Evaluation of the Lubricity of Soybean Oil-based Additives in Diesel Fuel

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Submitted by:

Jon H. Van Gerpen, Seref Soylu, David Y.Z. Chang

Mechanical Engineering Department
Iowa State University

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Jon H. Van Gerpen
Seref Soylu
David Y.Z. Chang

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Executive Summary

Diesel fuel lubricity has been a concern of diesel fuel injection equipment manufacturers for many years. The problem has drawn much recent attention because of the reduction in lubricity associated with the extreme hydrogenation needed to reach the low sulfur levels required in modern diesel fuels. While No. 2 diesel fuels generally have better lubricity than No. 1 diesel fuels, surveys have shown that many of the No. 2 diesel fuels sold in the United States and Canada do not meet the Engine Manufacturers Association recommendations for minimum lubricity levels. The lubricity problem is especially acute during winter when No. 1 diesel fuel and blends of No. 1 and No. 2 are used to combat gelling.

The objective of this project was to determine whether soybean oil, or products made from soybean oil, could be used as lubricity enhancing additives in diesel fuel. We tested soybean oil as a direct additive and compared it with methyl soyate, a soy-based product that has received considerable attention as a lubricity additive. We also tested a polyhydroxy esterified co-polymer of soybean oil that was prepared by International Lubricants, Inc. (ILI), our industrial partner on this project.

Soybean oil was found to be an effective lubricity additive although amounts of 1% or more are required to bring the poorest lubricity fuels into compliance with the recommendations of the Engine Manufacturers Association. Methyl soyate was also tested and the results confirmed the observations of other researchers that it is an effective lubricity additive. The methyl soyate appeared to be slightly more effective than soybean oil for equal treatment rates.

The soybean oil-based additive prepared by International Lubricants, Inc. was found to be very effective in improving diesel fuel lubricity. It provided an equivalent improvement in lubricity at about 1/25th the treatment rate for soybean oil and about 1/18th the treatment rate for methyl soyate. This additive was tested for 125 hours in a diesel engine at a variety of speeds and loads and no deleterious effects were found.

Although the process to produce the ILI additive is proprietary, so its cost cannot be estimated, the additive would appear to have significant commercial value. ILI has stated that they intend to proceed with commercialization and are conducting further testing with this intent. While the amount of soybean oil used may appear to be small, (at the highest treatment rate, 1 gallon of additive for 2000 gallons of diesel fuel) the market is still important due to the large amount of diesel fuel consumed in this country.

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Introduction

Diesel fuel lubricity has been a concern of diesel fuel injection equipment manufacturers for many years. The problem has drawn much recent attention because of the reduction in lubricity found in some modern diesel fuels. This is usually attributed to the extreme hydrogenation needed to reach government mandated low sulfur levels. While No. 2 diesel fuels generally have better lubricity than No. 1 diesel fuels, surveys have shown that many of the No. 2 diesel fuels sold in this country and Canada do not meet the Engine Manufacturers Association recommendations for minimum lubricity levels. The lubricity problem is especially acute during winter when No. 1 diesel fuel and blends of No. 1 and No. 2 are used to combat gelling.

The objective of this project was to determine whether soybean oil, or products made from soybean oil, can be used as lubricity enhancing additives in diesel fuel. We tested soybean oil as a direct additive and compared it with methyl soyate, a soy-based product that has received considerable attention as a lubricity additive. We also tested a polyhydroxy esterified co-polymer of soybean oil that was prepared by International Lubricants, Inc. our industrial partner on this project.

This report documents the tests that were conducted and the results that were found. The first part of the report describes the test fuels and additives that were used. Then, the lubricity test results are presented. Finally, the results of a brief engine test are discussed.

