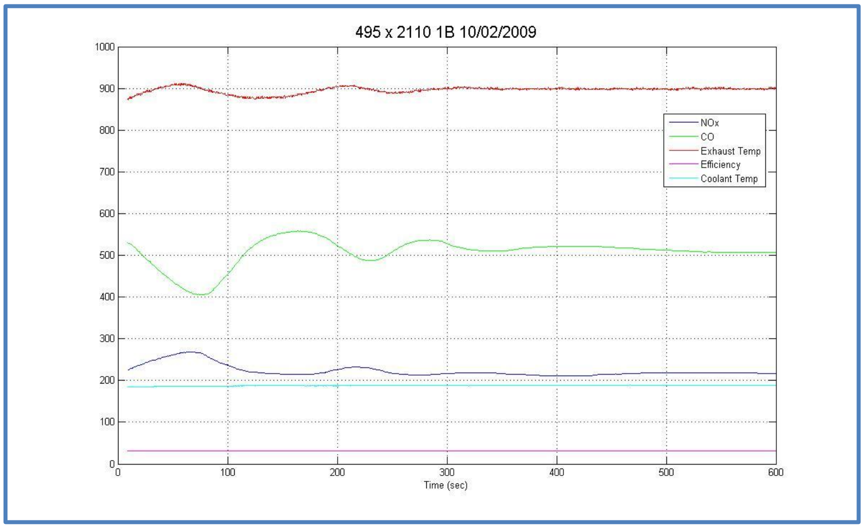


Figure 2 - Damped variation typical of high load, high speed operation.

In summary, the 95% Confidence Interval and error range are significantly reduced. We also identified the major error sources and devised methods that minimized their effect. We will use the extended runs and trimmed data during the next phase of testing.

Measurement error of the data acquisition system was measured by making repeated measurements during the same CTCS test. After the system reached steady state, measurements were made at 4 Hz for several minutes. This was performed for each CTCS test. A Taguchi Signal to Noise ratio calculation was made to identify the measurement noise compared to the measured effects. The Signal to Noise (S/N) ratio was calculated for each combination of set-points and for each response. Table 1 shows the calculations in dB.

ByTorque	ByRPM	SNO2	SNNOx	SNCO	SNExh	SNEff
165	1370	-35.6252	-48.2036	-46.3375	-54.2664	-42.15
165	1740	-35.7801	-47.3915	-47.1336	-54.692	-41.6483
165	2110	-36.057	-44.8032	-45.2429	-54.6863	-40.9603
330	1370	-33.7023	-52.3333	-48.4342	-57.0608	-43.0334
330	1740	-34.3947	-47.7099	-55.1092	-57.0435	-42.5392
330	2110	-34.8334	-45.2467	-52.0279	-57.1953	-41.6851
495	1370	-32.3194	-51.9588	-52.8037	-58.7807	-42.9715
495	1740	-33.3813	-47.1969	-55.4552	-58.5665	-42.3727
495	2110	-33.0184	-46.4843	-55.4159	-59.0518	-42.0374

Table 1 - Table of Taguchi S/N ratio calculations in dB.

To determine the run to run variation of the dynamometer and engine combination, the same CTCS tests were run repeatedly and a 95% Confidence Interval calculated for each of the exhaust products and for efficiency. The results ranged from 0.2% to 10.6% of measured value. Figure 3 shows the error for emissions, exhaust temperature and efficiency.

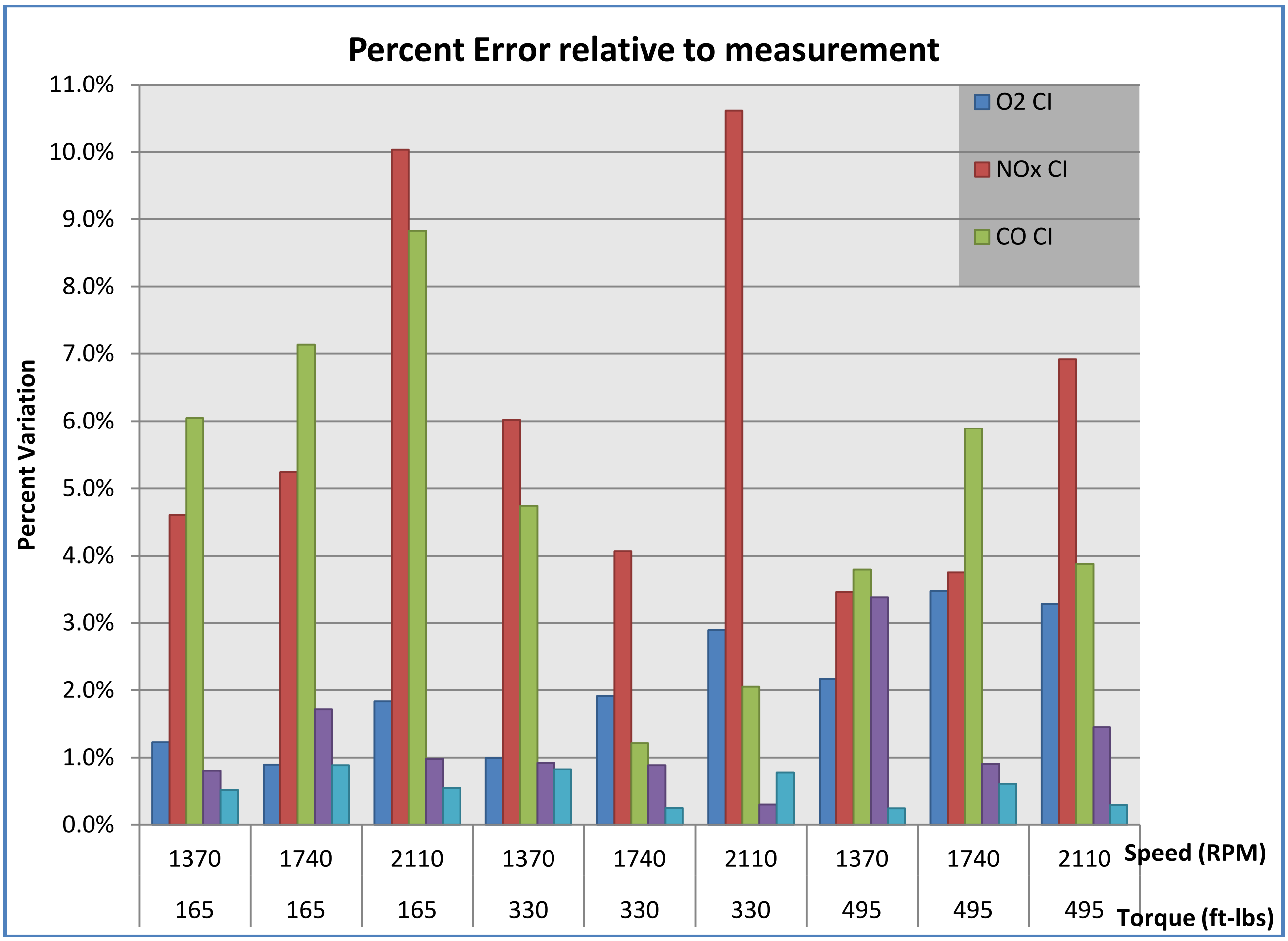


Figure 3 - 95% Confidence Interval of measurement as a percentage of error.

A copy of the full Gage R&R Study is available upon request.

Experimental Test Setup and Measurement Apparatus

The centerpiece of this project was the engine dynamometer. The dynamometer is a commercial Mustang eddy current brake capable of 350 hp and up to 1000 lb*ft of torque. The control software is also by Mustang and allows flexibility to automate test sequences and perform standardized emissions tests. Figure 4 is a photograph of CIMS' engine dynamometer lab.

Figure 4 - CIMS Engine Dynamometer Lab with Cummins ISC engine installed

Two exterior 300 gallon tanks – one for ULSD and one for B100 feed an automated mixing station that refills the 50 gallon internal day tank as needed. Heaters on both exterior tanks maintain a minimum tank temperature and reduce the probability of clouding or gelling. The fuel blend is programmed into the batch controllers manually. The blended fuel is then run through a chiller to maintain a stable temperature and therefore density. A volumetric flow meter measures fuel use.

A data acquisition module built around an Iotech Daqbook 2000 modular system provides thermocouple, transducer, digital and frequency inputs as well as digital and relay outputs. A weather station monitors temperature, humidity and barometric pressure and provides a correction factor to the dynamometer computer. Figure 5 shows the data acquisition module and the fuel automation panel.

Figure 5 - 'Boombox' data acquisition module (right) and fuel automation panel (left).

An ECOM 5 gas analyzer measures the exhaust stream for levels of O_2 , NO, NO_2 , CO, CO_2 and SO_2. CO, O_2, NO and NO_2 are transmitted to the control computer. Data input channels can be created for the emissions measurements within the Mustang EDT Cell software. Data input channels can be created for all data acquisition module channels within the Mustang EDT Cell software.

Two Cummins ISC240 8.3L common rail turbo-diesel engines will be used as test subjects (for the durability measurements) and as conversion mechanisms to convert the blended fuels to heat, torque and exhaust products.

Engine dynamometers are designed to measure torque and speed of a test engine. Additional equipment is often added to the test apparatus to measure fuel flow, heat loss and emissions. A precision fuel flow meter, a weather station, and a multi-gas combustion analyzer were added to CIMS Engine Dyno Lab. With the added equipment, CIMS is able to measure or calculate:

Engine torque
Power
Power corrected for weather conditions
Engine speed and acceleration
Efficiency
Brake specific fuel consumption (BSFC)
Nitrogen oxide
Nitrogen dioxide
Carbon monoxide
Oxygen content of exhaust
Exhaust temperature
Intake manifold pressure
Engine and coolant temperatures

During the final research, CIMS will measure the effects of fuel blends on the above characteristics. Measuring fuel effects necessarily makes the engine part of the measurement apparatus instead of the test subject as is normally the case with an engine dynamometer. That adds engine control system variation to the measurement system error.

Our control of the engine is limited to a throttle request and the load applied by the brake. The engine control module (ECM) converts the throttle input and demand to fuel flow rate and intake manifold air pressure (turbocharger boost). Typical control algorithms include Proportional Integral Differential (PID) closed loop control. The P or Proportional term, also known as gain, varies the output relative to the difference between the set point and the actual response (error). The greater the error, the greater the output either positive or negative. The I or Integral term sums the error over time and multiplies that sum by an integration coefficient and adds that to the output. The I term can affect the output both positively or negatively. The I term is sometimes known as the reset term and it is used to eliminate steady state error. The I constant is often replaced by a form of time constant (τ), indicating the process can be simulated by a first order system. Finally, the D or Derivative term adjusts the output in proportion to the slope of the error. Increasing error increases output while decreasing error reduces output. This allows the system to reduce overshoot and settle in on the set point. The D term acts as a damping coefficient.

A periodic variation in engine exhaust temperature and exhaust emissions was discovered during the Gage R&R study. The source of the variation is not known, but is suspected to originate in the control algorithms of either the dynamometer controller or the ECM or interference between the two. CIMS minimized the variation as much as possible with the equipment available, but could not eliminate it. The amplitude, frequency and damping characteristics of the oscillation changed at various constant torque constant speed (CTCS) levels. The CTCS test sequences were lengthened to allow the oscillation to either damp out or, in the case of those that did not diminish with time, to complete at least two complete cycles. The raw data was then trimmed using Matlab™ to select stable data.

Environmental factors affect engine performance. The weather station on the data acquisition module allows the control computer to adjust the output calculations of power by an environmental factor. The temperature in the room is subject to the variation allowed by the HVAC system.

Fuel Screening Study

Previous Research and Fuel Selection

Prior to planning the research scope of the biodiesel portion of this project, CIMS performed a review of pervious research studies to determine the target ranges of biodiesel blends for this study. Previous studies of blend ratios of 20% biodiesel in 80% petroleum diesel (B20) or less were found to be abundant. Very little information was available on the impact of higher blend ratios above 20%. Many of the previous studies have seen reductions in carbon monoxide (CO) and hydrocarbons (HC) with increased biodiesel use. Biodiesel effects on oxides of nitrogen, NO and NO2 (NOx combined) were not as clear. Some studies reported NOx increase and some reported NOx decrease. CIMS decide to pursue research on higher blends of biodiesel (>20%) to fill gaps in the overall research database on biodiesel fuels.

Objective of Fuel Screening Study

This fuel screening study was designed to uncover any cause and effect relationships between the engine operating parameters (fuel blend, load and speed) and the engine responses (exhaust products, performance, engine wear, combustion deposits and lubricating oil dilution. These characteristics are of particular interest to vehicle owner/operators because they directly impact total operating cost. Research and theoretical analysis have determined that turbo-diesel engines operate most efficiently at high loads and low speeds[27] but little is known about interrelationships between engine operating parameters and fuel blends. A design of experiments (DoE) was developed to test the effects of engine load, engine speed and fuel blend on exhaust emissions, exhaust temperature, power and efficiency.

Additionally, CIMS plans to expand the knowledge base of oxides of nitrogen production variation caused by biodiesel use in a modern diesel engine.

Operating Parameters

Operating parameters tested included:

- Fuel blend ranging from pure Ultra Low Sulfur Diesel (ULSD) to a blend of 90% soy-based biodiesel mixed with 10% ULSD.
- Engine loads as calculated for the European Stationary Cycle (ESC).[1] For the Constant Torque Constant Speed (CTCS) runs, we used 165, 330 and 495 lb-ft of torque.
- Engine speeds as calculated for the ESC. For the CTCS runs, we used 1370, 1740 and 2110 RPM.

As stated, engine temperature, lab temperature and fuel temperature were held constant throughout the testing as much as possible.

In addition to the CTCS runs, we performed an ESC cycle and a full throttle engine mapping run on each fuel blend. For each fuel blend, CIMS personnel executed a full series of tests, then ran the engine 16 hours and repeated the tests. The 16-hour runs were automated driving simulation cycles

[1] Definition of the European Stationary Cycle is found at http://www.dieselnet.com/standards/cycles/esc.html

in which two FTP driving cycles and one EPA driving cycle were repeated for 16 hours. For every fuel blend, the test sequences were randomized to simulate a more realistic driving environment.

Measured Parameters

During the test runs described above, the following responses were measured and recorded:

Exhaust Products
O_2
NO
NO_2
CO
Soot
Maximum power
Maximum torque
Efficiency
Brake Specific Fuel Consumption (BSFC)
Exhaust Temperature
Engine Temperature
Power

After every fuel blend series of runs, the exhaust manifold and one injector were removed from the engine and the cylinder, piston top, injector tip and valves were examined with a bore-scope. These components were inspected for any differences in combustion deposits that might be related to fuel differences. Finally, all the collected data were analyzed to determine significant relationships between fuel blend, performance, efficiency, emissions and durability.

The operating parameters included fuel blends, engine loads and operating speeds. Biodiesel was blended with Ultra Low Sulfur Diesel (ULSD) #2 summer blend (no kerosene or cold weather additives). The biodiesel feedstock was virgin soybean oil. The biodiesel was manufactured in accordance with ASTM D-6751. The following blends were tested:

Blend Name	Biodiesel (%)	ULSD (%)
B0	0	100
B20	20	80
B50	50	50
B70	70	30
B90	90	10

Table 2 - Tested Fuel Blends

The fuel blends were independently randomized within each test series.

Data Analysis

The data analysis portion of this Fuel Screening study focused on determining the significance and nature of the effects of fuel formulation, engine run time and operating conditions on exhaust products, efficiency and power. The data were analyzed using MiniTab™ statistics software employing a General Linear Model form of Analysis of Variance (ANOVA) to calculate the P-statistic for each effect thought to be possible. A study of residuals was performed to verify the quality of the data as well. A detailed discussion of the P-statistic and residual is presented in pages 9 and 10 of the Gage R&R Study Report.

Experimental Procedure

Testing Blocks

CIMS performed two test blocks during the Fuel Screening study. The tests and run-in hours were identical with the exception of randomization. To avoid confusing any time dependent variation, the fuel mixture batches were randomized within each block. The actual test sequences were then randomized within each fuel mixture batch.

Each block of testing included a first series of tests, followed by a 16-hour run-in cycle followed by a second series of tests for each fuel blend described in Table 2. Figure 6 shows the organization of one block of testing. The test series and run-in cycle are described in the following sections.

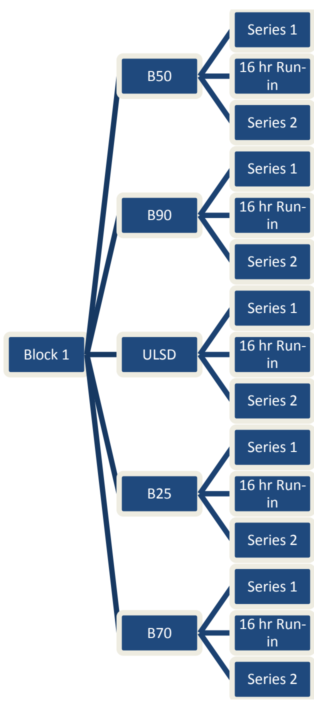


Figure 6 - Example of Test Sequence for each Block

Equipment changes between blocks

Between the first and second test blocks of the Fuel Screening study, CIMS made two significant improvements to our data acquisition capabilities in the engine dynamometer lab: better definition of Nitrogen oxides and Soot (unburned carbon) measurement. All new measurements were added to the data files collected throughout Block 2.

Software change to differentiate NO and NO2

During the first block of testing, CIMS' ECOM five-gas analyzer transmitted levels of CO, NO_x and O_2 to the Mustang control computer. In addition to those gases, the analyzer displays CO_2, SO_2, NO and NO_2 levels on the screen on its faceplate. After the first block of testing, CIMS contacted ECOM about transmitting some of these channels to the control computer as well. ECOM was able to send us a software upgrade that enables transfer of the NO and NO_2 levels to the Mustang control computer instead of the combined NO_x.

Added AVL Soot meter

CIMS had purchased an AVL Model 483 Micro Soot Meter for another program. As a result, we were able to use this equipment during the time period when we ran the second block of the Fuel Screening study. Throughout the second block, we used the soot meter to gather relative soot measurements of the exhaust gas. The soot meter communicated to the Mustang control computer through analog input channels on one of the Daqbook DBK-65 modules.

Test Series 1

Block 1 testing consisted of a series of nine Constant Torque Constant Speed (CTCS) runs, one full throttle performance mapping run and a European Stationary Cycle run. The order of the test sequences, including the nine-test matrix shown in Table 3, the ESC and Mapping test were randomized every time they were run. The full series of tests as described in the following sections was performed for each fuel blend shown in Table 2.

Constant Torque, Constant Speed Testing

The CTCS runs include a complete matrix of three torques and three engine speeds run in all combinations. The magnitudes of the engine speed and torque settings were determined by the 25%, 50%, and 75% levels calculated in the ESC. The matrix is shown in Table 3.

Torque \ Speed	1370 RPM	1740 RPM	2110 RPM
165 lb*ft	165-1370	165-1740	165-2110
330 lb*ft	330-1370	330-1740	330-2110
495 lb*ft	495-1370	495-1740	495-2110

Table 3 - Torque and Speed Test matrix

The length of each test ranged from about 12 to 35 minutes. The test lengths were determined during the previous Gage R&R study. That study revealed periodic variations in intake manifold pressure, exhaust gas temperature and exhaust products over time. The chosen test lengths allow the engine and control system to stabilize and provide a reliable set of data.

European Stationary Cycle (ESC)

The European Stationary Cycle is a 13-mode test used for emission certification of heavy-duty diesel engines from the Euro stage III (2000). Table 4 lists the ESC test modes and weight factors used to calculate ESC Emissions ratings. The test includes all of the modes of the CTCS tests plus an idle mode and three 100% load modes. The main purpose of the ESC test is to calculate an average of engine emissions weighted by operational modes.

Mode	Engine Speed	% Load	Weight factor, %	Duration
1	Low idle	0	15	4 minutes
2	A	100	8	2 minutes
3	B	50	10	2 minutes
4	B	75	10	2 minutes
5	A	50	5	2 minutes
6	A	75	5	2 minutes
7	A	25	5	2 minutes
8	B	100	9	2 minutes
9	B	25	10	2 minutes
10	C	100	8	2 minutes
11	C	25	5	2 minutes
12	C	75	5	2 minutes
13	C	50	5	2 minutes

Table 4 - European Stationary Cycle Test Modes

CIMS included the ESC test to provide a standardized test for comparison to data collected from other labs.

Engine Map

The engine mapping sequence is a full-throttle test designed to accurately map the engine's torque, power and efficiency over its useful speed range. It is an automated test controlled by the Mustang controller based on engine specifications entered by the operator. At the start of the sequence, the engine throttle is fully opened and the brake applies the proper torque to hold the engine speed down to its idle speed. The controller then continuously adjusts the brake torque to allow the engine speed to increase at a specified rate; for this specific series of tests, we used 10 RPM/second. Upon reaching the engine's governed speed or a predefined safe operating speed limit, the throttle is closed, the torque is released and the engine speed is reduced to idle.

Throughout the test sequence, the torque, engine speed and fuel flow rate are constantly measured and logged. Power, corrected power, efficiency and Brake Specific Fuel Consumption (BSFC) are calculated and logged in the same output file as are all other monitored channels. A MATLAB™ function was used to sort and plot various measurements and results. A sample of an engine mapping plot is shown in Figure 7.

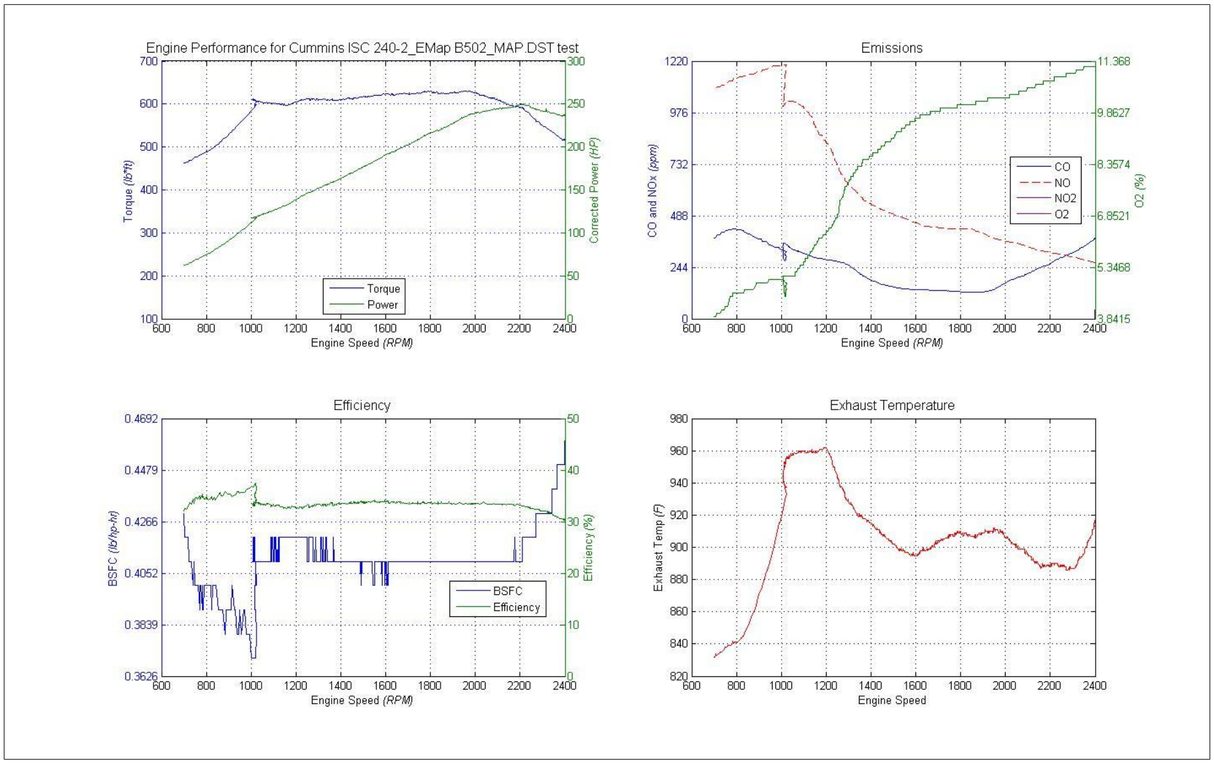


Figure 7 – Performance Plots of Cummins ISC-240 operating on B50 Blend

Run-In

After each round of performance, efficiency and emissions testing as described above, the test engine was run on its test fuel for 16 hours. The Mustang controller ran a custom driving cycle made up of the FTP Heavy Duty Urban Driving Cycle (HD-UDDS) and the EPA Dynamometer Highway Driving Cycle (EPA-HWFET).[2] Figure 8 shows the two cycles that make up the custom driving cycle. The custom cycle uses two parts of the HWFET cycle and one part UDDS. The cycle is repeated for 16 hours. The operator starts the custom cycle at the end of a day of testing and lets the engine run until the next morning.

After 16 hours of operation in the custom driving cycle, the engine was prepared for another complete series of performance, efficiency and emission tests.

[2] Definition of these EPA cycles can be found at: http://www.dieselnet.com/standards/cycles/esc.html.

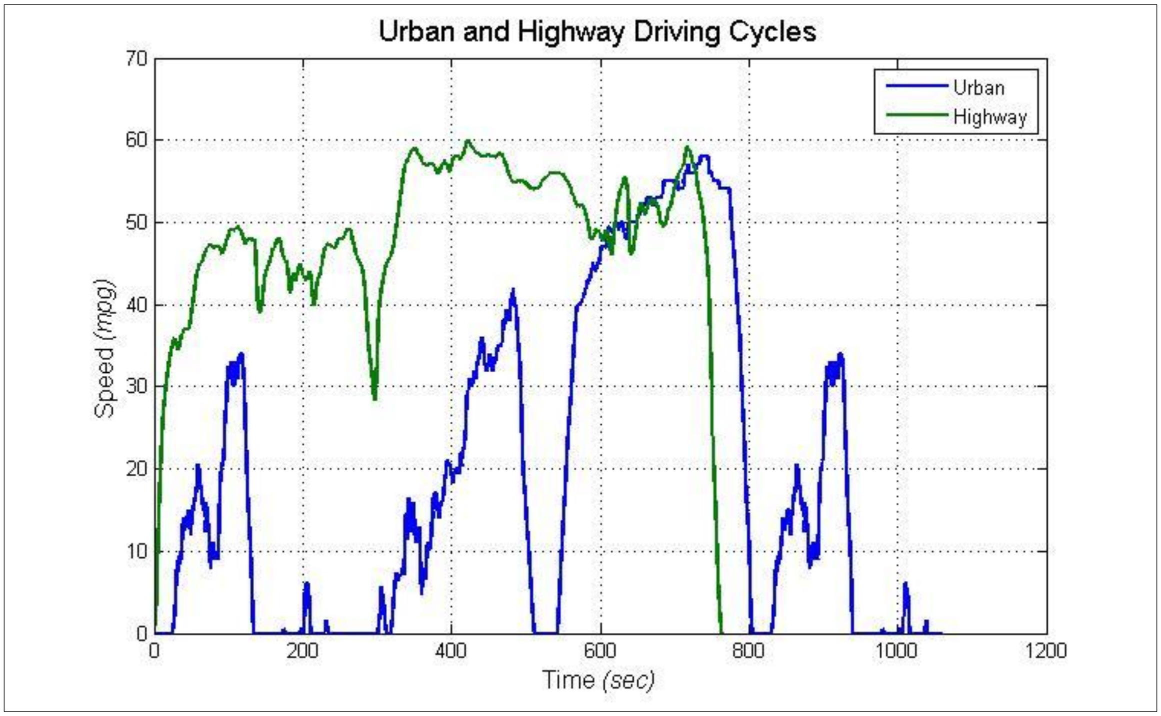


Figure 8 - Urban and Highway Driving Cycles

Test Series 2

After each 16-hour run-in, a second series of performance, efficiency and emissions tests was run. Test Series 2 included the same tests as Test Series 1. The sequence of tests in the second series differed due to independent randomization, but the tests were otherwise identical to those in Test Series 1.

Results

Exhaust Products

During each Test Series, CIMS used our five-gas analyzer to record engine exhaust products. During the first block of testing CO, O_2, and the combined product of NO and NO_2 (known as NO_x) were recorded. During that first block, the effect of fuel formulation on NO_x was not found to be significant. After the first block of testing, CIMS had the ECOM 5-gas analyzer modified to differentiate and record NO and NO_2 instead of the combined NO_x.

Minitab™ was used to perform an Analysis of Variance (ANOVA) on the measured results. The P-statistic, along with an analysis of residuals (difference between empirical means and predicted means) was used to determine the statistical significance of each factor on each response.

Definition of Power or P-Statistic

Power (the P value) is the probability that the test rejects the null hypothesis when the alternate hypothesis is true (Moore and McCabe 1989). A statistical hypothesis is a statement about the parameters of a probability distribution. For example, our null hypothesis is that the mean of operator 1 effects is the same as the mean of operator 2 effects and the alternate hypothesis is that they are not the same.

$$H_0: \mu_{Operator1} = \mu_{Operator2}$$
$$H_A: \mu_{Operator1} \neq \mu_{Operator2}$$

To test the null hypothesis, we take a random sample of measurements from each population and reject or fail to reject the null hypothesis based on the population means and combined standard deviations. A specified set of values called the *critical region* or *rejection region* is specified for the test.

There are two types of possible errors when testing hypotheses. A Type 1 or α type error rejects H_0 when H_0 is true and a Type 2 or β type error fails to reject H_0 when H_0 is false. The Power of the test P = (1 – β) = P(reject H_0 if H_0 is false). In English, the power of the test is the probability that the null hypothesis was rejected when it was indeed false. The power of each of the tests in the ANOVA above is zero, or that there is no possible way we falsely rejected the hypothesis that there is no difference between operator effects. To attain a 95% confidence that we falsely rejected H_0, we accept a maximum power or P-value of 0.05 (Montgomery 1994).

Oxygen (O_2)

Mean exhaust O_2 content increased slightly from 13.05% to 13.55% with increased biodiesel content – about a 4% change. Figure 9 shows the effects of fuel blend, torque and engine speed on exhaust O_2 production during Block 2 of the Fuel Screening tests. The P-statistic for the O_2 main effect is 0.000, indicating that the effect is caused by the change in biodiesel ratio.

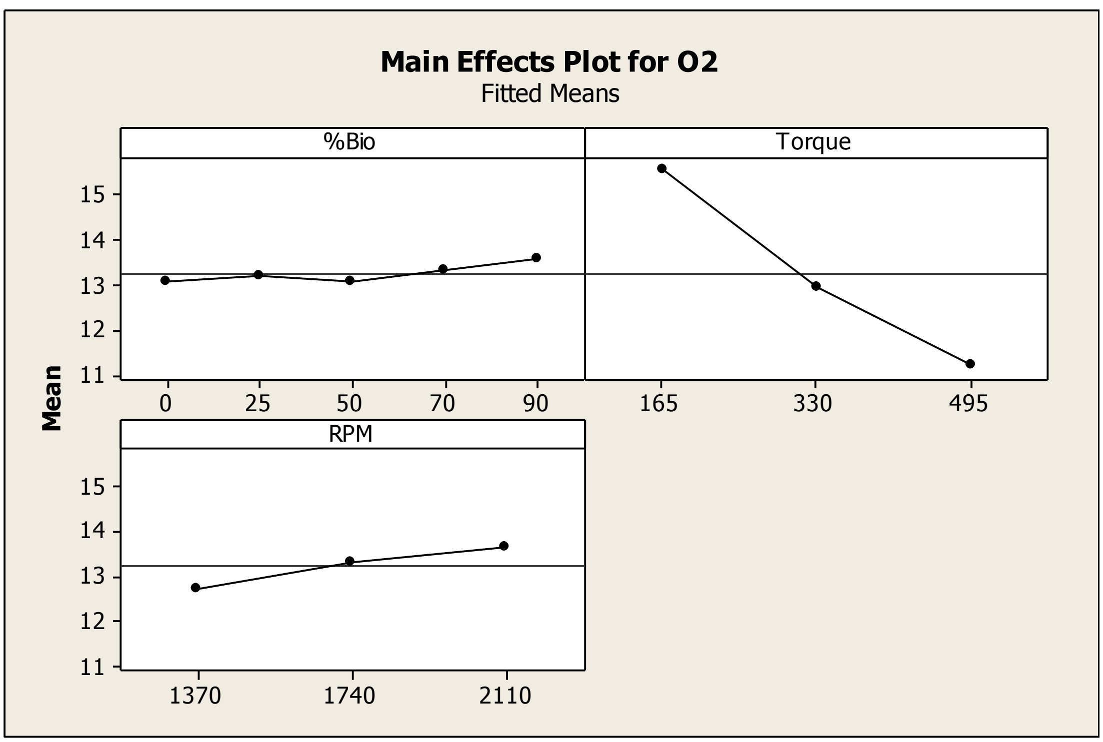


Figure 9 - Effects of fuel blend, torque and engine speed on O_2 production in engine exhaust.

During the conversion of vegetable oils or animal fats (triglycerides) to biodiesel, the triglycerides react with short-chain alcohol to produce three monoalkyl esters and a glycerin. The monoalkyl esters are comprised of a carbon-hydrogen (CxHy) chain bonded to a hydroxyl (OH). The hydroxyls add oxygen to the biodiesel, typically 11% by weight. There are two potential explanations for the increased O_2 in the exhaust: directly from the fuel borne oxygen or from excess airborne oxygen. The excess airborne oxygen is likely because the shorter C-H chains in biodiesel, compared to ULSD, do not require as much oxygen for complete combustion.

Oxides of Nitrogen (NO_x)

In the first block of testing, the nitrogen emissions NO and NO_2 were combined into one group, NO_x. The P-statistic of the NO_x response from fuel blend was 0.35, indicating that the effect is indistinguishable from experimental noise. Figure 10 shows a slight random variation around the NO_x mean for fuel blend. Torque and engine speed have a significant effect on NO_x production.

After evaluation of the Block 1 NO_x data, it appeared that any effects of individual nitrogen species may be lost in the combination. For the second block, a change was made to the ECOM five-gas analyzer to differentiate NO and NO_2.

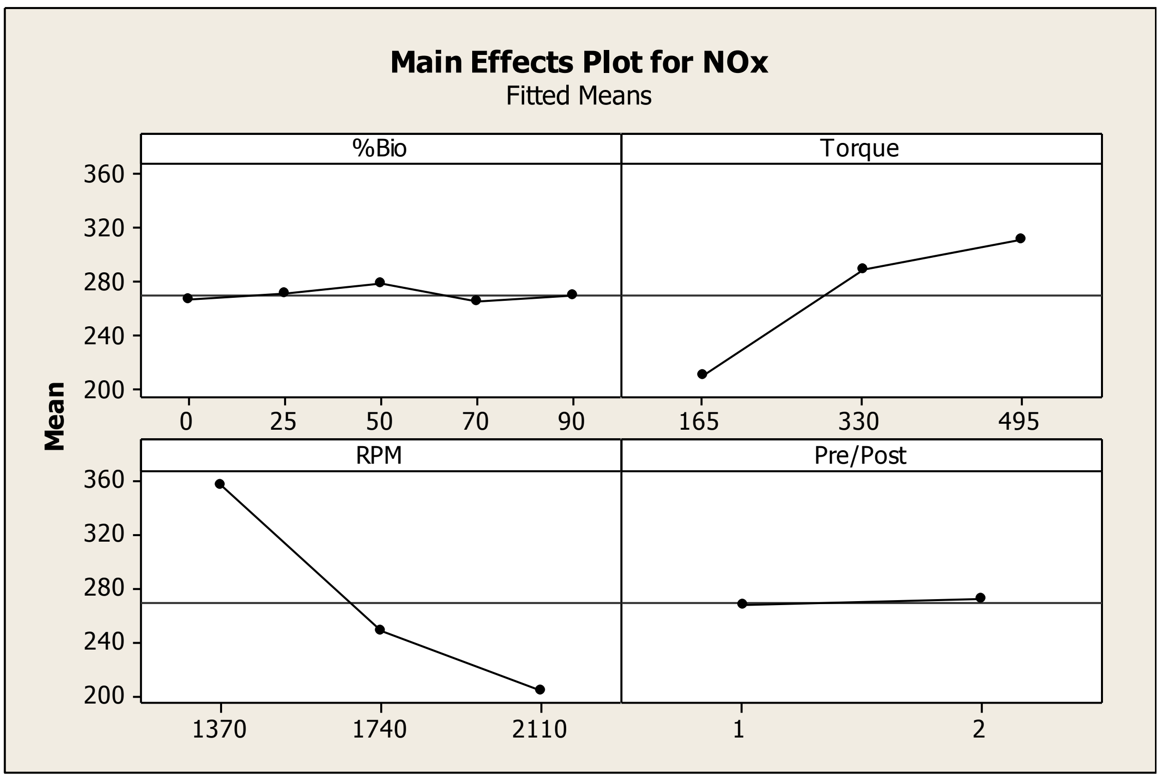


Figure 10 - Effects of fuel blend, torque, engine speed and run-in time on NO_x production.

Nitric Oxide (NO)

Fuel blend was found to be a significant factor in the formation of NO in the engine exhaust during Block 2 of the Fuel Screening study. The P-statistic of fuel blend on NO is 0.035, indicating that fuel blend is likely to affect NO production. While the trend in the data shows increasing levels of NO with increasing levels of biodiesel, there is much variation in the data. The average standard deviation of the data in Table 5 is 40%. The large variance makes it difficult to accurately predict the trend in NO. The ESC weighted levels and the CTCS unweighted levels predict similar trends: about an 8.5% increase in NO with biodiesel. In contrast, the change in NO due to engine torque is 39.5% and the change due to engine speed is 47.6%. Figure 11 shows the effect of fuel blend on exhaust products including CO, NO, NO_2, and Soot using the European Stationary Cycle weighted ratings.

%Bio	Mean NO (ppm)	NO Std Deviation
0	219.0	87.0
25	238.1	96.8
50	222.9	93.3
70	217.1	87.3
90	229.9	90.4

Table 5 - Mean NO exhaust levels at various fuel blends.

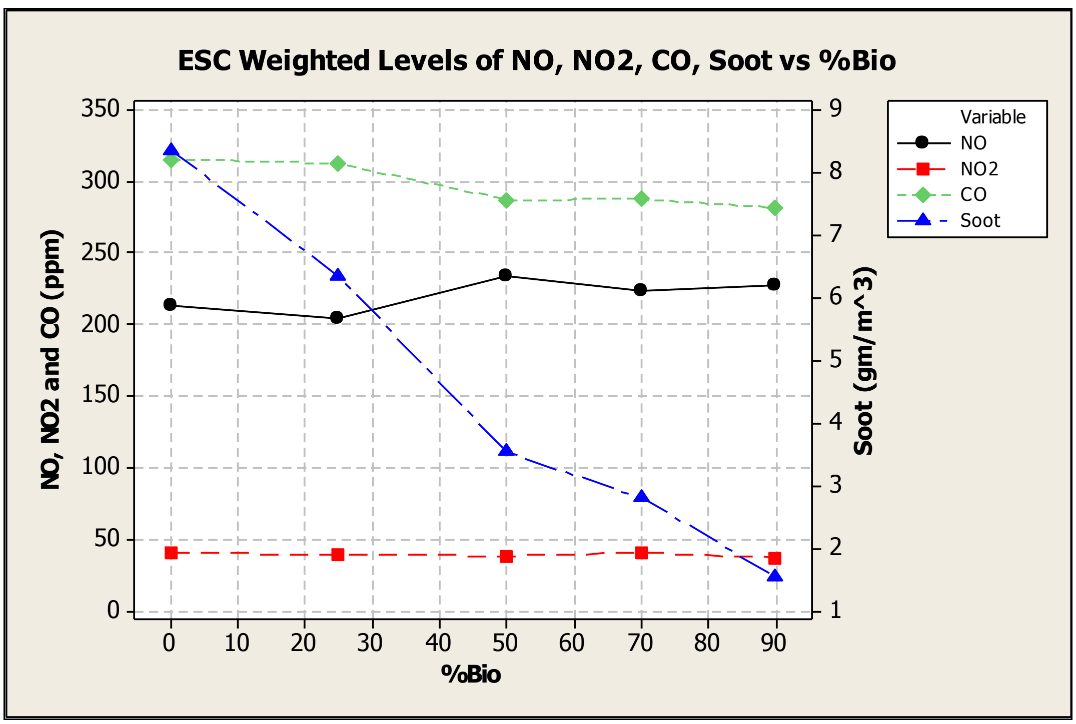


Figure 11 - European Stationary Cycle weighted levels of NO, NO_2, CO and Soot vs. fuel blend.

Nitrogen Dioxide (NO_2)

%Bio	Mean NO_2 (ppm)	NO_2 Std Deviation
0	37.28	9.9
25	40.76	9.55
50	41.55	6.91
70	48.36	11.52
90	35.07	8.50

Table 6 - Fuel Blend Effect on NO_2 in Block 2 of the Fuel Screening Tests.

In the second test Block, fuel blend was found to be significant to NO_2 production in the engine exhaust. The variation in the NO_2 data was lower. The average standard deviation of the NO_2 vs. fuel blend data was 23%. The fuel blend effect on unweighted CTCS NO_2 measurements showed a 30% increase. The ESC weighted NO_2 measurements showed an 8.5% reduction. In either case, the effect was a general trend with considerable point-to-point variation. Figure 11 and Table 6 show the two different trends in NO_2 production.

It was hypothesized that an interrelationship or interaction effect between fuel blends and operating parameters exists on some or all of the response factors of this experiment. An ANOVA was calculated for the fuel – torque and fuel – RPM interactions on emissions and efficiency. The P-statistics for NO and NO_2 for those interactions were all well above the significant level of 0.05 indicating that no interaction can be proved with this data.

Carbon Monoxide (CO)

The P-statistic for the fuel blend effect on CO is 0.000, indicating a strong correlation between the two factors. CO means for each fuel blend indicate a 15.5% reduction in CO between ULSD and B90 fuels. Table 7 shows fuel blend mean CO production from the Block 2 screening tests. Fuel blend effect is 15.5%. Torque effect is over 50%. RPM effect is about 50%.

%Bio	Mean CO (ppm)	CO Std Deviation
0	353.4	138.4
25	317.7	126.6
50	322.7	130.1
70	316.7	134.9
90	298.6	137.7

Table 7 - Fuel Blend Effect on CO in Block 2 of the Fuel Screening Tests.

As in other exhaust products, engine operating conditions cause a larger change to CO production than fuel blend. Torque and engine speed each produce a 50% change in CO production. Figure 12 compares the fuel blend effect on CO with the torque and speed effect. Figure 11 shows the fuel blend effect on the ESC weighted CO measurements.

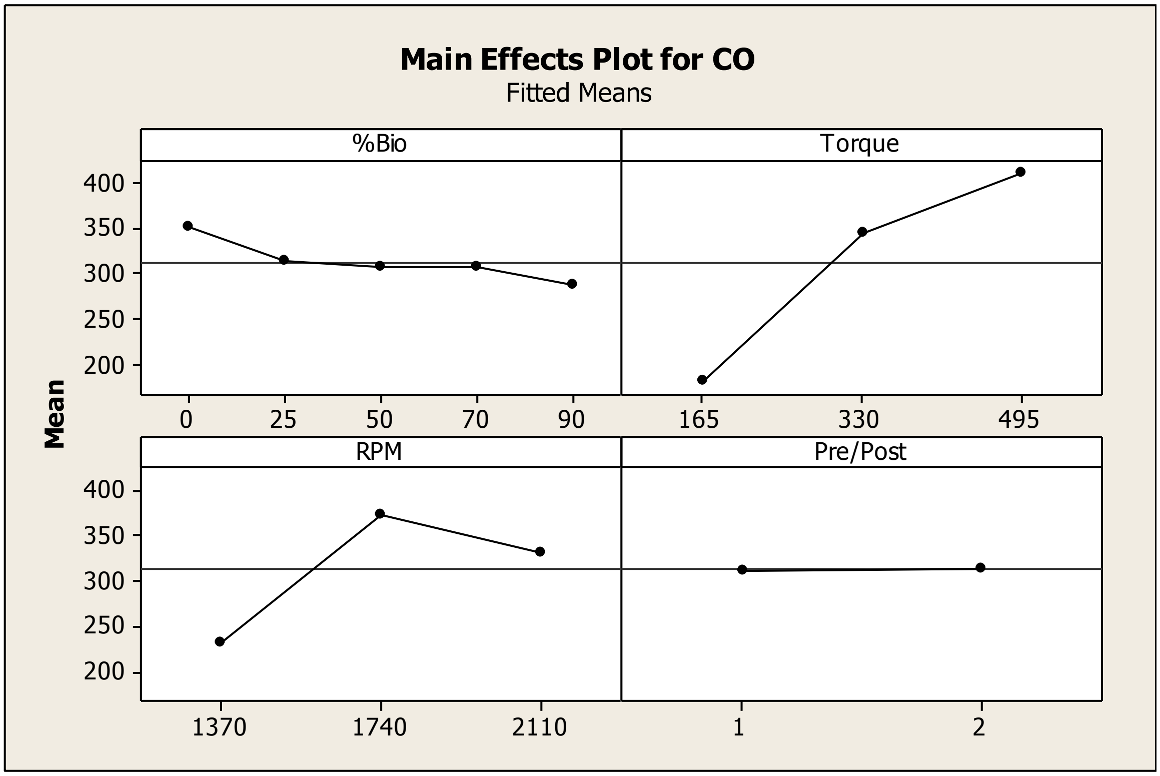


Figure 12 - Main Effects plot of CO production.