Results and Discussion

Test Fuels

Four different lubricity enhancing additives were tested in this study: soybean oil, methyl soyate, and two additives from International Lubricants, Inc. (ILI) designated as HSS-1.6.5 and SSS-1.7.7. The soybean oil was a food grade oil and was purchased from a local grocery store (Flavorite Brand). The methyl soyate was purchased commercially from NOPEC corporation. It was a fuel grade biodiesel that met all of the specifications of the National Biodiesel Board. To insure that the biodiesel had been completely esterified, it was analyzed for mono-, di-, and triglycerides. The laboratory results confirmed the fuel was within specifications and is provided in Appendix A.

The two additives from ILI were vegetable oil-based and although their formulation is proprietary, they were identified as polyhydroxy esterified co-polymer of high erucic acid rapeseed oil (HSS-1.6.5) and polyhydroxy esterified co-polymer of soybean oil (SSS-1.7.7).

Six different diesel fuels were selected for testing with the additives. They were designated as F1 through F6 and are described below:

F1: This was a commercial grade of #1 diesel fuel purchased from a local truck stop. While we do know whether it has been treated with a lubricity additive, it is highly likely that it was treated. Industry sources have informed us that most commercial fuel is currently additized for lubricity.

F2: A commercial-grade #2 diesel fuel purchased from the same location as F2. Again, it is probable that this fuel had been additized for lubricity.

F3: This fuel was fuel grade kerosene (or #1 diesel fuel) supplied by Engineering Test Services, our lubricity testing laboratory. They had purchased a large quantity of this fuel from a supplier for an earlier project and knew that it represented a "worst case" fuel. It had a very poor lubricity and had not been treated with additives.

F4: Through contacts with Amoco, we procured a sample of #2 diesel fuel that contained corrosion inhibitor but no other additives. This was done because the corrosion inhibitor is usually added at the refinery as a requirement of the pipeline companies so virtually all diesel fuel contains this additive. There is also widespread belief that the corrosion inhibitor offers some lubricity benefits.

F5: This fuel is the same diesel fuel as F4 but contained no corrosion inhibitor. This fuel contained no additives.

F6: This fuel was provided by ILI and was an additive-free No. 2 diesel fuel from a Tosco refinery.

The relevant properties of the diesel fuel samples were analyzed and are given in Appendix A. Originally the properties of the fuels after blending with the additives were to be measured also. However, the treatment rates for the additives were so low that no impact on the fuel properties could be measured. Therefore, the properties of the additized fuels are not reported separately from the non-additized fuels.

Lubricity Testing

The fuels and additives were tested following the test matrix shown in Figure 1. The lubricity of all of the fuels was tested in their non-additized state. Then, additives were blended at two levels with some of the fuels to determine their effect.

Two different lubricity tests were used to characterize the lubricity of the samples: the Scuffing Load Ball on Cylinder test (SLBOCLE) and the High Frequency Reciprocating Rig test (HFRR). Both of these tests are widely used for measurement of lubricity in diesel fuels. The SLBOCLE test determines the maximum load (in grams) that can be applied to a ball sliding on a rotating cylinder in the presence of the lubricant before there is excessive friction. The test result is a weight value and the Engine Manufacturers Association (EMA) has recommended that diesel fuels have a SLBOCLE level of greater than 3150 grams. The HFRR test uses a similar concept but the load is applied as a high frequency alternating load and the result is given as the size of the wear scar produced on a replaceable element. This scar is reported in microns and the EMA recommends that the scar diameter be no greater than 450 microns. All of the lubricity testing was performed by Engineering Test Services of Charleston, South Carolina.

Fuel: Treatment	F1	F2	F3	F4	F5	F6
None	X	X	X	X	X	X
0.25% Soybean Oil	X	X	X	X	X	
1% Soybean Oil	X	X	X	X	X	
0.25% Methyl Soyate			X	X		
1% Methyl Soyate		X	X	X		
0.02% HSS-1.6.5			X			
0.2% HSS-1.6.5			X			
0.01% SSS-1.7.7			X	X		X
0.05% SSS-1.7.7			X	X		X