The fuel + torque and fuel + speed interactions were significant to CO production. The P-statistics for each were 0.000 and 0.014 respectively. However, the F-statistics were very small in comparison to the F-statistics for the main effects, indicating that the interaction effects are real but small. Inspection of the interactions plots (Figure 13) shows a couple subtle differences in CO production at different ratios of biodiesel. Of course the main effect is that CO levels are reduced with increased biodiesel ratio as already stated. The variation between CO production rates at medium and high torque and medium and high speeds shows that the variation is smaller at increased speeds, torques and biodiesel ratios. In other words, when using high quantities of biodiesel, torque and speed are not as critical.

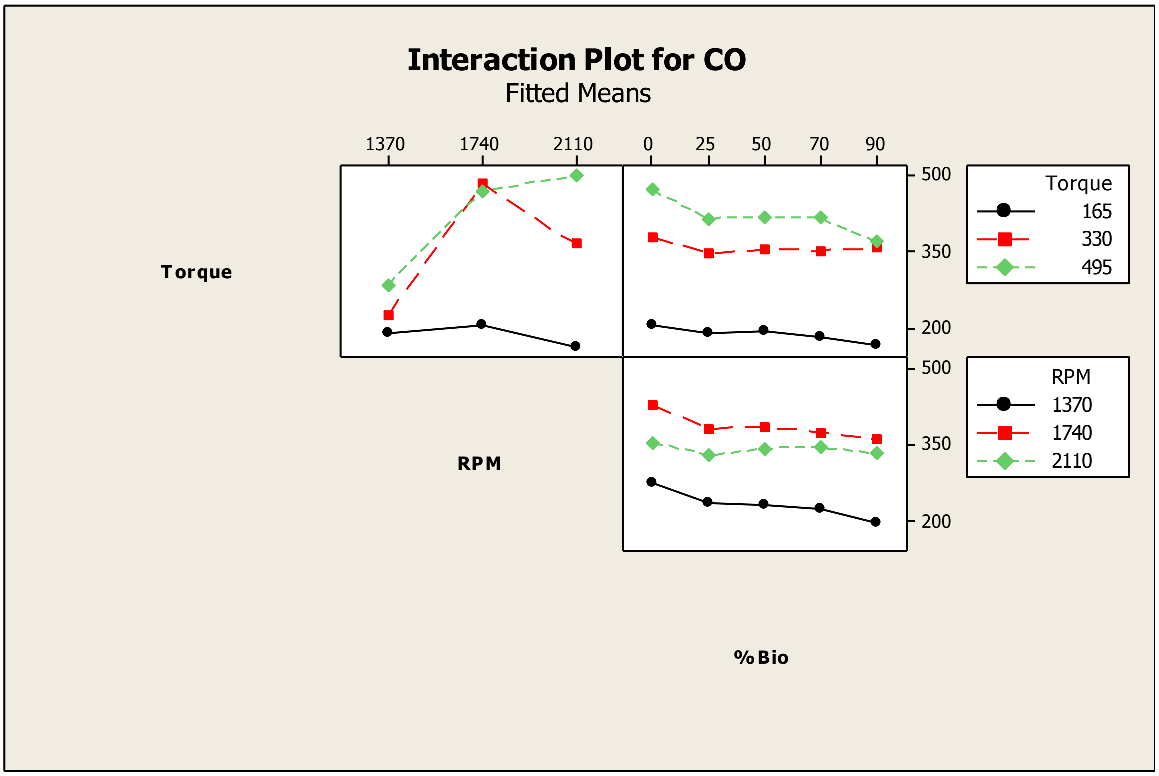


Figure 13 - Interaction effects of fuel + torque and fuel + speed on CO production.

Soot

The effect of fuel blend on soot production was by far the most dramatic. Figure 14 demonstrates that the fuel blend effect exceeds the torque and speed effects. During the CTCS runs, increasing the fuel blend from ULSD to B90 reduced the soot content from 6.45 g/m^3 to 0.95 g/m^3 for a total reduction of 85.3%. Figure 11 includes the ESC weighted Soot values in g/m^3 over various fuel blends. The ESC weighted measurements dropped from 8.35 g/m^3 to 1.55 g/m^3, an 81.4% reduction.

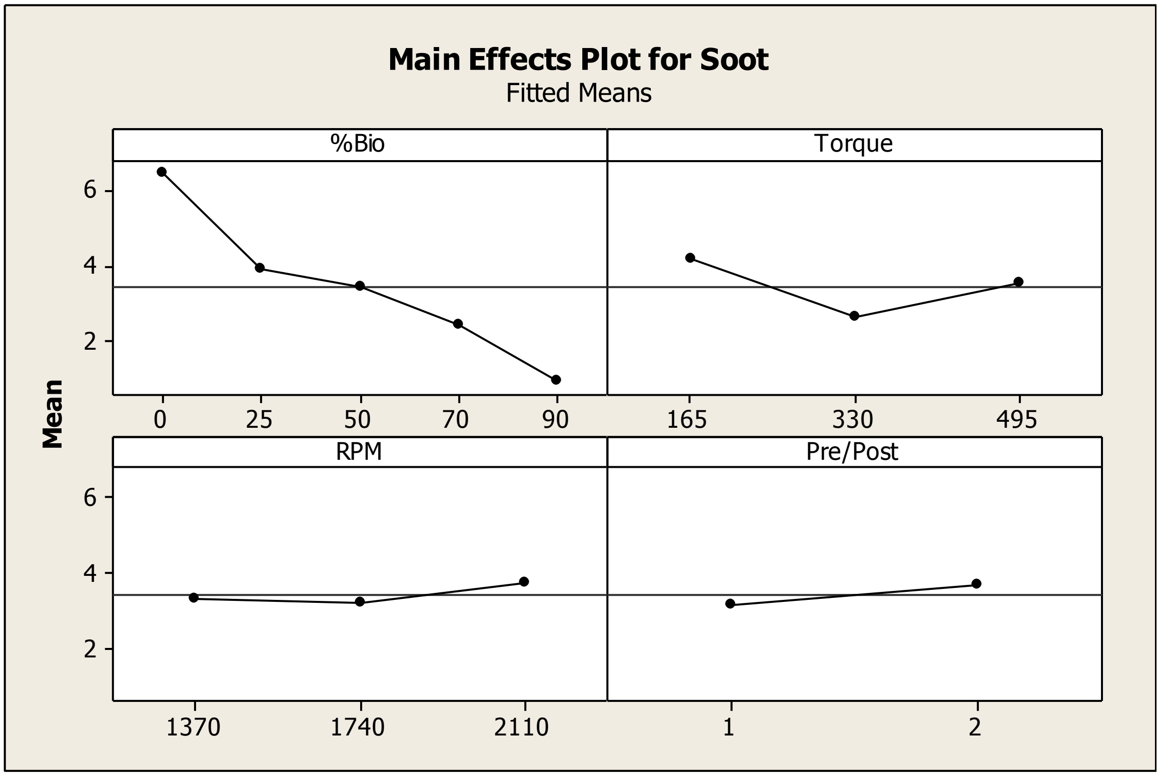


Figure 14 - Comparison of fuel, torque and speed effects on soot production.

Fuel + torque and fuel + speed interactions on Soot production showed no significant effect. The P-statistics for each were 0.227 and 0.368 respectively.

Performance

Engine performance was measured using the Engine Mapping Test. Sample means for maximum engine torque and power were calculated and compared for each fuel blend. Using MiniTAB™ ANOVA, CIMS calculated the significance of the fuel effects on maximum torque and power. The P-statistics for the fuel blend effect on maximum torque and power were both less than 0.05, indicating that the measured effect is not likely caused by anything other than the fuel blend.

% Biodiesel	Max Torque (lb*ft)	Max Power (hp)
0	660	254
25	653	245
50	629	236
70	618	222
90	604	210
Change	-8.48%	-17.32%

Table 8 - Summary of sample means of maximum torque and power using various fuel blends.

Table 8 is a summary of the mean maximum torque and power values by fuel type. Note the reduction in torque of 8.48% when using B90 instead of ULSD. A more dramatic change can be seen in the mean maximum power reduction from 254 hp to 210 hp. The greater change in power occurs because the torque reduction is larger at higher engine speeds. Notice that the torque curve for the B90 appears very similar to that of ULSD, but displaced between 600 RPM and 1800 RPM. Above 1800 RPM, the B90 torque begins to drop while the ULSD curve remains consistent for another 200 RPM. It is at the same 1800 RPM that the power curves for the two fuels begin to diverge. Since power is the product of torque and speed, and since the maximum power usually occurs at around 2200 RPM, the larger change in power is expected, given the torque curve. Figure 17 and Figure 18 show the effects of fuel formulation on torque and power respectively.

The change in high RPM power and to some extent, the reduction in torque is likely due to the maximum flow rate of the injectors or to programming limitations of the Engine Control Module (ECM). Increasing injector flow or modifying injector timing may restore the engine to its ULSD power and torque potential, but efficiency will not improve. Such changes were not made to the engine because the purpose of this study is to determine the impact of biodiesel to existing vehicles. Further investigation into engine mapping and its effect on power and efficiency is recommended.

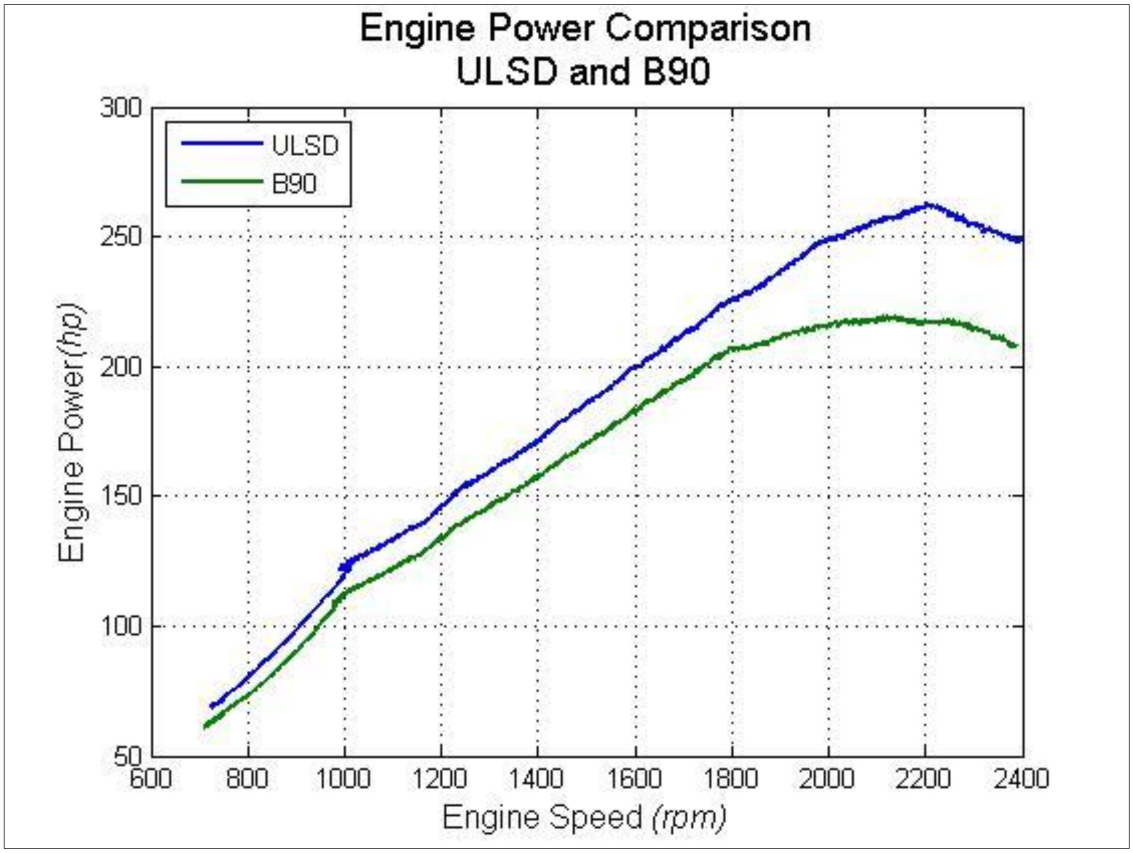


Figure 15 - Engine Power Comparison using ULSD and B90.

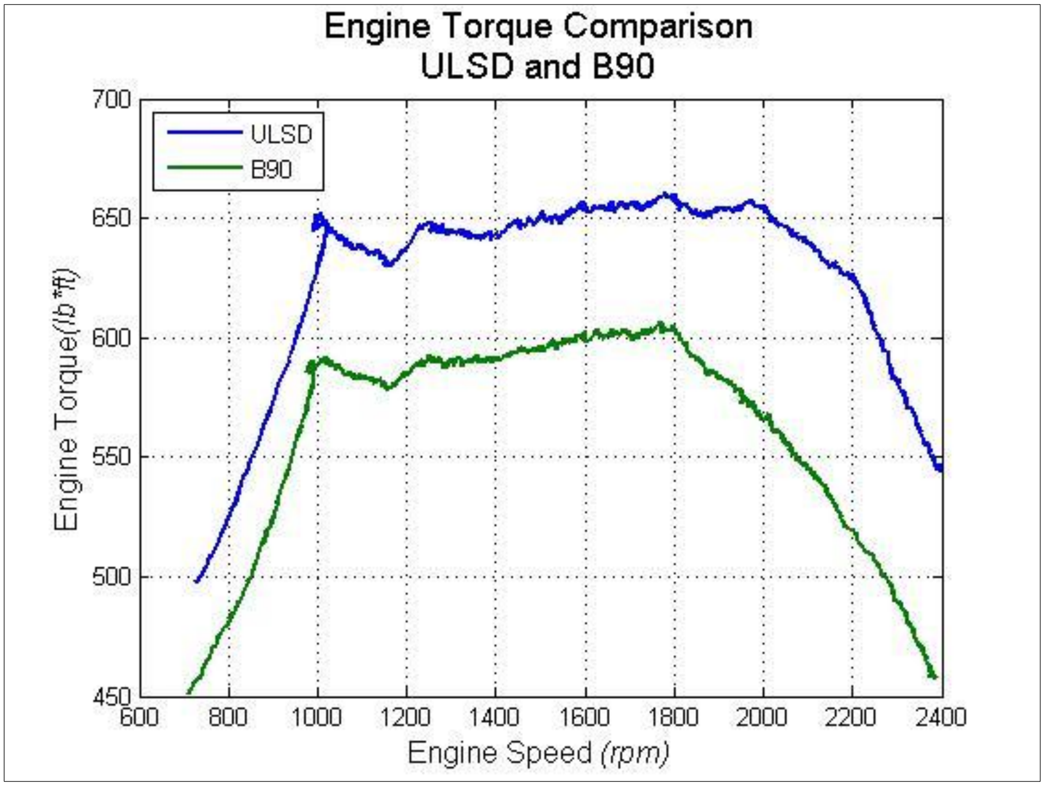


Figure 16 - Engine Torque Comparison using ULSD and B90.

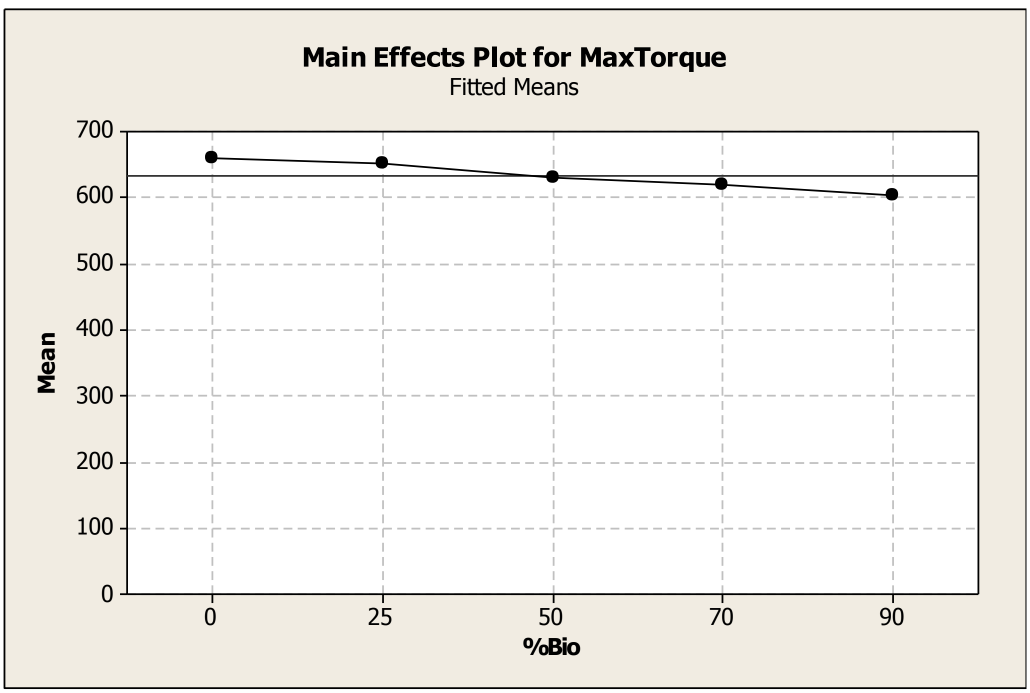


Figure 17 - Shows the effect of fuel blend on mean maximum torque.

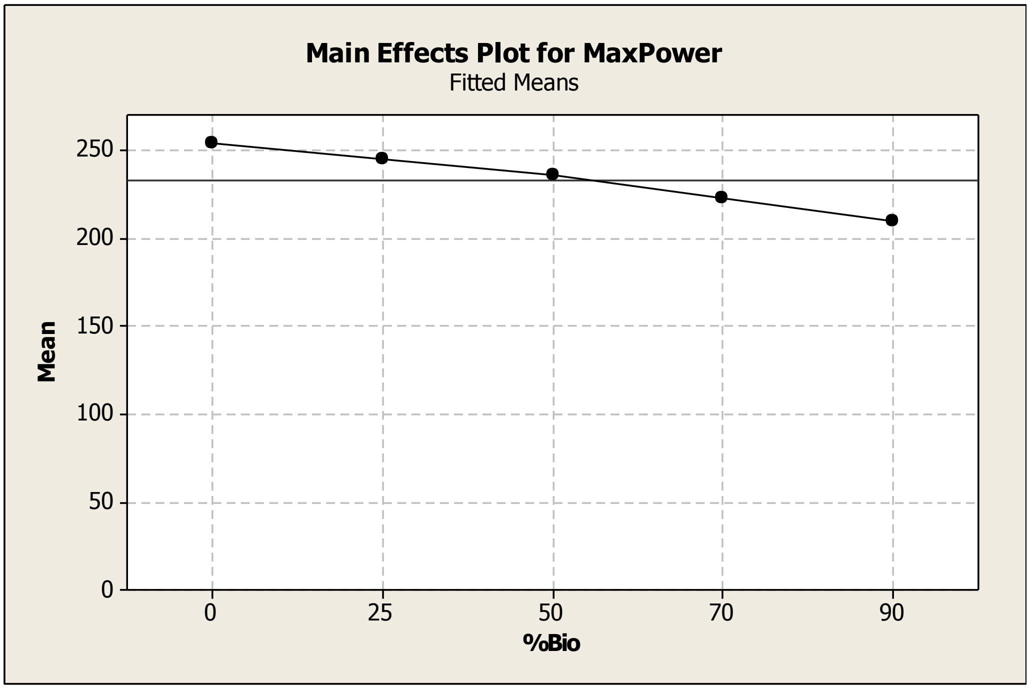


Figure 18 - Shows the effect of fuel blend on mean maximum power.

Efficiency

Efficiency was measured using the CTCS series of test runs. That allowed us to compare changes in efficiency due to fuel blends to engine speed and torque demands. The P-statistic calculated in the ANOVA showed that the fuel blend, torque and engine speed were all significant. The Pre/Post term refers to Test Series 1 and 2 – before and after the 16-hour run-in. That term was determined not to be a significant factor in efficiency.

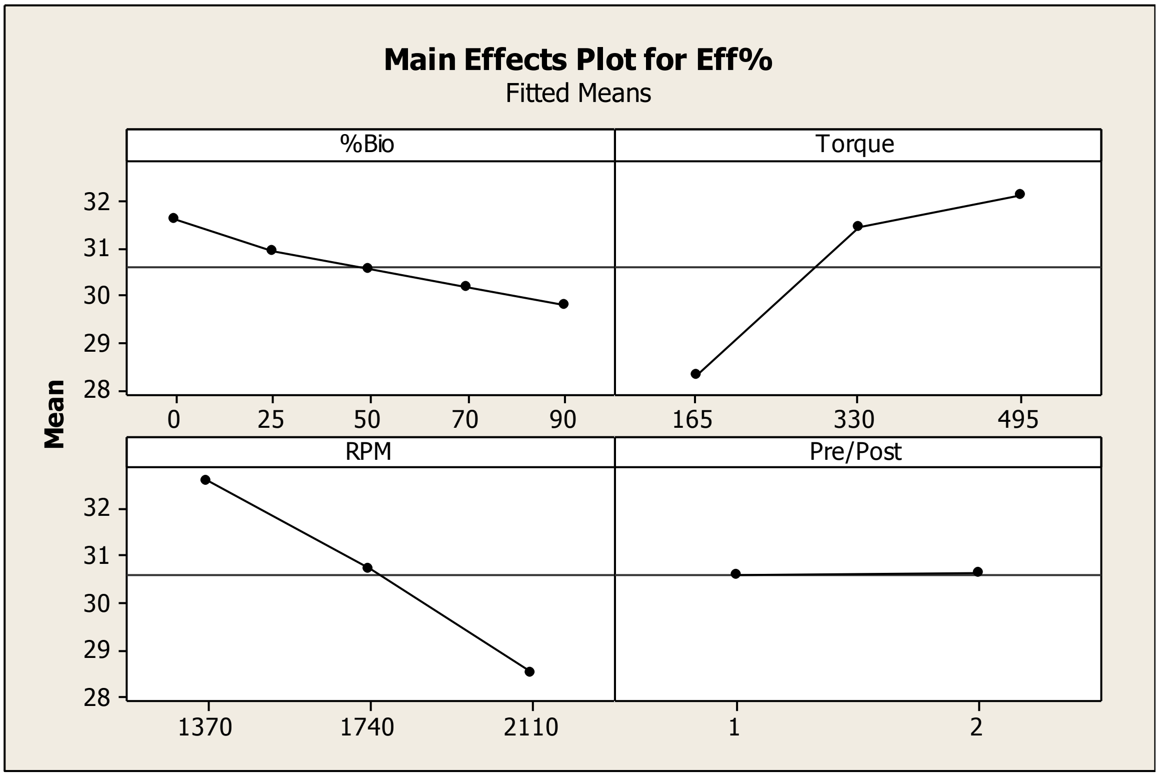


Figure 19 - Plots of the tested factors and their effect on efficiency.