Figure 1. Lubricity Test Matrix

Lubricity of the Base Fuels

The results of the lubricity testing are reported in Table 1. It can be seen that the fuel designated as F3 is by the far the worst fuel in its non-additized condition. This fuel was tested twice and the SLBOCLE levels were 1250 grams and 1300 grams for the two tests. The HRFF scar measurements were 675 microns and 642 microns. This fuel shows a lubricity level that is clearly outside the acceptable range of the EMA. The commercial #1 diesel fuel (F1) was also unacceptable, although the SLBOCLE score at 3050 was only slightly below the acceptable level of 3150. The HFRR score of 578 microns was well above the acceptable level of 450. All three of the non-additized #2 diesel fuels (F4-F6) had SLBOCLE scores that were acceptable but their HFRR scores were in the unacceptable range. These results are typical of lubricity data in general. Often, one of the tests will be more severe. Previous experience with the test as reported by the testing laboratory is that the tests will correlate fairly well with each other for pure fuels but that the HFRR test seems to respond better to additives.

These data support the assertion that the presence of corrosion inhibitor has some impact on the lubricity. The Amoco fuel with corrosion inhibitor (F4) had a SLBOCLE score that was 500 grams higher than the AMOCO fuel with no corrosion inhibitor (F5). The HFRR test showed no effect of the corrosion inhibitor.

Lubricity testing with Soybean Oil

Foodgrade soybean oil was added to 5 of the 6 fuels at two levels, 0.25% and 1%. When the soybean oil was added to the commercial #1 diesel fuel (F1), the SLBOCLE

	F1 Commercial D1 Fuel		F2 Commercial D2 Fuel		F3 ETS Kerosene		F4 Amoco D2 Fuel With Corrosion Inhibitor but no other additives		F5 Amoco D2 w/o Corro Inhibitor a other add
Additive	SLBOCLE (grams)	HFRR (microns)	SLBOCLE (grams)	HFRR (microns)	SLBOCLE (grams)	HFRR (microns)	SLBOCLE (grams)	HFRR (microns)	SLBOCLE (grams)
None	3050	578	4150	376	1250	675	4200	531	3700
None					1300	642			
.25% Soybean Oil	3300	579	4150	365	2200	631	4200	492	4650
1% Soybean Oil	3900	432	5200	319	3050	468	4550	303	4300
.25% Methyl Soyate					2650	600	4450	499	
1% Methyl Soyate			5000	251	3700	294	4775	233	
.02% HSS-1.6.5 Additive					3150	585			
.2% HSS-1.6.5 Additive					5350	176			
.01% SSS-1.7.7 Additive					2250	656	4100	500	
.05% SSS-1.7.7 Additive					3650	303	5050	261	

increased from 3050 to 3300 at the 0.25% level and to 3900 at the 1% level. The fuel's SLBOCLE score was very close to being acceptable as received, and was brought into the acceptable range by the addition of as little as 0.25% soybean oil. The HFRR test was not affected by the addition of 0.25% soybean oil and the fuel was still unacceptable. However, at the 1% level of soybean oil, the HFRR test was brought into the acceptable range.

The commercial #2 diesel fuel (F2) was already acceptable in its non-additized state. The addition of 0.25% soybean oil did not seem to have an appreciable effect. At the 1% level, the lubricity was measurably improved.

The low lubricity kerosene supplied by ETS (F3) showed a significant improvement in both the HFRR and the SLBOCLE tests although 1% soybean oil was still required to bring it close to the acceptable range. The two AMOCO fuels (F4 and F5) showed some effect of the soybean oil at the 0.25% level with the HFRR score improving 30-40 microns although they were still above the 450 micron level. The SLBOCLE measurement of 4650 grams for 0.25% soybean oil in F5 is probably a measurement error since the increase is well above what was observed for other fuels and the level came back down to 4300 grams at the 1% level. At the 1% soybean oil treatment rate, the HFRR scores of both AMOCO fuels were brought below the 450 micron level on the HFRR test.