Figure 19 shows the relative effect of fuel blend, torque, engine speed and 16 hours of run-time. The overall mean of Efficiency is 30.63%. The change in efficiency due to fuel blend is 6%. The changes in efficiency due to torque and speed are 12% each.

Factor	Eff Min	Eff Max	Eff Change
%Bio	29.85	31.76	0.0601385
Torque	28.32	32.13	0.1185808
Speed	28.59	32.65	0.1243492

Table 9 - Comparison of fuel blend, torque and power effects on efficiency.

The ANOVA calculation of the fuel + torque and fuel + speed effects on efficiency produce P-factors of 0.000 and 0.001 respectively, indicating that these two interaction effects are significant. Similarly to the CO effects, the F-statistics for these interactions are small in comparison to the main effects. Examination of the interaction plots (Figure 20) show a slight increase in variation between the mid- and high-torque levels with increased biodiesel ratios. It then becomes more important to maintain high-torque levels and low speeds to achieve maximum efficiency at high biodiesel blends.

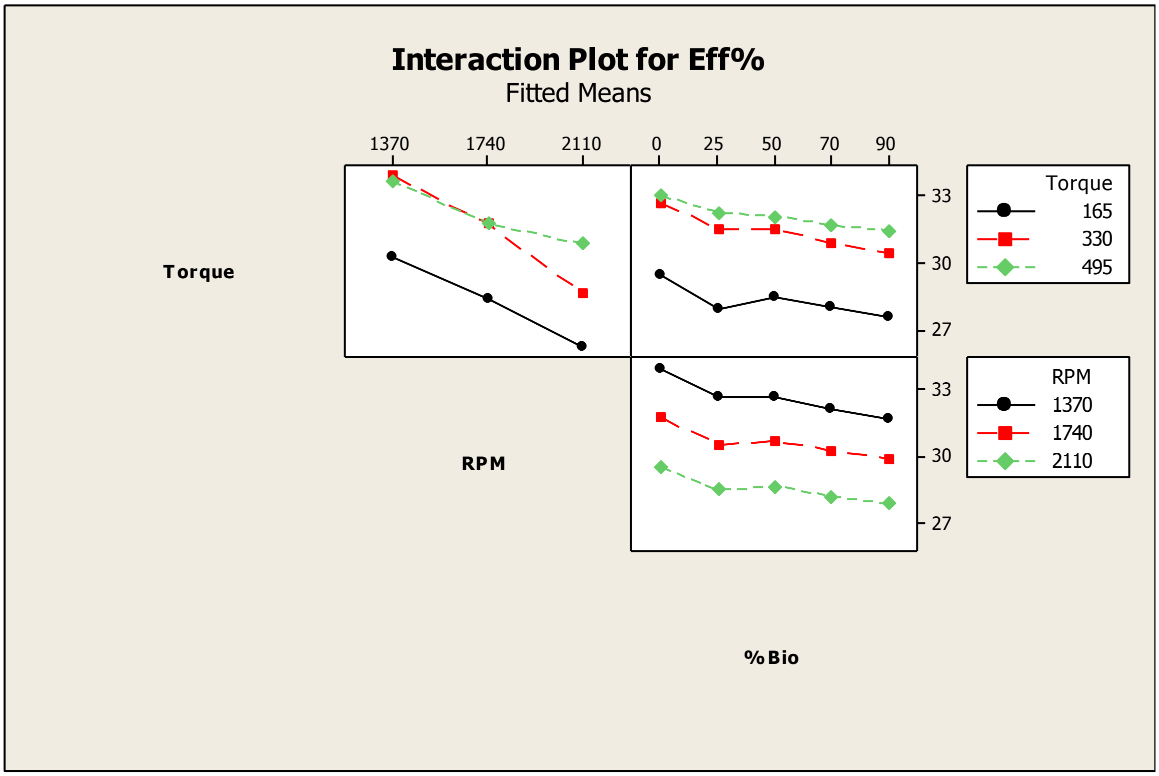


Figure 20 - Effects of fuel + torque and fuel + speed interactions on operating efficiency.

Combustion Deposits

After every fuel blend run, the exhaust manifold and an injector were removed and the engine's valves, combustion chamber and exhaust ports were visually inspected using a bore scope. Images were captured using a CCD camera through the bore scope. Images of the removed injectors were captured via photo-micrograph.

In the relatively short run-cycles at each fuel blend in the Fuel Screening Study, no visible changes to the internal engine deposits were noticed.

Fuel Screening Study Summary

The fuel screening study was run on CIMS' engine dynamometer in two blocks. Each block included a series of measurement runs, 24 hours of run-in and a second series of measurements on each of five fuel blends. The fuel blends were: ULSD, B20, B50, B70 and B90. The measurement runs included nine CTCS runs, a full-throttle engine mapping test and a European Stationary Cycle. The test sequence was a randomized Design of Experiments (DoE).

Factor	Response Significance (Y/N) NO	NO_2	CO	Soot	% Efficiency	Max Torque	Max Power
Torque	Y	Y	Y	Y	Y	N/A	N/A
Speed	Y	Y	Y	N	Y	N/A	N/A
Fuel	Y	Y	Y	Y	Y	Y	Y
Fuel*torque	N	N	Y	N	Y	N/A	N/A
Fuel*speed	N	N	Y	N	Y	N/A	N/A
Torque*speed	Y	Y	Y	Y	Y	N/A	N/A

Table 10 - Response significance of torque, speed, fuel and two-way interactions on exhaust emissions and performance responses.

The data were analyzed using the statistical analysis package MiniTab™ using ANOVA techniques. All factors and two-way interactions were analyzed for normal distribution and statistical significance. Table 10 shows which factors have a significant effect on each of the responses.

The production levels of NO, NO_2, and CO were largely driven by the engine operating conditions, but the fuel blend was a significant factor in to all exhaust products. Due to fuel blend: NO increased by 4.5%, NO_2 decreased by 6%, CO decreased by 17%, O_2 increased by 4% and Soot decreased by 81%. In addition, the fuel*torque and fuel*speed interactions affected CO production, reducing the importance of engine operating conditions at high biodiesel blends.

Efficiency decreased by 6% using B90 over ULSD. Maximum torque decreased 8.5% and maximum power decreased 17.3%. Power is the product of torque and speed and the maximum torque occurred at lower engine speed when using B90. This accounts for the greater reduction in power than torque.

Biodiesel Engine Dynamometer Durability Study

Objectives

This portion of the Alternative Fuels study will investigate differences that exist in engine wear, reliability and maintenance items caused by the use of high mix ratios of biodiesel vs. conventional ultra-low sulfur petroleum diesel. This investigation studied aging of two identical Cummins ISC-240 engines for 1500 hours. Every 100 hours, the engines were run through a series of performance and emissions tests. At 500 hour increments, the engines were disassembled, inspected and reassembled. All performance, emissions and inspection data were recorded and analyzed.

As described in the introduction of the Biodiesel Final Report, biodiesel can be produced by the process of transesterification through a reaction of vegetable oil (or tallow) with an alcohol in the presence of a catalyst. While acid or base catalysis can be used, the most common catalysts are strong bases, generally sodium hydroxide (NaOH) or potassium hydroxide (KOH). Excess alcohol and catalyst are needed to drive the reaction to completion. After the reaction is complete, the fuel must be separated from the byproducts, catalyst and unused alcohol. ASTM D6751 specifies the maximum content of each of the byproducts in the finished fuel.

The fuel purchased for this study was certified by the vendor to meet ASTM D6751. Since the operation of the Durability Study required two to three fuel deliveries per week and since ASTM testing is costly, each fuel batch was not tested for compliance. Random samples were periodically tested and met the ASTM specification.

Equipment/Procedures

The Engine Durability Study was performed in three phases. The first phase was a Gage Repeatability and Reproducibility (Gage R&R) study that was also used for measurement system baseline performance. In that phase we discovered that the Cummins engines respond to torque and speed set-points with a periodic variation. The variation drove the used of extended length Constant-Torque-Constant-Speed (CTCS) runs that allowed the variation to settle out or to allow capture of full variation wave forms. The Gage R&R Study is fully described in the Gage R&R report.

During the second phase, a Fuel Screening Study was performed running a single engine on various blends of ULSD and biodiesel. Primarily, engine performance and emissions were compared across the fuel blends, although a bore-scope was used to look at valves and pistons after testing with each blend. As a result of that study, pure ULSD and pure soy-based biodiesel were chosen for the third phase, the Durability Study. The Fuel Screening Study is described in a separate report.

The following sections provide a detailed description of the test equipment and procedures used in the Durability Study.

Measurement Apparatus

The dynamometer is a Mustang eddy current brake capable of 350 hp and up to 1000 lb*ft of torque. The control software provided by Mustang allows flexibility to automate test sequences and perform standardized emissions tests.

Two exterior 300 gallon tanks – one for ULSD and one for B100 feed an automated mixing station that refills the 50 gallon internal day tank as needed. Heaters on both exterior tanks maintain a minimum tank temperature and reduce the probability of clouding or gelling. The fuel blend is programmed into the batch controllers manually. The blended fuel is then run through a chiller to maintain a stable temperature and therefore density. A volumetric flow meter measures fuel use.

A data acquisition module built around an Iotech Daqbook 2000 modular system provides thermocouple, transducer, digital and frequency inputs as well as digital and relay outputs. A weather station monitors temperature, humidity and barometric pressure and provides a correction factor to the dynamometer computer.

A five-gas analyzer manufactured by ECOM American Ltd. measures the exhaust stream for levels of O_2, NO, NO_2, CO, CO_2 and SO_2. CO, O_2, NO and NO_2 are transmitted to the control computer. Data input channels can be created for the emissions measurements within the Mustang EDT Cell software.

Data input channels can be created for all of data acquisition module channels within the Mustang EDT Cell software.

Two Cummins ISC240 8.3L common rail turbo-diesel engines were used as test subjects (for the durability measurements) and as conversion mechanisms to convert the blended fuels to heat, torque and exhaust products.

Test Procedure

The test procedure incorporates a series of performance and emissions tests repeated periodically throughout engine aging cycles. The performance and emissions tests were repeated after every 96 hours of aging operation. The combined aging and test cycles each lasted one week. The aging cycles were run every Monday through Thursday. On Fridays, the performance and emissions tests were run and the engine and dynamometer were shut down for the weekends.

After every five aging and test cycles (about 500 hours of engine operation or 18,975 equivalent miles), the engines were disassembled inspected and reassembled. At this time the engine oil was changed and samples sent for oil analysis.

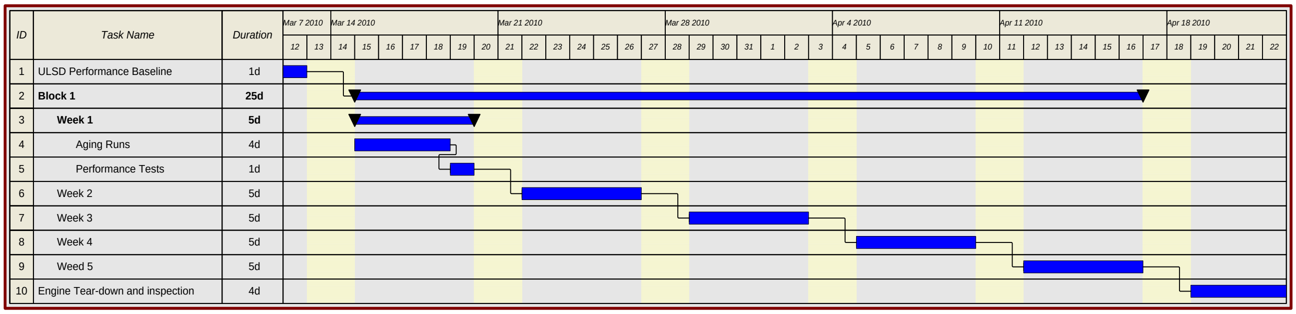


Figure 21 - Weekly schedule of Block 1 which is typical of all blocks. Each week, the aging cycle was run for 96 hours followed by the performance tests.

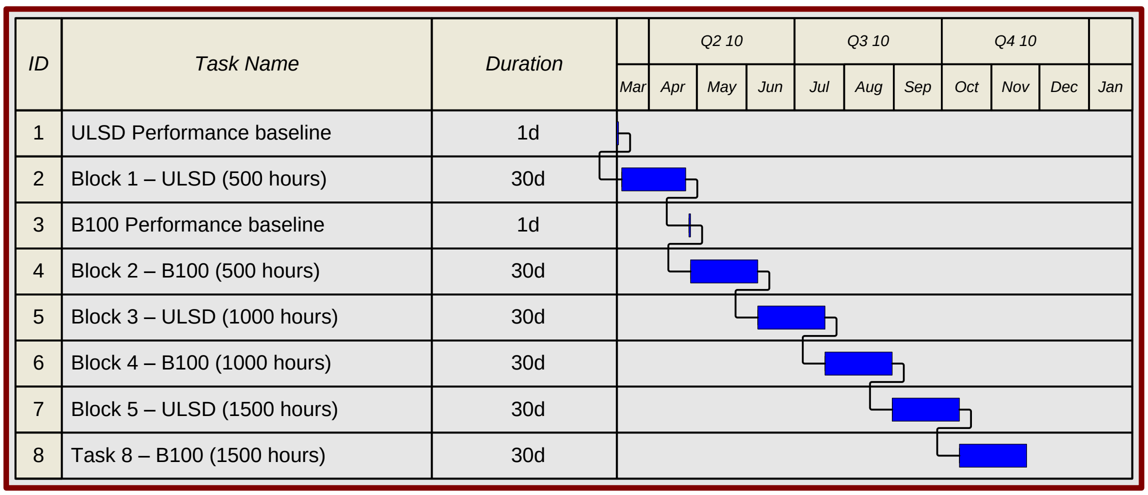


Figure 22- Extended Durability schedule. Weekly task detail is shown in Figure 21.

Figure 21 shows the run schedule for Block 1 of the Durability testing. All blocks were run to the same schedule. The overall schedule is shown in Figure 22.

Aging

The aging cycle was a simulated driving cycle consisting of FTP Heavy Duty Urban Driving Cycle (HD-UDDS) and the EPA Dynamometer Highway Driving Cycle (EPA-HWFET).[3] One complete HD-UDDS and two complete EPA-HWEET cycles repeated continuously for 24 hours to make up the aging cycle. The aging cycle was run every Monday morning through Thursday afternoon for a total of 96 hours of vehicle driving simulation every week. The average speed of the aging cycle is 37.95 mph, so the equivalent distance travelled each week was 3643 miles.

[3] Definition of these EPA cycles can be found at:

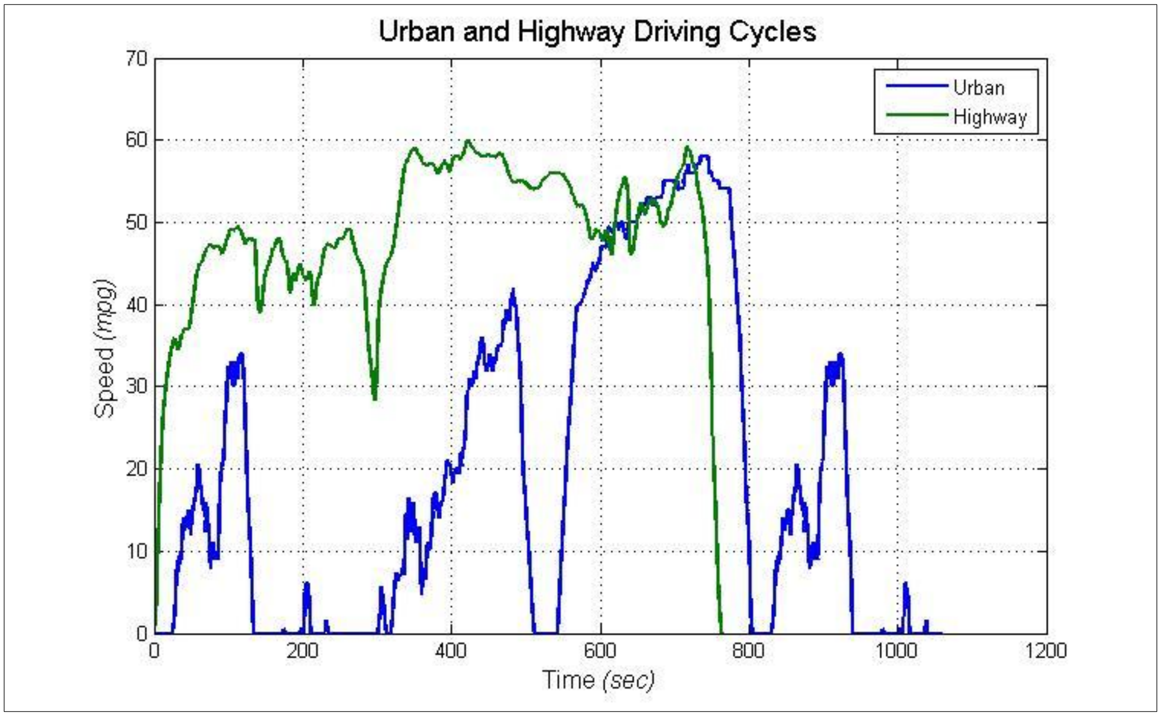


Figure 23 - HD-UDDS Urban and EPA-HWEET Highway Driving Cycles. The aging cycle consisted of two Highway for every Urban cycle.

Performance and Emissions Tests

The performance and emissions tests used in the Durability portion of this project were the same as those used in the second block of the Fuel Screening study. The test series consists of nine constant torque constant speed (CTCS) runs, one European Stationary Cycle (ESC) and one full throttle engine mapping test. Test descriptions can be found in the Fuel Screening Study portion of this report.

Constant Torque, Constant Speed Testing

The CTCS runs include a complete matrix of three torques and three engine speeds run in all combinations. The magnitudes of the engine speed and torque settings were determined by the 25%, 50% and 75% levels calculated in the ESC. The matrix is shown in Table 3.

Torque \ Speed	1370 RPM	1740 RPM	2110 RPM
165 lb*ft	165-1370	165-1740	165-2110
330 lb*ft	330-1370	330-1740	330-2110
495 lb*ft	495-1370	495-1740	495-2110

Table 11 - Torque and Speed Test matrix

The length of each test ranged from about 12 to 35 minutes. The test lengths were determined during the previous Gage R&R study. That study revealed periodic variations in intake manifold pressure, exhaust gas temperature and exhaust products over time. The chosen test lengths allow the engine and control system to stabilize and provide a reliable set of data.

During the CTCS tests, emissions production, exhaust temperature, coolant temperature and efficiency were recorded at steady state conditions.

Engine Map

The engine mapping sequence is a full-throttle test designed to accurately map the engine's torque, power and efficiency over its useful speed range. It is an automated test controlled by the Mustang controller based on engine specifications entered by the operator. At the start of the sequence, the engine throttle is fully opened and the brake applies the proper torque to hold the engine speed down to its idle speed. The controller then continuously adjusts the brake torque to allow the engine speed to increase at a specified rate; for this specific series of tests; we used 10 RPM/second. Upon reaching the engine's governed speed or a predefined safe operating speed limit, the throttle is closed, the torque is released and the engine speed reduced to idle.

Throughout the test sequence, the torque, engine speed and fuel flow rate are constantly measured and logged. Power, corrected power, efficiency and Brake Specific Fuel Consumption (BSFC) are calculated and logged in the same output file as are all other monitored channels. A MATLAB™ function was used to sort and plot various measurements and results. A sample of an engine mapping plot is shown in Figure 7.

Engine 2 was only run on B100 throughout the Durability portion of this study and Engine 1 was only run on neat ULSD. There was not a direct comparison of engine to engine performance running on the same fuels. During the Fuel Screening study, however, Engine 1 was run on B90 among other blends. We can compare Engine 1 on B90 to Engine 2 on B100 to understand engine to engine performance variation. The average maximum torque and power of Engine 1 on B90 were 604 lb*ft and 210 hp respectively. The average maximum torque and power of Engine 2 running on B100 were 593 lb*ft and 224 hp. Applying $\pm 3\delta$ to the torque measurement gives a 95% confidence interval of 567 to 618 lb*ft and to the torque measurement yields 197 to 251 hp. Clearly the Engine 1 performance on B90 falls within normal measurement variation of Engine 2 on B100. The torque and power of Engine 1 on ULSD were 660 lb*ft and 254 hp respectively. These values fall outside the $\pm 3\delta$ range of Engine 2 on B100. The conclusion can be drawn that Engine 1 and Engine 2 perform the same (within measurement variation) of each other when operating on similar fuel blends (B90 vs. B100) and they perform differently when running on different fuel blends (B0 vs. B100).

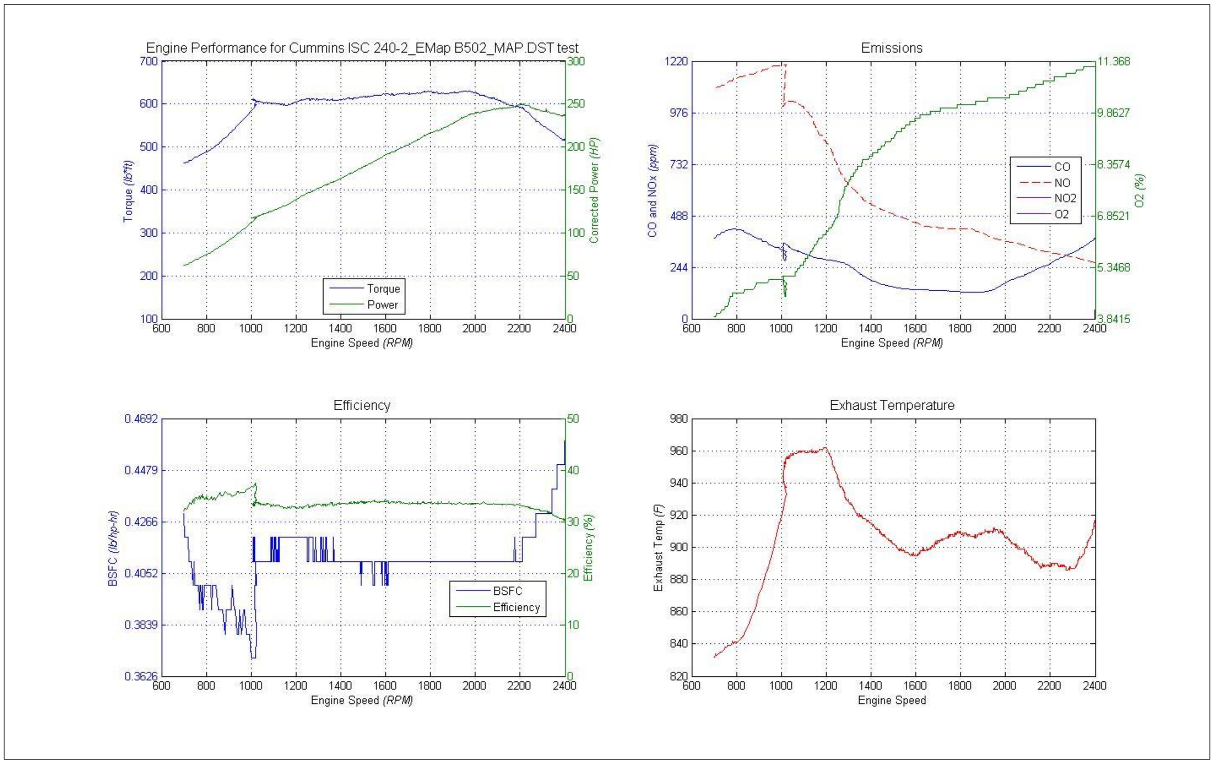


Figure 24 – Performance Plots of Cummins ISC-240 operating on B50 Blend

Engine Inspection

After every five aging and test cycles (500 hours of operation), the engines were disassembled and inspected. The inspection procedure included measurement of cylinder, valve, piston, bearing and oil pump components along with lubricating oil analysis, and engine deposit analysis.

Results

Responses and Statistics

During the Durability Testing, six five-week blocks were run; three blocks on ULSD and three blocks on B100. Fifteen sets of eleven performance tests were collected for each fuel as described in the Test Procedure section. Of the eleven, one run was a full throttle performance map used to measure maximum torque and power. The remaining 10 runs were used to measure efficiency, exhaust temperature and emissions products.

The Mustang software is structured to capture data from the dynamometer, the local data acquisition board and the Iotech Daqbook™ data acquisition system (also known as the "Boom Box"). The Mustang SW produces a comma-separated-variable (CSV) table with one column per recorded channel and one row for each captured data set; in this case, the data collection rate was four Hz. The dynamometer operator started and stopped the logging operation as required by the test procedure.

CIMS wrote several functions using Matlab™ by The Mathworks to extract the pertinent data from the raw CSV data sets and to calculate level statistics from the CTCS runs. The statistics were then exported to MiniTab™ which was used to analyze the data for statistical significance and determine the magnitude of the effect each factor had on the various responses. The General Linear Model form of Analysis of Variance (ANOVA) was used to check data for normal distribution, determine significance in the form of P-factor and calculate effects.

Performance

Performance effects include engine efficiency, torque and power. Efficiency was measured during each CTCS test. Maximum torque and power were measured during full throttle engine mapping runs.

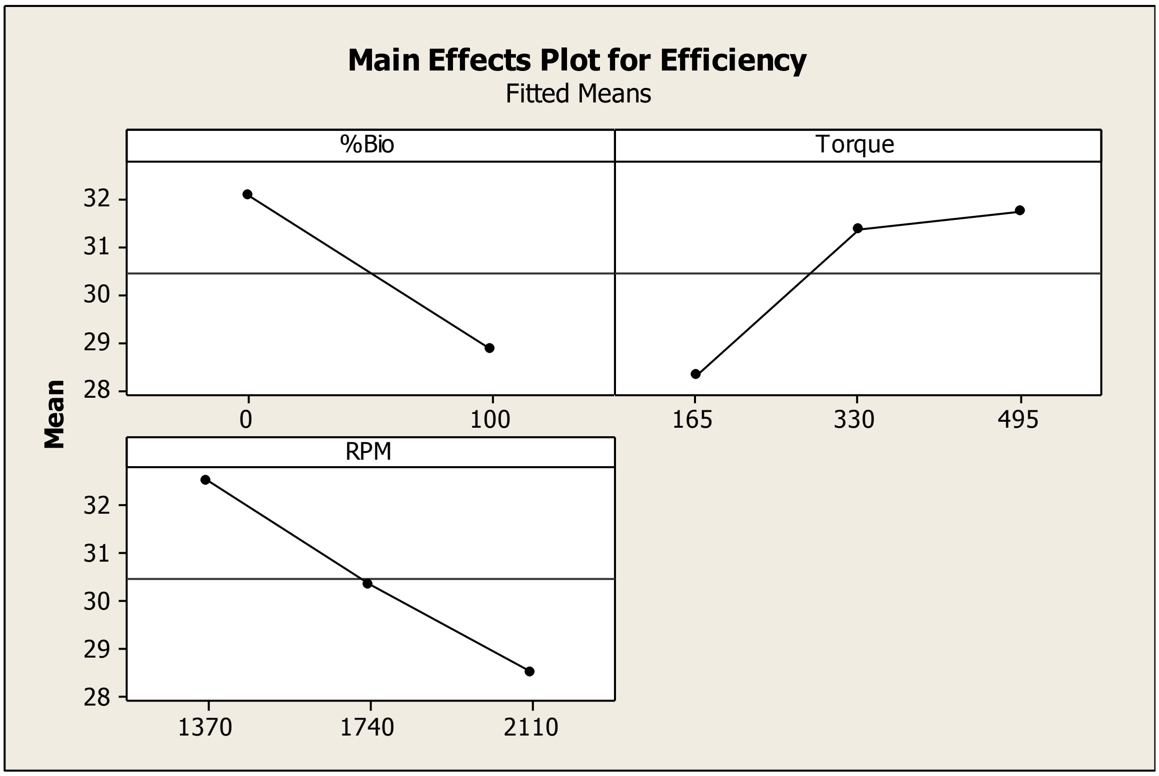


Figure 25 - Main Effects Plot shows the relative effects of Torque, Speed and Fuel on Efficiency

Analysis of the variance (ANOVA) of efficiency, torque and power showed that the fuel formulation is a significant factor to all three response variables. Figure 25 shows the relative effects of fuel blend, engine load and engine speed on fuel efficiency over the entire durability test program. Each point represents the average of all data at that particular factor set point. For example, consider the “Torque” panel in Figure 25. The plotted point at 165 represents the mean of all data gathered for tests run at 165 lb*ft of torque. Likewise, all other plotted points represent the average of all data gathered at that set point. This is the average response for each factor level. All main effects plots are calculated in the same way.

Because the data in the Main Effects plot of Figure 25 are plotted means, they do not include the entire raw data range. For example, the range from the Main Effects plot includes averages that span from 28.5% to 32.5%. Ignoring the five outliers, the maximum efficiency from the raw data as seen in Figure 26 is 36% and the minimum is 25%.

The ISC-240 engine experienced an average reduction in efficiency of 10% when using B100 vs. ULSD. The higher heating value (HHV) of ULSD is 129,050 BTU/gallon and is 118,170 for soy-based biodiesel according to the 2004 Biodiesel Handling and Use Guidelines published by the U.S. Department of Energy. Based solely on published HHVs, the expected change in efficiency is 8.4%.

While HHV is a major factor in determining engine efficiency, it is not the only factor. Fuel viscosity, density and cetane number combined with engine design all influence combustion efficiency and therefore fuel efficiency. These other factors and their interaction with the engine operating parameters may account for the additional 1.6% difference in efficiency. Perhaps an engine could be optimized for use with biodiesel by adjusting injection timing, pressure and volume, limiting the efficiency to that of the HHV difference of 8.4%.

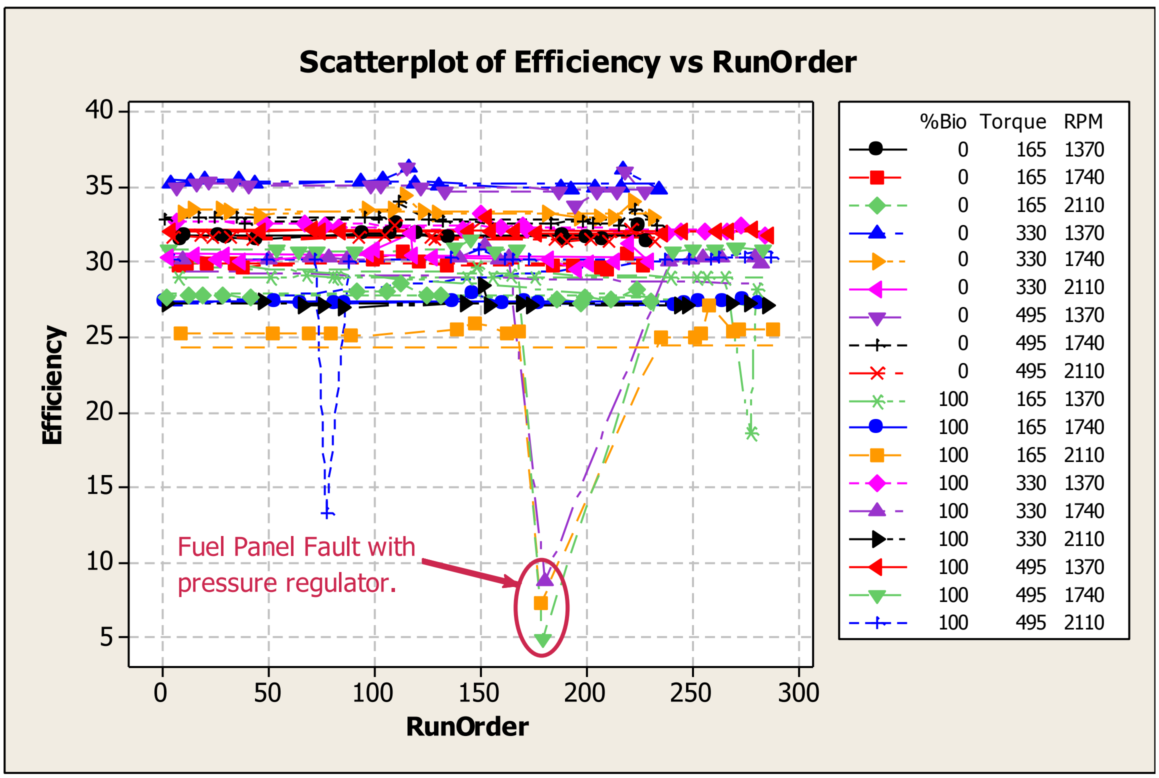


Figure 26 - Time Series plot of Efficiency

Time series plots of efficiency are shown in Figure 26 and show that the efficiency remained nearly constant for each torque-speed-fuel combination over the test period. Consider that a full series of performance runs were performed every 100 hours and that one and only one of each CTCS were run in each series. Therefore every sequential plotted point on each trace represents 100 hours of engine life or about 3700 miles of road use. 1500 hours or about 57,000 miles separate the first and last data points. The Time Series plot shows no discernible trends or wear effects on efficiency.

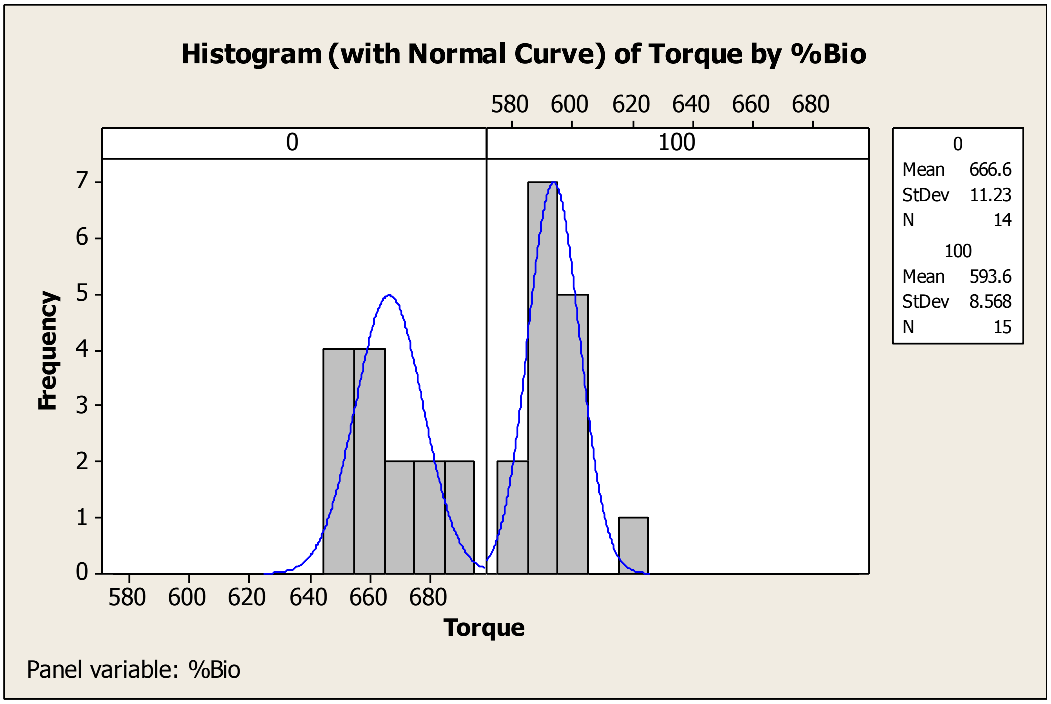


Figure 27 - Histograms of engine torque running on ULSD and B100.

Figure 27 and Figure 28 show histograms of torque and power means of ULSD and B100 fuels from all of the CTCS tests. The normal distribution curves encompass the 95% confidence intervals of the data sets. From the torque curves, it can be seen that there is no overlap between the data sets, indicating that the effects are statistically significant. Since the peak power is the product of the torque and the engine speed at peak torque, there is more variation in the mean peak power measurements. Some overlap of the normal distribution curves exists and statistical significance must be calculated by other methods. ANOVA was used and a P-Statistic of 0.000 was calculated indicating the effect is significant and caused by fuel blend. Table 12 lists the power, torque and efficiency means of both fuels.

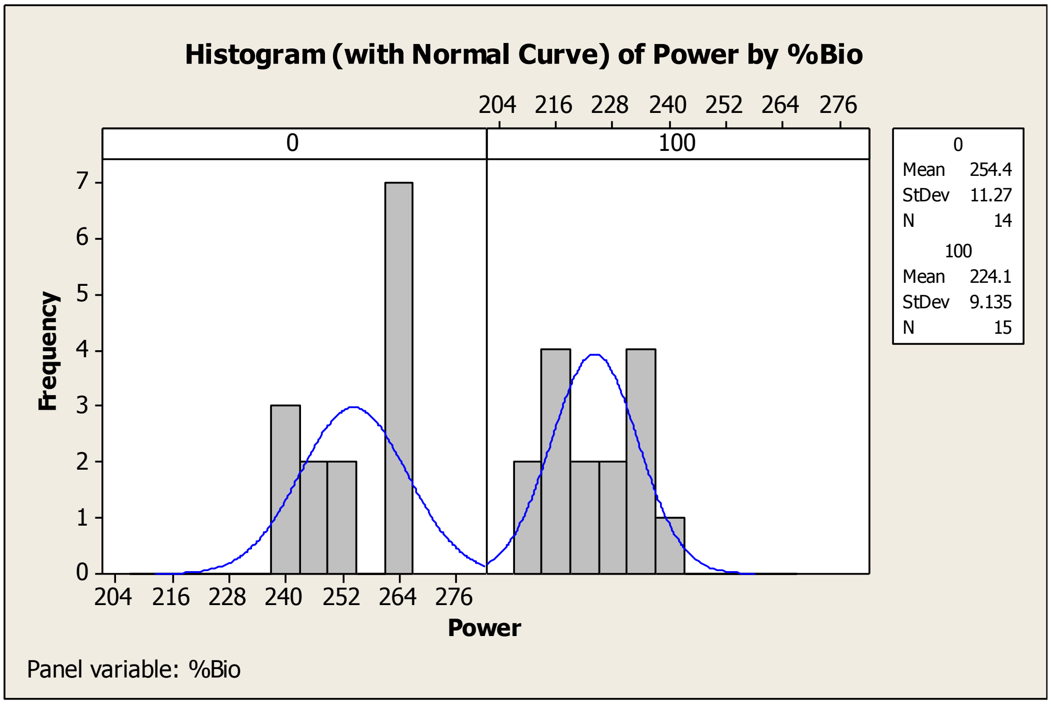


Figure 28 - Histograms of engine power running on ULSD and B100.

The mean maximum engine torque of the Cummins engines running on ULSD was 666.6 lb*ft and the mean maximum power was 254.5 hp. The mean maximum torque running on B100 was 593.6 lb*ft and the mean maximum power was 224.1 hp. This represents an 11% reduction in maximum torque and a 12% reduction in maximum available power when using B100. A slight reduction in the mean engine speed at maximum torque contributes to the larger reduction in power than torque. See Table 12 for a summary of performance changes.

Figure 29 is a time-series plot of maximum torque over the test period. The linear reduction in engine torque indicates a likely aging effect. Both engines and both fuels show a similar reduction in peak torque over time.

Fuel	Torque	Power	Efficiency
ULSD	666.6	254.5	32
B100	593.6	224.1	29
ULSD vs. B100 % Difference	-11%	-12%	-10%

Table 12 –Variations in maximum torque, maximum power and efficiency due to fuel formulation as calculated using MiniTab's ANOVA.

Table 12 lists the ANOVA calculated means in maximum torque, maximum power and efficiency caused by fuel blend. Since the data includes the entire Durability Study, the time related torque and power decreases are included in the average values listed.

The reader is likely to notice that both maximum torque and maximum power dropped over time, but efficiency remained constant. Engine 1 (ULSD) suffered a 1.9% torque loss over 1500 hours. Engine 2 (B100) suffered a 2.6% torque loss over the same period. Note that the efficiency was measured during the CTCS tests and the maximum torque and maximum power were measured during the full throttle mapping tests. The actual cause of engine performance loss is not certain at this time, but the consistent decline over the test duration indicates and aging effect of some sort. Possible aging effects include:

- Combustion deposits in the exhaust system. Both engines ran through the same exhaust system including the same muffler. While it is possible that muffler flow restriction increased over time, any increase was too small to detect with our differential pressure transducers monitoring the muffler back pressure. Buildup of carbon on upstream components like valves or turbocharger blades would not influence the muffler pressure readings. Still, the build-up on these components was too small to measure reliably.
- Fuel injection blockage or loss of flow volume. A change in fuel rail pressure or restriction of the injector nozzles would certainly change the spray pattern of the injectors. A change to the injection spray would affect exhaust products as well as torque and power. Since no time-related emissions effects were found, fuel pressure and flow changes are not likely the cause of the performance loss.
- Piston ring seal integrity. Wear of piston rings and cylinder liners over time is normal and expected. Initially, the rings and liners lap in and the compression often improves. As an engine ages, however, the seal between the rings and liners degrades and compression degrades due to leakage past the rings. Loss of pressure past the rings reduces the available force on the piston tops and therefore reduces the available engine torque. The 1500 hour durability test represents one-quarter to one-third of the engine expected life. A 1.8% reduction in torque due to ring wear seems a little high, but is not unreasonable. Even though ring/liner wear usually also causes a reduction in efficiency, it is a likely cause of the torque loss experienced in this experiment. It may just not be severe enough to show up in efficiency measurements.
- Turbocharger performance degradation. Loss of turbocharger performance, either in pressure or flow rate, could also affect peak torque and horsepower. Additionally, at lower power steady state conditions, the turbo may self-correct by spinning a faster at part throttle conditions thereby not affecting engine efficiency during the CTCS tests. Although no visible wear was seen, the turbocharger parts were not measured during the test.

Once again, the actual cause of the torque loss is not known with certainty. Figure 29 shows that the rate of torque degradation is very close for both engines and fuels (0.7% difference). Using the mean maximum torque $\pm 3\delta$ ranges, the differences fall well within the measurement variation. The fuel blend cannot be determined as the cause of the increased variation measured with B100 operation.

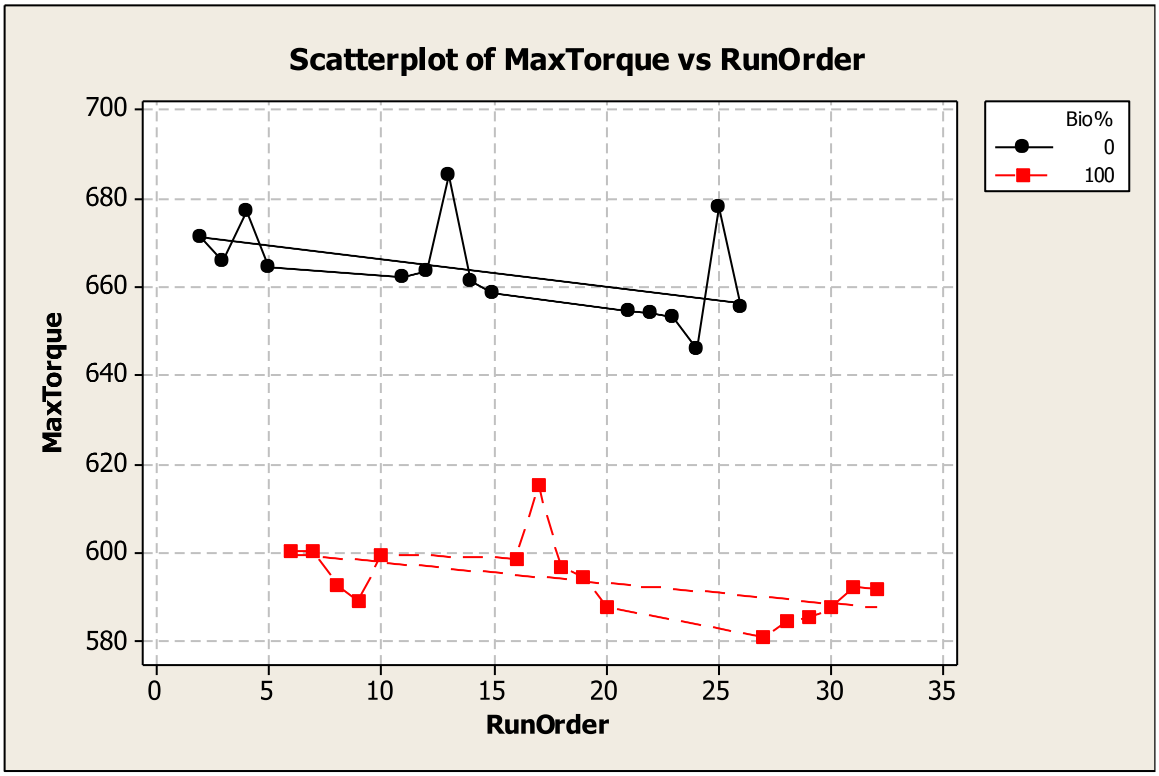


Figure 29 - Time Series Plot of Maximum Torque showing a reduction over 1500 hours of use.

Emissions

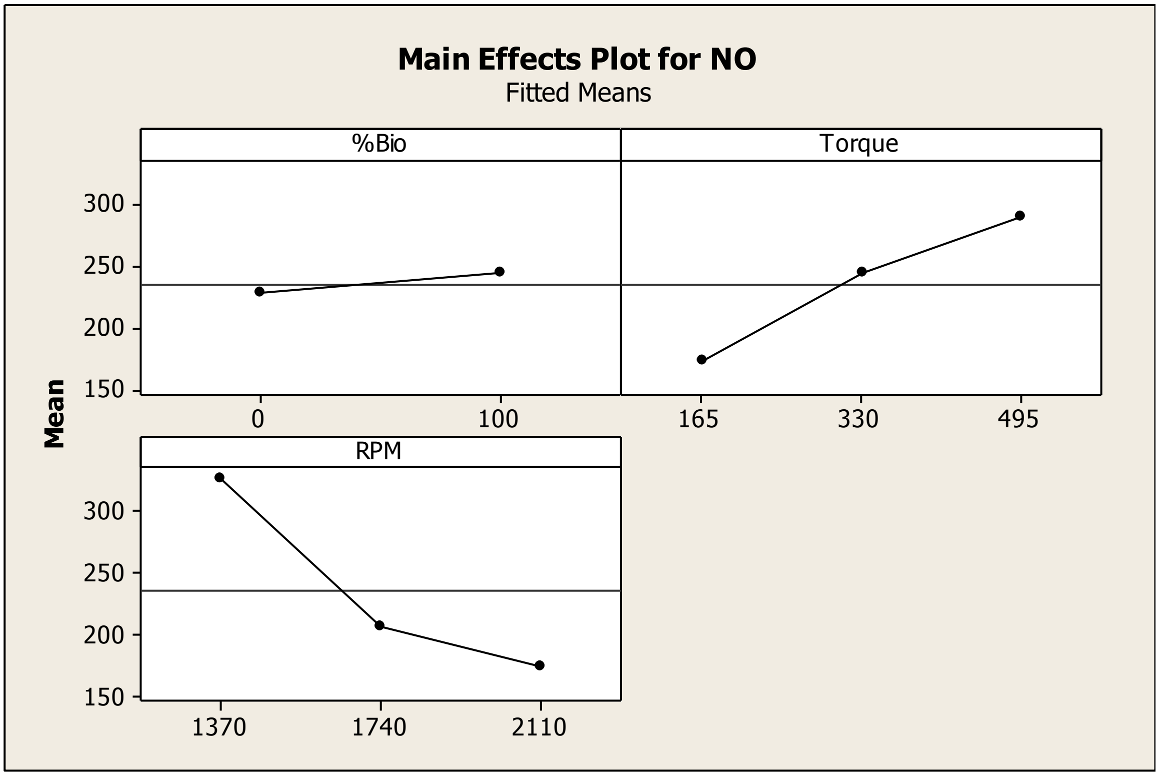


Figure 30 – Main Effects of fuel, torque and speed on Nitric Oxide production in a Cummins ISC-240 Diesel engine.

Although small, the changes in NO and NO_2 due to biodiesel use are statistically significant. Using B100 caused an increase in NO of 15 parts per million (ppm) or 6% when tested over all nine CTCS profiles. B100 caused a 6 ppm decrease (-13%) in NO_2 production over the same test points.

Examination of Residuals Plots is included in each of RIT's ANOVA computation. The Residuals vs. Run Order Plot is always inspected as part of the analysis. That plot easily identifies time-related trends in the data: either changes in the mean over time or changes in variance over time. Only the torque and power data exhibited time-related changes. The exhaust products and efficiency remained steady over the 1500 hour test period. The source of the torque and power variation does not appear to have affected any other measured factors.

Figure 30 and Figure 31 show the fuel, load and speed effects on NO and NO_2 production over those CTCS test profiles. The fuel effect on NO is very small in comparison to engine operating effects. One can envision conflicting results of NO measurements made on identical vehicles used in different environments such as city vs. highway driving. While the fuel effect on NO_2 is a larger portion of overall variation, the speed and torque effects are not linear, adding additional confusion to NO_2 measurements.

Previous research studies show conflicting results of biodiesel effects on nitrogen emissions. Many studies measure only the combined quantities of NO and NO_2 known as NO_x. Often the fuel effect on NO_x is a slight increase in production. Our results indicate that this is likely caused by the NO increase of 15 ppm overwhelming the 6 ppm decrease in NO_2 even though the NO_2 is considered the more toxic substance.[28]

In order for oxides of nitrogen to form, N_2 must dissociate into monatomic N atoms. These N radicals can then combine with O_2 or O radicals to form NO_2 and NO. The dissociation of N_2 during combustion is a thermal process; the N_2 molecule becomes excited with enough thermal energy that the N atoms break their covalent bond and separate. It is commonly theorized that an increase in NO_x production is due to increase combustion temperature. During our nine CTCS tests, no significant or measureable changes in exhaust temperature were observed due to the fuel factor.

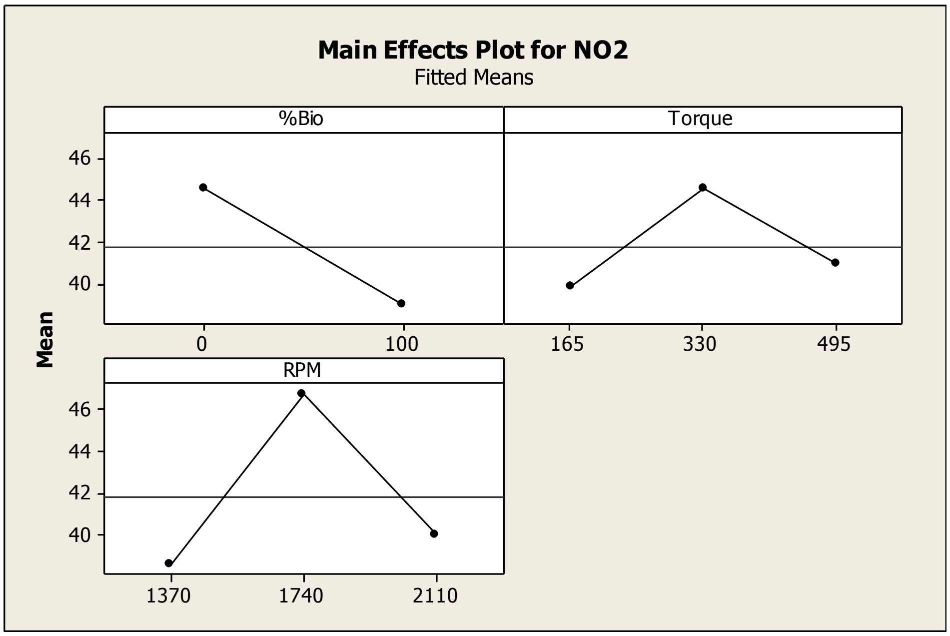


Figure 31 – Effects of fuel, torque and speed on NO_2 production in a Cummins ISC-240 Diesel engine over nine CTCS modes.

CO production decreased from a nine profile CTCS average of 379 ppm to 257 ppm which is a 32% reduction. Figure 32 shows the relative effects of fuel, torque and speed on CO production. While torque and engine speed affect CO production, biodiesel use is a statistically significant factor.

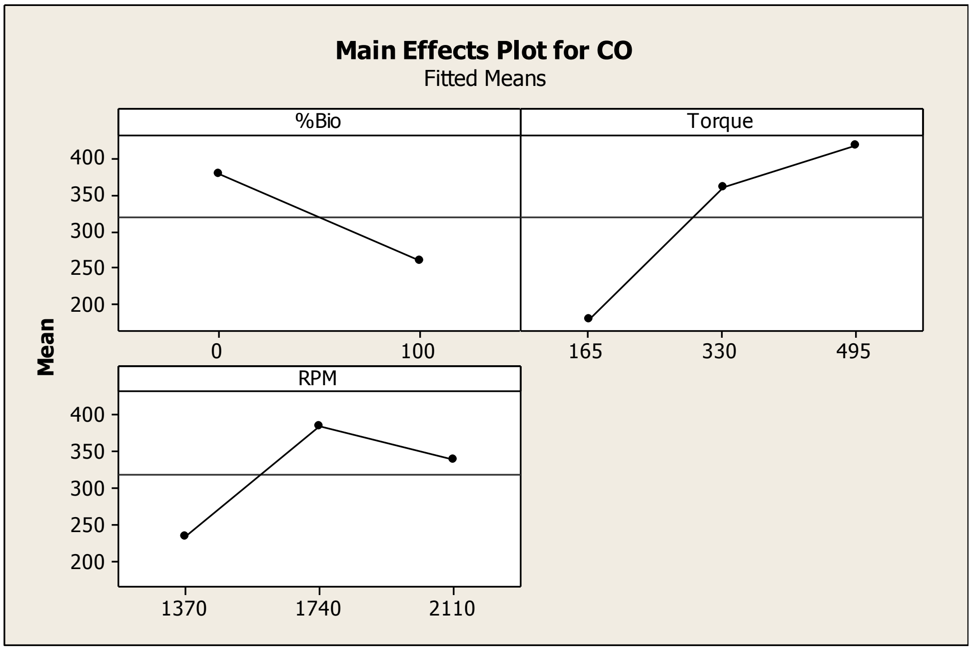


Figure 32 - Effects of fuel, torque and engine speed on CO production. The test engine is a Cummins ISC-240 common rail turbo-diesel.

An AVL Soot Meter was used to measure the soot content of the exhaust gas throughout the durability testing. The soot meter measures the opacity of the exhaust stream. It does not characterize the size distribution of the particulate matter. Figure 33 shows the fuel, torque and speed effects on exhaust soot content. Statistically, only biodiesel content produce a measurable effect on soot. The exhaust opacity (which is an indicator of soot content) was reduced by 71% using B100 versus ULSD. Because the soot meter was only sporadically available, and because the data acquisition cards gave baseline data even when the soot meter was not present, the accuracy of soot results is suspect. Visibly, there appeared to be less soot in the exhaust plumbing after running B100 for a period of weeks.

The soot meter was available regularly throughout the second series of Fuel Screening tests. During that phase of the Dynamometer Biodiesel testing, the results of Soot content showed a decrease from 320gm/m^3 on ULSD to about 25gm/m^3 when running on B90.

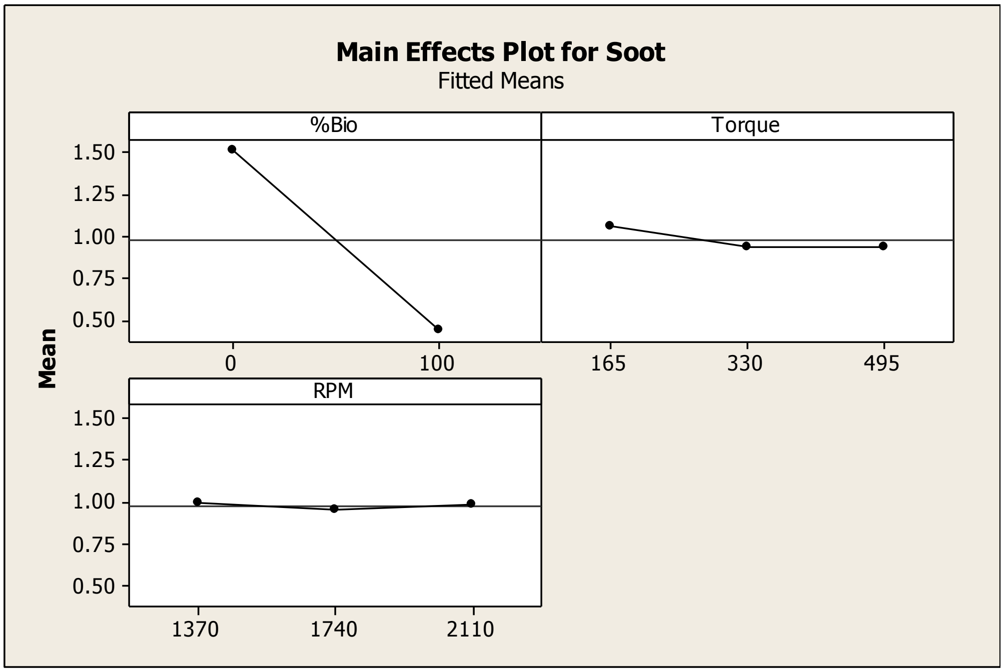


Figure 33 - Fuel, torque and engine speed effects on Soot content of exhaust.

Fuel	NO	NO_2	CO	Soot
ULSD	227	45	379	1.512
B100	242	39	257	.443
% Change	+6%	-13%	-32%	-71%

Table 13 - Summary comparison of exhaust emisslions when running B100 versus ULSD. Data is averaged over the entire Durability Study.

Engine Component Wear

Before the engine durability tests were started, both Cummins ISC-240 engines were disassembled and samples of critical parts were measured and logged before the engines were re-assembled. After every 500 hours, the engines were disassembled, remeasured and reassembled. The operation and measurement process was repeated until 1500 hours of used on each fuel were completed. A final series of measurements was made.

The measurements included the following:

- Cylinder Inside Diameter, top
- Cylinder Inside Diameter, Reversal Ridge
- Cylinder Inside Diameter, bottom
- Ring End Gap, top – end gap on ring placed inside cylinder
- Ring End Gap, Reversal Ridge
- Ring End Gap, bottom
- Main Bearing Clearance
- Rod Bearing Clearance

- Oil Pump Clearance
- Intake Valve Depth – distance from deck to bottom of intake valve
- Exhaust Valve Depth
- Intake Valve Stem diameter, top
- Intake Valve Stem diameter, bottom
- Exhaust Valve Stem diameter, top
- Exhaust Valve Stem diameter, bottom
- Intake Valve Guide diameter, top
- Intake Valve Guide diameter, bottom
- Exhaust Valve Guide diameter, top
- Exhaust Valve Guide diameter, bottom
- Intake Valve Deposits, mass
- Exhaust Valve Deposits, mass
- Injector Deposits, thickness
- Wrist Pin Diameter
- Wrist Pin Bearing clearance
- Piston Diameter, bottom
- Piston Wall Resistivity, ohms

All measurements are in inches except the Piston Wall Resistivity, which is measured in ohms.

The effect of fuel on the above measurements was not statistically significant over the 1500 operational hours of the testing. Some of the graphs that follow appear to show differences between the ULSD and B100 measurements that exhibit reasonable trending behavior. Those differences may be real but there isn't enough change in the measurement as compared to measurement resolution to be certain.

The trend line in each graph is important to understanding if potential differences exist between the B100 and the ULSD engine measurements. Most of the engine measurements change over time in both engines. We are interested in the differences in the rate of change between one engine (ULSD) and the other (B100). If the trend lines are parallel, there is not likely a difference in the rate of change between the engines. Those plots that exhibit trend lines with different slopes such as RodBrgCl may exhibit a difference in the change rate.

For example, the trend lines for B100 and ULSD in IGDia-bot (Intake Guide diameter at the bottom of the guide) are nearly parallel. This indicates that the diameter of each guide grew by approximately the same amount. In contrast, for the Intake Valve Stem diameter at the bottom of the guide (IVStemDia-bot) measurements, trend lines are not parallel. The ULSD Intake valve stem has a small negative slope, indicating its diameter was reduced slightly. The B100 intake valve guide stem has a positive slope indicating its diameter grew, perhaps from deposits.

Likewise, similar conclusions can be drawn from the other plots. However, the reader is reminded that the measurement variation was large in comparison to the measured changes, so the conclusions drawn from the plots may or may not be caused by the changes in fuel. A longer test period may expose true effects that are not clearly shown at 1500 hours of engine operation.

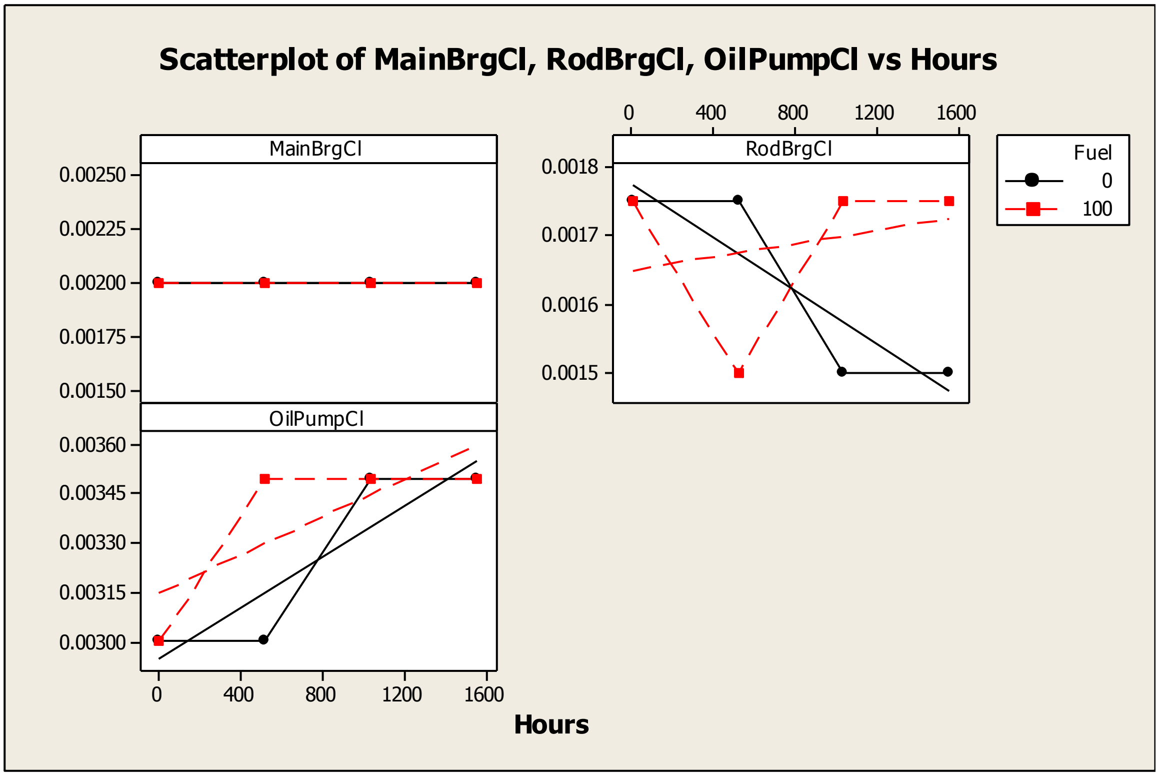


Figure 34 - Measurement comparisons of Main Bearing Clearance, Rod Bearing Clearance and Oil Pump Gear Clearance.

Figure 34 shows comparisons of main bearing clearance, rod bearing clearance and oil pump gear tooth clearance for the different fuels. The change in main bearing clearance and oil pump gear clearance are nearly the same. The rod bearing clearance change appears to be different between the two engines, but one must question if the clearance could really get reduced by 0.002-inches. There is no other evidence of deposits on the bearing or journal.

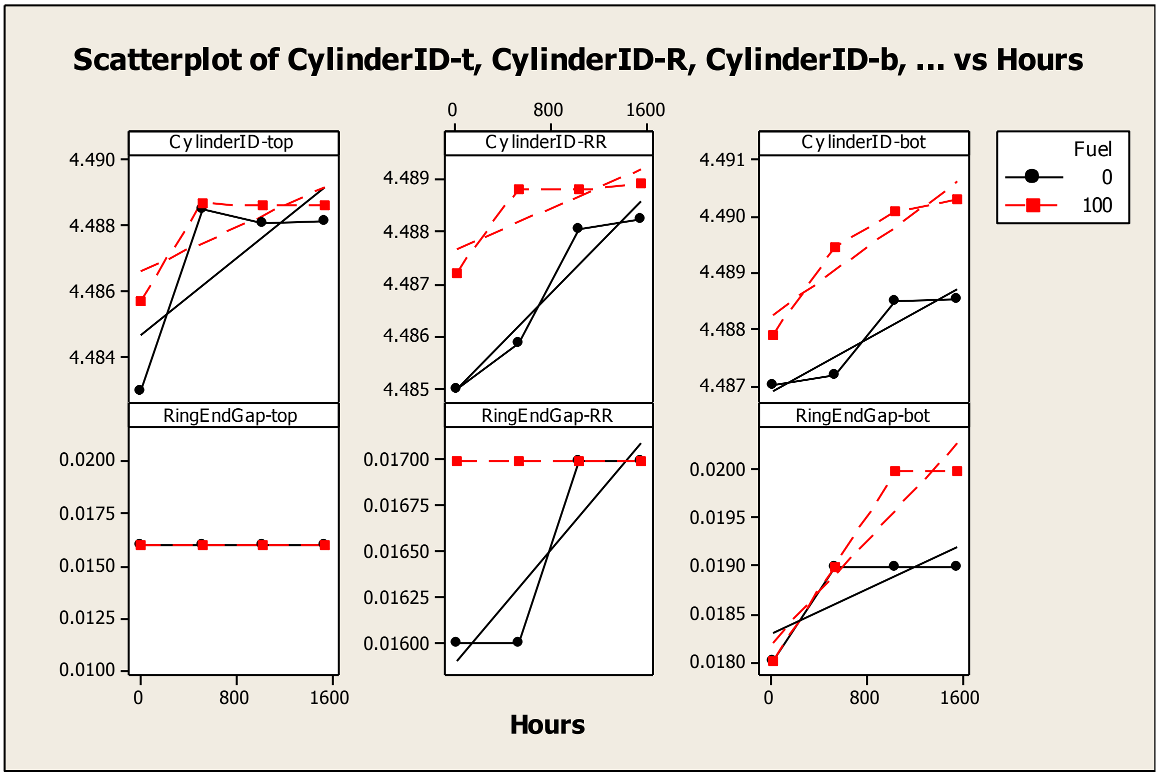


Figure 35 - Comparison of Cylinder Inside-Diameter at the top, bottom and at the reversal ridge. It also shows the changes in Ring End Gap at the same locations.

The cylinder diameter of one cylinder in each engine was measured in three locations: at the top of the cylinder (after cleaning carbon deposits from the wall), at the reversal ridge created by the top ring, and at the bottom of the ring stroke. Ring End Gap is the measure of the gap between the ends of a piston ring reserved only for that purpose. It is a measure of cylinder circumference and should be more sensitive to change than diameter. Since the measurement was made with feeler gages, the resolution of ring end gap is 0.001-inches. For consistency, the measurement locations were controlled with a custom gage designed and built specifically for that purpose.

Figure 36 shows a comparison of the intake and exhaust valve guide diameters measured both at the top (valve cover side) and bottom (port side) of the guide. The top of the guides are likely be influenced by the lubricating oil and the bottom by combustion and fuel deposits. The figure also includes weight measurements of the exhaust valve and a size measurement across the tip of the injectors; both measurements designed to quantify combustion deposits. Note that the first weight measurement for the exhaust valve deposits is apparently erroneous, since the bare valve weighs more than 100 grams. It appears that neither exhaust valve revealed a measureable change in mass. The B100 injector did exhibit less carbon build-up at the end of testing that the ULSD injector as measured and by visual inspection.

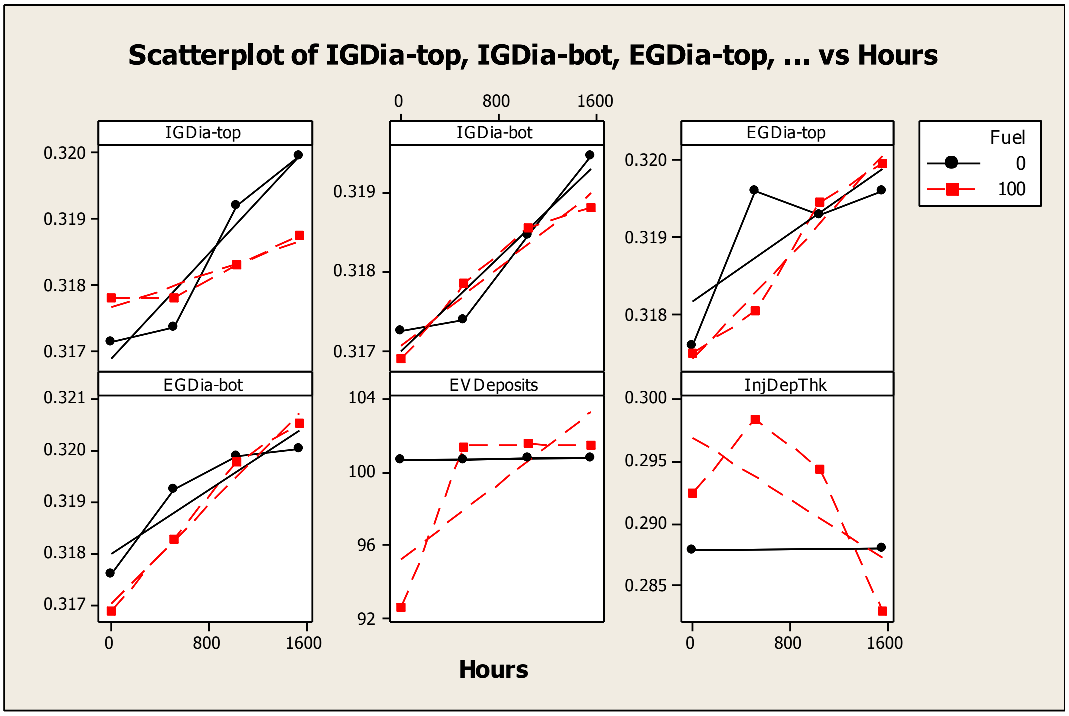


Figure 36 - Comparison of Intake and Exhaust valve guide diameters at the top and bottom of the guides, mass of exhaust valve deposits and the thickness of injector tip carbon deposits.

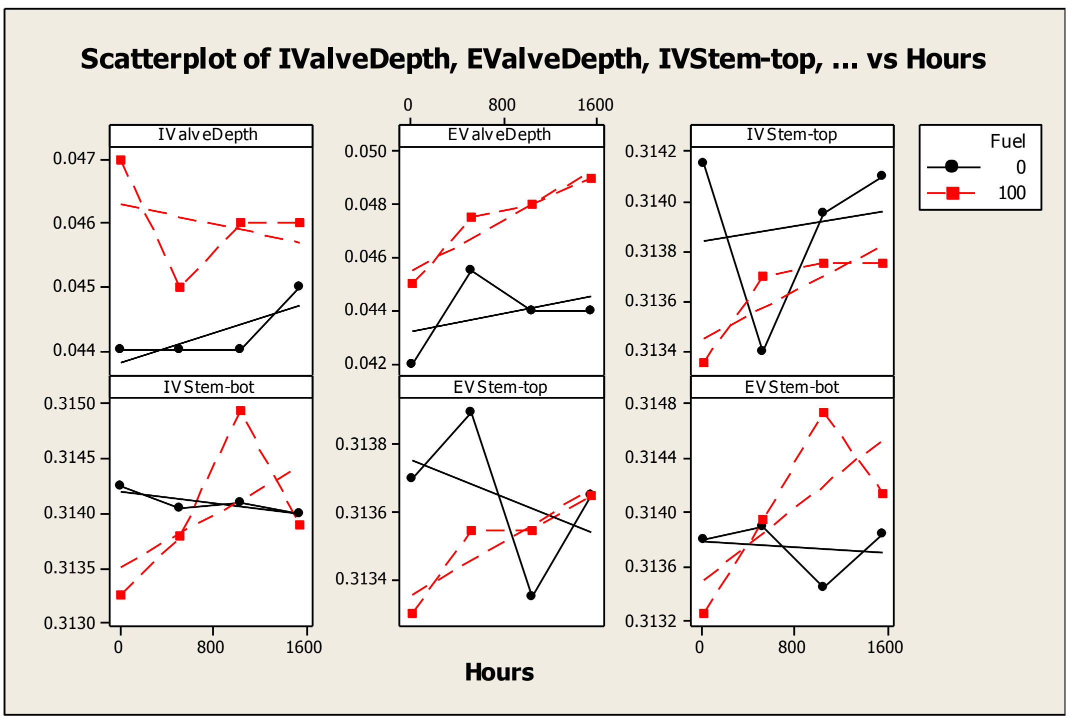


Figure 37 - Comparison of valve depth and stem diameters from the intake and exhaust valves at the top and bottom of the stem.

The plots in Figure 37 show the measurements for valve depth, and stem diameter at the top and bottom of both the intake and exhaust valves. The valve depth is a measure of the distance from the cylinder head deck to the valve face. Changes in valve depth indicate valve seat wear (depth gets larger) or deposits on the seat (depth gets smaller). Stem diameter is a measure of stem wear or deposits. The total variation in intake valve depth was only 0.002-inches and is about equal to the accuracy of that measurement. The exhaust valve depth change was 0.004-inches for the B100 engine and 0.003-inches for the ULSD engine. While the measurements are possibly accurate, both fuels exhibited similar change. The top and bottom intake valve stem diameters on the ULSD engine showed little or no change. The intake and exhaust valve stem diameters for the B100 engine show evidence of increasing in size, signifying some contaminant build-up on the stems.

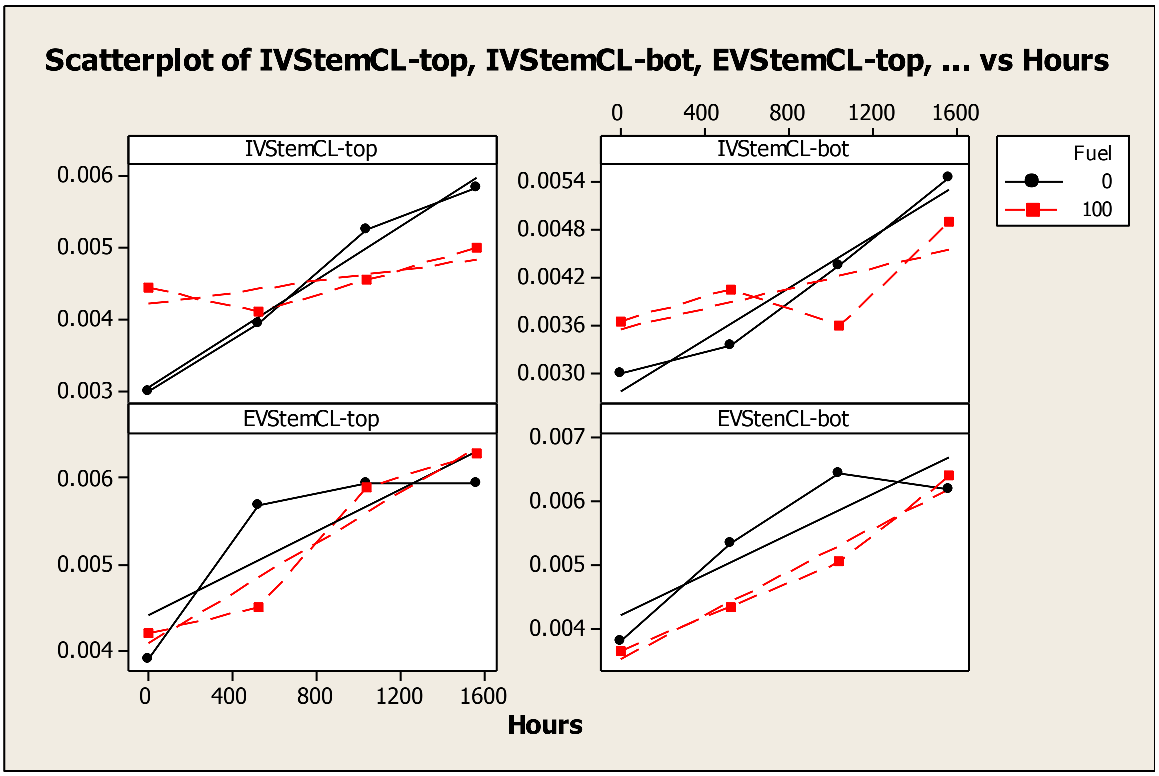


Figure 38 shows valve stem clearance for the top and bottom of the valve stems on the intake and exhaust valves. Both fuels showed similar trends.

Maintenance Items

This section discusses additional observations and measurements that may be relevant to long-term engine durability or to maintenance schedules and practices.

Engine Oil Analysis

According to the U.S. Department of Energy's Alternative Fuels Data Center website[29], the vapor pressure of #2 Diesel fuel is 0.2 psi at 100°F. The vapor pressure of biodiesel is 0.04 psi at 100°F. It is commonly theorized that biodiesel fuel that escapes into the engine crankcase will vaporize more slowly than petroleum diesel and therefore dilute the engine lubricating oil more quickly. CIMS replaced the engine oil and filter at every teardown (500 hour increments) and had an oil analysis performed by NOCO Energy which showed the following:

Engine Oil Analysis:

- Viscosity consistently lower from B100 engine
  - 13.7 CS for ULSD vs. 11.7 CS for B100
  - 11.5% reduction
- Oxidation was critically high for all samples from B100 engine
- Wear Metals
  - Iron and Copper were significantly lower in B100 the samples from the B100 engine
  - Lead was much higher from the B100 engine
- Contaminant Metals
  - Either Sodium or Potassium levels were high in each B100 engine oil sample.

ine 1 - Durability Testing Oil Anal

Oil: Valvoline All Fleet Plus SAE 15W40

0	1	2	3	4
NORMAL		ABNORMAL		CRITICAL

													Wear Metals - PPM										Metals - PPM			Multi-Source Metals - PPM						Additive Metals - PPM				
Sample #	Engine	Block #	Fuel Type	Date Sampled	Engine Hours	Oil Hours	Fuel (est)	Soot (Vol.)	Water (Infrared)	Viscosity 100C (CS)	I-R Oxidation	I-R Nitrates	Iron	Chromium	Nickel	Aluminum	Copper	Lead	Tin	Cadmium	Silver	Vanadium	Silicon	Sodium	Potassium	Titanium	Molybdenum	Antimony	Manganese	Lithium	Boron	Magnesium	Calcium	Barium	Phosphorous	Zinc
1	1	1	ULSD	4/26/2010	650	*500*	<1%	0.10%	<.1	13.9			100	2	0	2	470	1	1	0	0	0	22	2	1	0	0	0	0	0	4	759	1415	0	974	1261
2	1	3	ULSD	7/27/2010	1160	510	<1%	0.10%	<.1	13.6			48	1	0	0	74	1	0	0	0	0	25	4	0	0	0	0	0	0	0	743	984	0	930	1086
1	1	5	ULSD	11/7/2010	1761	601	<1%	0.10%	<.1	13.7	15	17	61	1	0	0	12	5	0	0	0	0	31	1	0	0	0	0	0	0	1	907	1269	0	1158	1330
1	2	2	B100	6/7/2010	790	472	0.50%	<.1%	<.1	12	31	18	58	0	0	1	122	17	0	0	0	0	20	13	0	0	0	0	0	0	3	795	1305	0	1081	1317
2	2	4	B100	9/24/2010	1287	497	0.30%	<.1%	<.1	11.5	28	17	30	0	0	1	14	15	0	0	0	0	20	6	20	0	0	0	0	0	0	701	1020	0	811	994
1	2	6	B100	1/13/2011	1895	608	0.60%	<.1%	<.1	11.6	38	19	29	0	0	0	4	4	0	0	0	0	17	3	23	0	0	0	0	0	0	623	885	0	705	888

Table 14 – Tabulated Oil Analysis Results from all durability oil change samples.

Reduced viscosity and increased levels of sodium and potassium could indicate contamination of the engine lubricating oil with biodiesel. The reduced iron and copper levels are possible indicators of reduced engine wear, though the physical measurements do not necessarily support that. The increased lead content in the B100 engine oil is likely from wear of the main bearings. One of the main bearings showed signs of damage during the 500 hour teardown of the B100 engine. Figure 39 shows the surface of one of the main bearings at the 500 hour teardown. The marks appear to be scratches caused by contaminants in the engine lubricating oil.

Oxidation of engine oil, also known as aging is triggered by increased temperature and is a chemical reaction of hydrocarbons with oxygen in the surrounding air. This reaction can be influenced by metals and certain chemical compounds which can act as catalysts. Metal surfaces in the engine or particles already in the oil can act as oxidation catalysts. Additives in the lubricating oil deactivate the metal. Sulfur and phosphor compounds, among others, are used for this purpose. Once the oxidation inhibitors are depleted, oxidation of the lubricating oil can occur rapidly.[30] Oxidized or aged oil typically thickens and begins to leave sludge deposits in the engine. In a collaborative research effort, Cummins and Chevron found that oxidation occurs when engine lubricating oil is diluted with biodiesel.[31]

The oil from the B100 engine exhibited high levels of oxidation, although the viscosity was lower than the samples from the ULSD engine. It should be noted also that visible sludge had not yet begin to form in the B100 engine. The phosphorous levels in the B100 oil sample were slightly reduced in comparison to the ULSD engine, but not depleted. At 500 hours, it seems that the oxidation was in its early stages. Careful monitoring of engine lubricating oil life through periodic oil analysis is recommended if operating on high ratios of biodiesel until safe oil change intervals can be determined.

Research performed in the "Wear Testing of the Effect of Biodiesel Dilution in Engine Oil" section of this Alternative Fuels study found that biodiesel content up to 10% reduced wear of engine cylinder liners. The experiments performed at RIT tested biodiesel dilution of 5% and 10% in engine lubricating oil and showed reduced liner wear at both dilution levels when compared to straight lubricating oil. Per the results of the RIT experiments, reduced iron and copper levels measured in the B100 engine oil samples may be further evidence of engine oil dilution and of the lubrication benefits of biodiesel relative to ULSD.

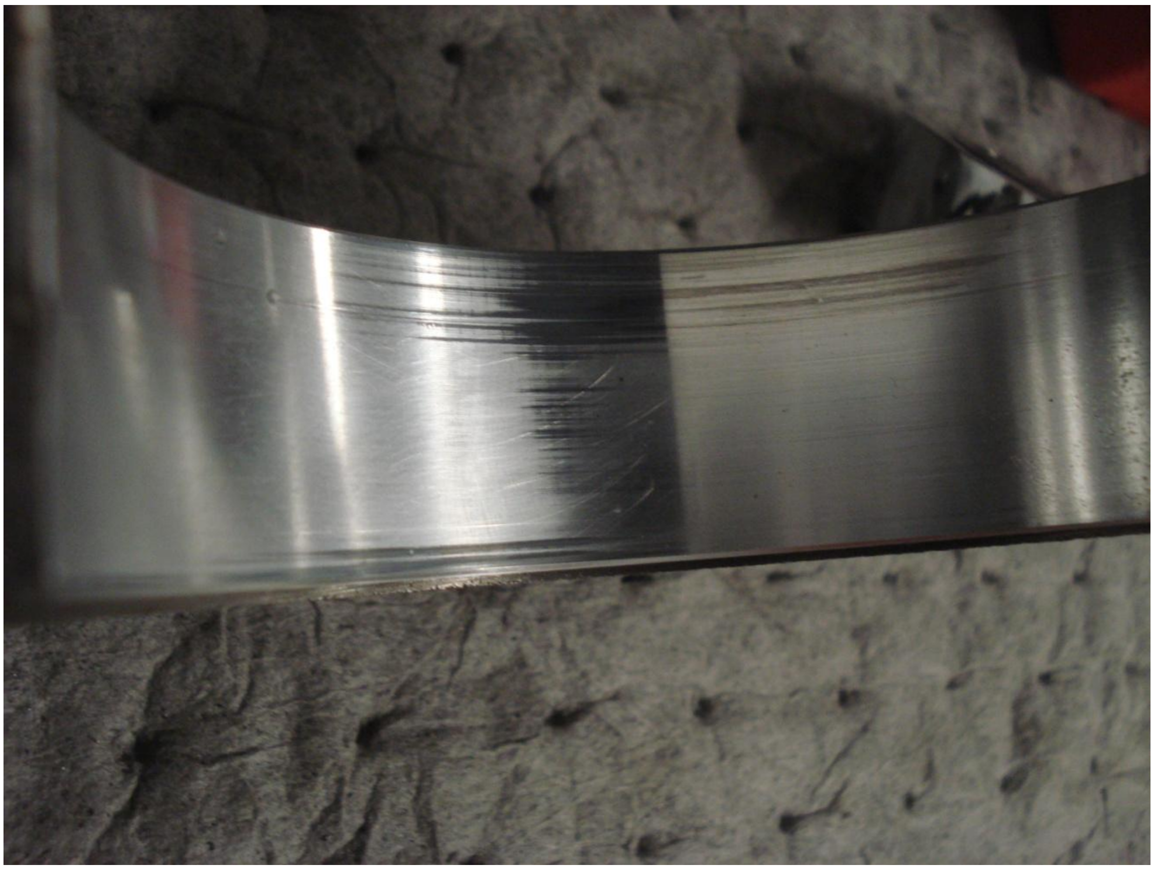


Figure 39 - Main Bearing from Engine 2 operating on B100

Fuel Filter Plugging

During the B100 operation portions of the Durability study, we were forced to change fuel filters after every 60 to 100 operating hours. In our dynamometer lab, a fuel inlet filter and screen protect the fuel metering equipment from fuel borne debris. We used a Fleetguard FS1221 water separator in front of a 5 micron screen at the inlet of the fuel panel. Both the FS1221 and the screen clogged every three to five days during B100 operation. A sample material from a clogged filter was analyzed by Vapor Trail Analytics at 179 Lake Avenue, Rochester, NY, using Fourier Transform Infrared Spectrometry. The sample material was determined to be mostly soybean oil with trace amounts of glycerol and water. The analysis indicates incomplete transesterification and incomplete washing and drying of the finished fuel.

At the end of 2009, U.S. government subsidies for biodiesel producers expired. In the spring of 2010, CIMS discovered that we could no longer buy neat soy-based biodiesel in Western New York. According to the fuel supplier Griffith Energy, feedstock used to make the biodiesel used for the Durability tests included undisclosed portions of waste cooking oil and animal tallow.

The fuel used in the previous fuel screening study was produced from pure virgin soybean oil. We did not notice any filter plugging during the earlier fuel screening tests which were run with blends between straight ULSD up to B90 and were run for only 24 hours on each fuel blend. At this point, we cannot correlate the filter clogging in the Durability study to the different feed stock or to the longer runs on straight biodiesel.

The tendency of biodiesel to cloud and gel at low temperatures is well known. Cold weather fuel problems were not investigated in the Durability Study. Our outside ULSD and B100 storage tanks were both heated as was the B100 feed line into our dynamometer lab. The ULSD tank was heated to avoid cold weather problems with the straight #2 ULSD we used throughout the test and to avoid precipitating paraffin out of the B100 when it was mixed with potentially cold ULSD during the Fuel Screening portion of the research.

Deposits

After extended operation on B100, the exhaust valves, exhaust manifold and turbocharger became coated with a white substance identified as sodium by means of RIT's scanning electron microscope. The sodium deposits did not appear to affect the cylinders or valves during the shorter Fuel Screening Study. Figure 40 shows intake and exhaust valves (top) from ULSD and B100 engines. Notice the white deposits on the top of the B100 exhaust valve.

The sodium deposits did not appear to affect cylinder liner, valve or valve guide wear. Still, there is cause for concern. When operating a modern vehicle with a catalytic exhaust after-treatment on high mix ratios of biodiesel, the catalyst could be damaged by the deposits. Each common catalyst type should be tested with the sodium deposits before the vehicle in question is certified for high mix ratios of biodiesel.

Figure 40 - Comparison of exhaust valves (top) and intake valves (bottom) from ULSD engine (left) and B100 engine (right). The white deposits on the B100 exhaust valve were mostly sodium.

Another potential concern of the sodium deposits is the turbocharger. The bearings, seals and turbine blades used in truck turbochargers may not be designed to withstand the corrosive or abrasive effects of sodium. Although we had no turbocharger failures, long-term operation in these conditions should be investigated.

As mentioned at the beginning of the Durability Report, sodium hydroxide and/or potassium hydroxide are typically used as a catalyst for the transesterification reaction in the manufacture of biodiesel. Since the catalyst is not consumed in the reaction, it must be separated from the finished fuel. ASTM D6751 specifies the maximum sodium and potassium allowed in the finished fuel. Since ASTM testing each batch of fuel was economically feasible, we cannot be sure all of the fuel met the D6751 specification, although the samples tested were in compliance. If further testing determines that the sodium deposits are detrimental to engine or exhaust components, the ASTM specification may need to be updated and improved processing of the fuel be implemented.

Other

Biodiesel is known to be corrosive to materials that petroleum diesel fuel is not. It has been linked to fuel pump failures, especially in older vehicles. Our 2007 model year medium-duty truck engine did not show any ill effects in its fuel system in 1500 hours of operation. Our engine repair stand did not fare as well. When some B100 was splashed on the engine stand, the paint blistered and peeled off as seen in Figure 41. Notice that the paint on the adapter plate was not affected.

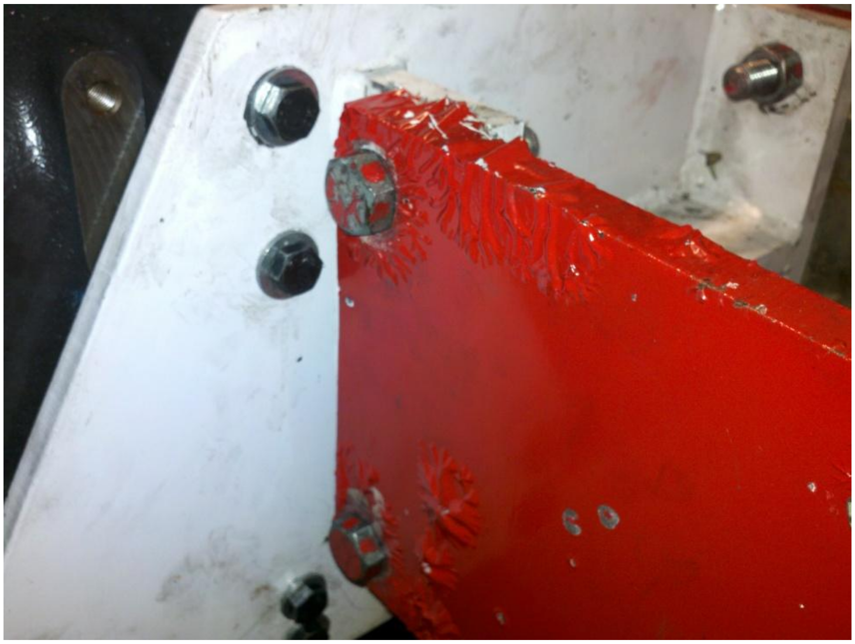


Figure 41- Paint affected by B100 during the dis-assembly of the B100 engine.

Durability Study Summary

The durability study was designed primarily to detect differences in engine wear or engine maintenance items. Since the engines required aging, exhaust emissions and performance data were also collected. Two identical Cummins ISC-240 engines were run; one engine was run exclusively on ULSD and the other on B100 only. Each engine was run in blocks of 500 hours (about 20,000 miles), during which time a full suite of emissions and performance measurements was taken every 100 hours. Every 500 hours, the engines were disassembled and all common engine wear points measured. This was repeated until each engine had accumulated 1500 hours (about 60,000 miles) of operation on its respective fuel.

The test sequence and test runs were the same as those determined in the Gage R&R Study and used in the Fuel Screening Study. The aging portion of the tests was extended to 96 hours instead of the previous 24. The test fuels were limited to ULSD and B100.

The analysis was a full factorial DoE with plenty of repetition yielding improved error estimates and improved resolution. As in the Fuel Screening Study, torque, speed and fuel blend were the input factors and exhaust emissions, torque, power, and efficiency were the responses. Also added were the physical wear measurements. Not surprising, the emissions and performance measurements were similar to the previous study. NO increased 6%, while NO_2, CO and Soot decreased by 13%, 32% and 71% respectively. Efficiency decreased by 10%, torque decreased by 11%, and power decreased by 12%.

Fuel blend failed to significantly affect any of the wear measurements. This may be due to the resolution of the measurement tools used – standard automotive measurement devices. Recall that there were only four sets of wear measurements taken per engine. Perhaps more repetitions would have increased the error estimate to ferret out some small effects. The point is, that any differences between the ULSD engine and the B100 engine were too small to detect with this experiment set-up. There were no noticeable wear issues with using high-ratio blends of biodiesel.

Maintenance items included engine lubricating oil analysis, fuel filter life, exhaust deposits and biodiesel's solvent characteristics. Some early lubricating oil degradation was seen in the oil analysis of the biodiesel engine, but the oil change interval was 20,000 miles – longer than the engine manufacture's recommendation. The interval was intentionally extended to magnify any potential effect.

During the biodiesel portions of the engine operation, fuel filter life was dramatically shortened. It was necessary to change filters every 60 to 100 hours (3000 to 4000 miles) to keep the engine running. Analysis of clogged filters revealed soybean oil, glycerol and oil. Also during biodiesel operation, significant sodium deposits collected on exhaust valves, in the exhaust manifold and in the turbocharger body. Our fuel was certified by the supplier to meet ASTM D6751. Random samples sent for analysis did meet the specification. Perhaps the ASTM specification should be re-evaluated if it is expected to protect engines operating at high biodiesel mix ratios.

Finally, we noticed that some of the paints on our engine repair stand were damaged by spilled biodiesel fuel. Care should be used when fueling a vehicle with biodiesel.

5. Conclusions

During the course of this extensive study of Biodiesel use in vehicles and engines, a few unexpected and conflicting results were discovered. In this section, these results will be explored in an attempt to understand the true relationships. In addition, CIMS has provided a brief discussion of fuel costs and availability that is relevant to the biodiesel industry.

NO_x Production

One of the least understood aspects of biodiesel use in Compression Ignition (CI) engines is the production of oxides of nitrogen during combustion. Many studies combine NO and NO_2 measurements into a convenient NO_x species. In reality, NO_2 is far more toxic than NO. The levels of NO_2 in modern CI engines are also much lower than typical NO levels. In the tested Cummins ISC 240 engines, the average NO_2 level was 41.7 ppm and levels remained below 60 ppm for most test conditions. NO levels reached much higher levels, exceeding 500 and averaging 235 ppm.

The Medium-Duty Truck Engine Dynamometer Biodiesel Study portion of this study showed that NO and NO_2 react differently to operational factors. NO increases linearly with increases in torque and reduces linearly with increased engine speed. NO_2 on the other hand increases as engine speed and torque rise from low levels to moderate levels, then drops as the torque and speed continue to rise to high levels. See Figure 30 and Figure 31 to visualize the effects. Meanwhile, increased biodiesel content causes NO to increase and NO_2 decrease. The NO increases are generally greater in magnitude than the NO_2 reductions and when combined into NO_x, the beneficial reductions in highly toxic NO_2 due to biodiesel are often overlooked.

The engine used in the Dynamometer Study did not have exhaust gas recirculation (EGR). EGR reduces oxides of nitrogen by introducing exhaust gas back into the intake air charge. The exhaust gas, with limited oxygen reduces the combustion temperature. Oxides of nitrogen form when airborne nitrogen (N_2) molecules dissociate as a result of thermal energy absorbed from the combustion of fuel and O_2. The free N atoms readily combine with O and O_2 molecules to form NO and NO_2. Since EGR valves operate at moderate speeds and light to moderate torques, one can see how the NO_2 non-linear effect could be minimized in an EGR engine.

The Fleet study data showed an increase in NO_x for both vehicles during the driving cycle measurement with increased biodiesel. NO_x in the Chevrolet truck decreased during the idle cycle test with increased biodiesel while the Ford Van NO_x increased under the same conditions. The malfunctioning EGR valve in the Ford Van could explain the difference between the two vehicles in the idle test.

Efficiency

RIT's Fleet Study data indicated that the efficiency increased with increased biodiesel content. It was noted that the high content biodiesel (B90) was only run during summer months. The winter months were limited to ULSD and B20-winter blend. It was also noted that one of the vehicles was used as a snowplow vehicle during the winter which puts heavy loads on the engine and includes many starts and stops. The other vehicle was used as a transport vehicle and spent much time idling to keep the cabin warm for passengers. Both uses increase fuel use. The increased efficiency seen of the higher blends is likely to be caused by the seasonal effect more than the biodiesel content of the fuel.

Efficiency during the Dynamometer Study showed a 10% decrease when using B100 versus ULSD. The predicted reduction in efficiency-based on the Higher Heating Value (HHV) of the two fuels is -8.4%. Other fuel factors like cetane number, viscosity, compressibility or density and their inter-relationships with engine tuning are the likely source of the difference in efficiency reductions.

Another important relationship that was demonstrated in the Dynamometer Study is the relationship between efficiency, torque and speed and the fuel*torque interaction. It is not a new discovery that turbocharged CI engine efficiency is highest at high loads and low speeds. At lower engine speed, there is more time available for the fuel and airborne oxygen to react, allowing complete combustion. The turbocharger ensures that there is enough air to fully oxidize the CH chains in the fuel. Producing the same torque at twice the engine speed requires the same fuel charge per power stroke but allows only half the time for the oxidation reaction. Another benefit of lower operating speeds is the reduced friction force on the rotating machinery in the engine. The frictional drag caused by the viscous film is an exponential function of the engine speed. At lower speed, more of the fuel's energy goes to the crankshaft in the form of torque and less goes into the engine's lubricating oil.

Fuel*torque and fuel*speed interactions were discovered in the Fuel Screening Study and show that the difference between efficiency levels due to torque and speed at high biodiesel ratios are greater than at low ratios. An increased reduction in efficiency at high speeds due to high biodiesel content means that it is more important to operate an engine at high loads and low speeds when running on high-biodiesel-ratio fuel.

Fuel Prices

Hand in hand with efficiency is installed performance in the vehicle, and ultimately, fuel economy. Vehicle operators will want to know the impact of biodiesel on their fuel mileage and total ownership cost.

For comparison purposes, the fuel prices for the period of the testing are provided below. Figure 14 shows the biodiesel prices and Figure 15 shows the price for standard ULSD for the same period. Biodiesel went from a low of $3.91 per gallon to a high of $6.22 while ULSD went from a low of $1.72 to a high of $3.23. The tax credit of $1 per gallon of biodiesel expired at the end of 2009. In April 2010, the price per gallon of biodiesel rose by $1 per gallon in the space of one week. There was much less fluctuation in the price of ULSD over the testing period.

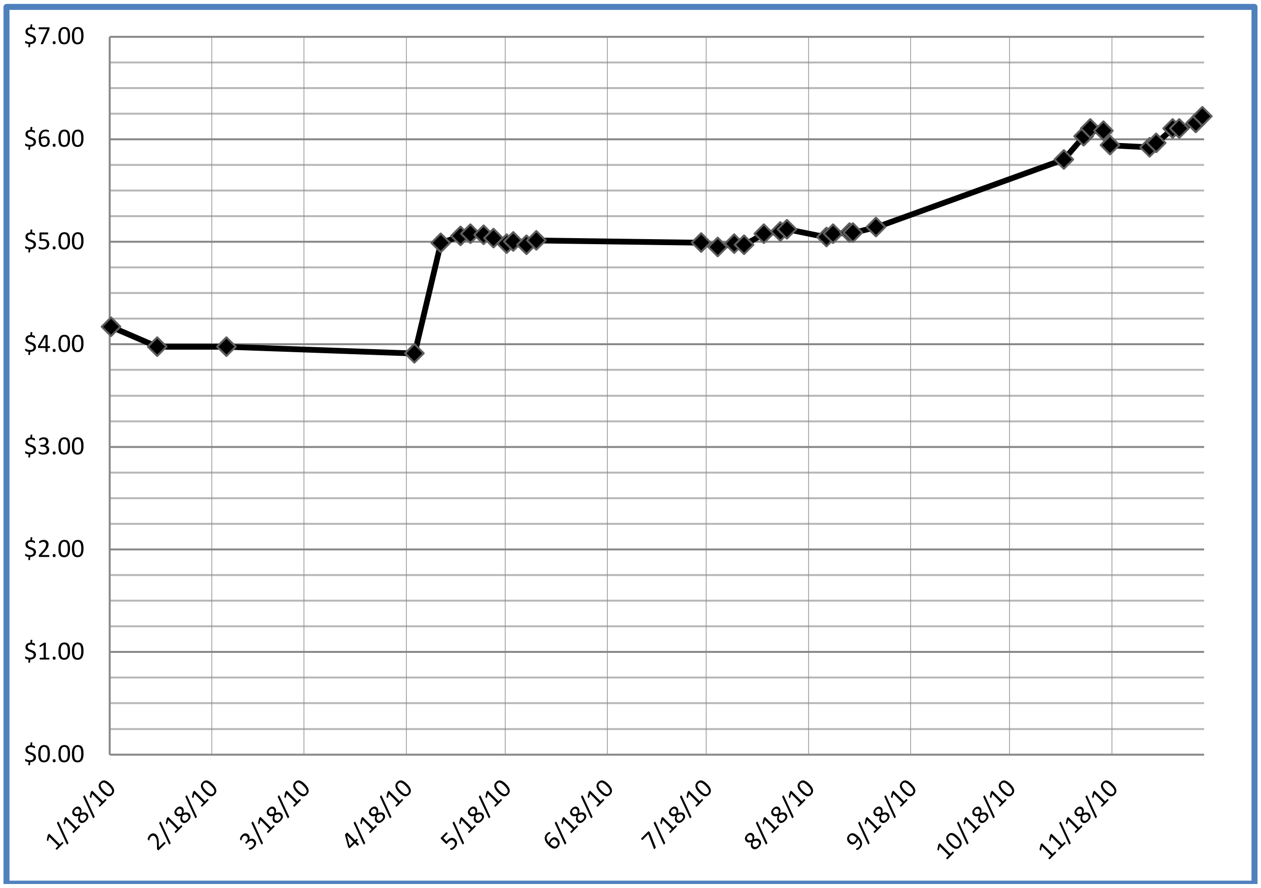


Figure 42 - Biodiesel Cost per Gallon - CY 2010

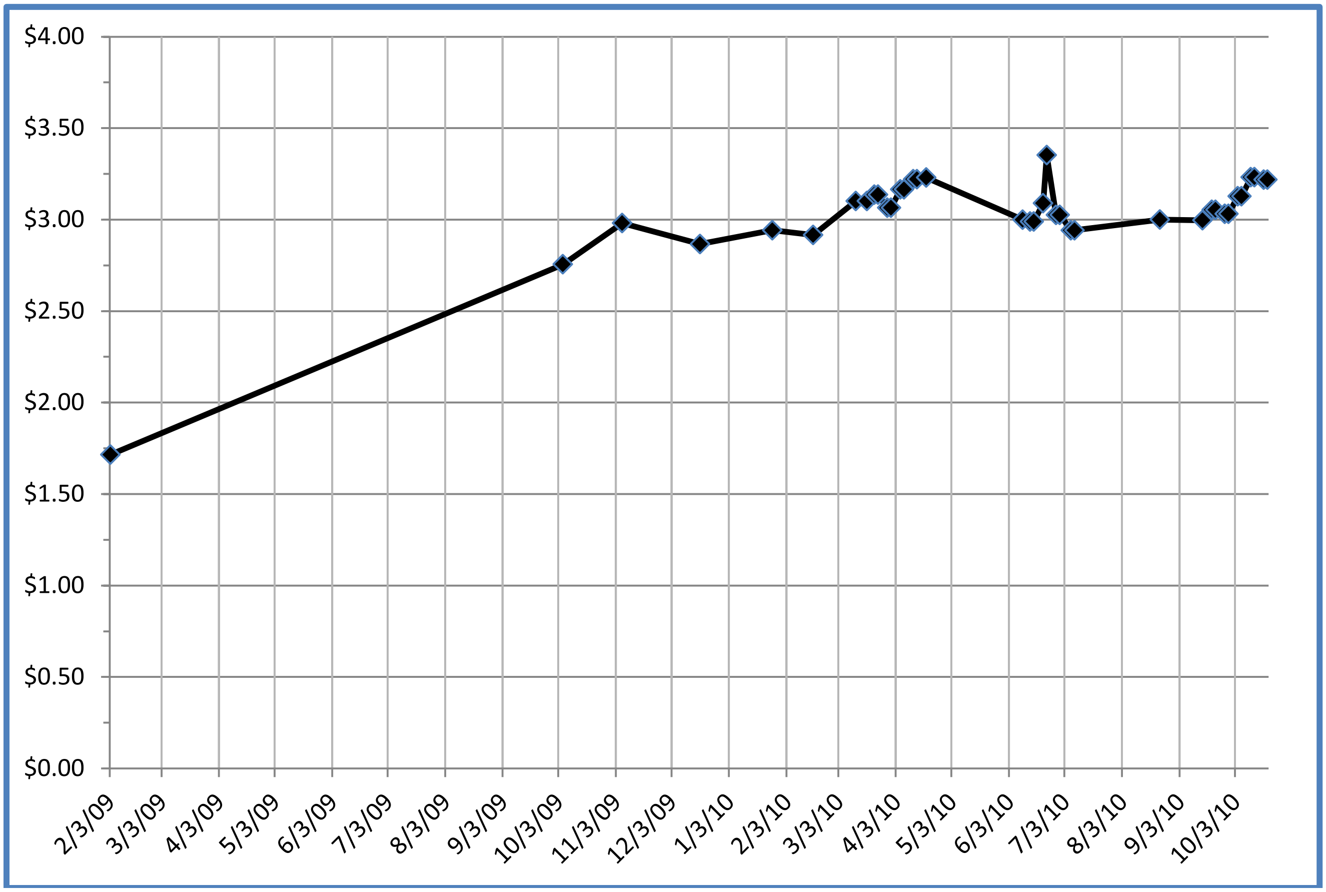


Figure 43 - ULSD Cost per Gallon - CY 2009-2010

Fuel Related Maintenance

During the three-year Fleet Study, no fuel system or fueling station problems were reported. During the summer months, the fueling station and vehicles ran on B90. In contrast, during the Durability portion of the Dynamometer Study, the laboratory fuel inlet filter began to clog every 60 to 100 hours of operation when running B100. It never became clogged when operating on ULSD. The fuel metering hardware in the engine dynamometer laboratory is protected by a 5 micron fuel filter/water separator and a secondary 5 micron screen filter. A vacuum gage was used to monitor the filter condition. When the draw across the filters reached 30 in-hg, the engine could no longer run. The filters were cleaned and changed before the engine stopped.

Samples of material removed from clogged filters were analyzed and found to contain soy vegetable oil, glycerol and water. The same fuel supplier was used for both the dynamometer lab and the fueling station. It is possible that the 5 micron filters are just fine enough trap the contaminants and that the vehicles and fueling station used coarser filters. The filters used in the lab were standard fuel filters though so the problem cannot be ignored. The fuel samples we tested met the ASTM D6751 specification for biodiesel. More research is recommended to determine if the ASTM specification is adequate to protect vehicles running high biodiesel content fuels.

Engine Lubricating Oil

Since biodiesel's has a higher heat of vaporization than ULSD, it has been a concern that biodiesel-based fuel will build up in an engine's crankcase. Normally, fuel that works its way into an engine's crankcase evaporates and is expelled through the crankcase ventilation system. Biodiesel requires a higher temperature to evaporate and so may not be removed in the same manner. Instead it is thought to build up, diluting the engine lubricating oil.

A common path for fuel to enter the crankcase is via the cylinder walls. During injection, some fuel makes it to the cylinder walls before it gains enough heat (or runs into free oxygen atoms) to oxidize. Once in contact with the cool cylinder wall, it is less likely to take part in the surrounding reaction. As the piston and ring travel to the bottom of their stroke and back up again, most of this fuel is scraped off the wall by the cylinder. A small amount remains on the wall and winds up on the crankcase side of the piston rings where it mixes with the lubricating oil.

In the Wear Testing of the Effect of Biodiesel Dilution in Engine Oil Study, it was presumed that dilution of engine lubricating oil with biodiesel would reduce the viscosity of the oil, possibly reducing its ability to protect engine components from wear. It was also presumed that presence of the biodiesel would lead to oxidation of the engine oil.

After testing lubricating oil on a simulated "piston ring on cylinder wall" reciprocating fixture, it was found that even small amounts of biodiesel (5%) reduced the wear between those parts. Increasing the dilution ratio of biodiesel to 10% provided further reduced wear between the parts. The results of the Dynamometer Durability testing were unable to associate a difference in wear between internal engine parts to fuel formulation.

The Wear Testing reciprocating fixture heated the lubricating oil/biodiesel blends to 300°F during testing. Subsequent oil analysis found no evidence of oil oxidation. Since the crankcase temperatures in a typical engine are always below 300°F, it was concluded that the diluted engine oil would not oxidize any sooner than undiluted oil.

After every 500 hours (approximately 20,000 miles) of engine operation during the Dynamometer Durability test, the engine oil was removed and analyzed. Each batch of engine oil recovered from the biodiesel tests showed critical oil oxidation. The crankcase temperatures in our engines did not approach the 300°F test temperature noted above; still there was oxidation. A possible source is from the process of fuel transfer itself. A thin film of fuel attached to the cylinder wall would not completely oxidize as stated earlier. The fuel farthest from the wall could partially oxidize when exposed to the flame front inside the cylinder leaving a small number of partially oxidized fuel molecules in the film attached to the wall. These partially oxidized molecules would be carried into the crankcase as described above.

Each biodiesel batch also showed reduced viscosity. As stated above, these properties did not lead to increased wear in a 1500 hour (60,000 mile) test. Even though oxidation exists and viscosity is reduced when operating on high content biodiesel blend fuel, there is no apparent adverse affect on the engine. There were not even any signs of sludge starting, which is a direct symptom of oxidized lubricating oil.

End Notes

[1] Warranty information from the National Biodiesel Board, http://www.biodiesel.org/resources/oems/default.aspx , accessed October 2010.

[2] Some of the material in this section is adapted from *Biodiesel Technical Information*, a pamphlet produced by Archer Daniels Midland Company, Decatur, IL.

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