Lubricity Testing with Methyl Soyate

Three of the fuels were tested with methyl soyate, the methyl ester of soybean oil. This product has been the subject of considerable study as a lubricity additive. When 1% methyl soyate was added to the commercial # 2 diesel fuel, it improved the lubricity according to both tests. When methyl soyate was added to the low lubricity kerosene, it improved the SLBOCLE test result from 1250 grams to 2650 grams at the 0.25% level and 3700 grams at the 1% blend level. The magnitude of this increase is larger than the increase observed with soybean oil at the same concentration. Similar results were observed for fuel F4.

Lubricity Testing with Co-Polymer Additives

Early in this test program, ILI provided a sample of a co-polymer product that was based on an earlier project involving high erucic acid rapeseed oil (HSS-1.6.5). This additive was tested at the ILI recommended treat rates of 0.02% and 0.2% with the low lubricity kerosene (F3). This additive brought the SLBOCLE rating of the kerosene into the acceptable range with only 0.02% blended with the fuel. At this rate, the HFRR score improved from 675 to 585 but was still unacceptable. However, at the 0.2% treat rate, the HFRR score improved to 176, the lowest measured for any of the fuels and additives tested.

Later in the test program ILI supplied us with a soybean oil-based product they identified as SSS-1.7.7. They recommended we test it at 0.01% and 0.05% treatment rates. We tested this product in three fuels. In the low lubricity kerosene (F3), 0.01% of the additive increased the SLBOCLE from 1250 to 2250 and the HFRR dropped from 675 to 656. The drop in HFRR is probably not significant since the variation in the two measurements is greater than this change. At the 0.05% rate, the SLBOCLE increased to 3650 grams and the HFRR dropped to 303 microns. Both of these tests are in the acceptable range. Similar results were obtained for the F4 fuel. However, the F6 fuel appeared to respond greatly to the additive even at the 0.01% level. The SLBOCLE score went from 4000 grams to 4875 grams and the HFRR went from 502 microns to 222 microns. These increases are larger than would be expected, particularly when the response with the AMOCO fuel was much less. However, since the increase is confirmed by both tests, it is probably not explainable as experimental error.

Figure 2 shows all of the lubricity data collected in this project plotted as SLBOCLE against HFRR. It is clear that the correlation between the two test methods is not ideal with a considerable number of data points above the 3150 gram acceptability figure for SLBOCLE while still unacceptable on the HFRR test. This data illustrates that lubricity data should only be used for initial screening of products and that further injection system and engine testing is required.

Engine Testing

One of the concerns about producing a fuel additive from vegetable oil was that the additive might cause an increase in engine deposits. While this deposit formation tendency has been observed in tests with high levels of vegetable oils, there are no data available for low level blends of 1% or less. We conducted a brief engine endurance test with the additive to determine whether there were any problems that would show up in short time periods.

The test was conducted on a John Deere 4276T turbocharged, direct-injected diesel engine. This is a four-cylinder engine with a displacement of 276 in^3. The engine was connected to a General Electric DC dynamometer that allowed the speed and load of the engine to be varied. The engine was operated for 125 hours under alternating high and low load conditions. This is the same sort of test used to measure injector deposits with the Cummins L-10 Injector Depositing Test. In our test, we did not disassemble the engine to look for wear or inspect the injectors for deposits. We measured the exhaust emissions at the start and end of the test and used this as an indicator of problems. Generally, if there is a problem with the quality of the fuel injection, it will manifest itself as higher carbon monoxide and unburned hydrocarbon emissions. When the problem becomes more severe it will also show up as higher smoke and lower oxides of nitrogen.

The actual test times and cumulative hours are shown in Appendix C. A summary of the emissions test results is shown in Table 2. The engine was tested at 3 operating conditions: 1400 rpm at 220 ft-lb of torque (peak torque), 2100 rpm at 187 ft-lb of torque (rated power), and 1200 rpm at 30 ft-lb of torque (light load). More detailed data on the engine test conditions are provided in Appendix D and plots of the exhaust emissions during the tests are given in Appendix E.

With the exception of NOx emissions, the differences between the initial and final values of the exhaust emissions are within the expected range of the test variability. For some reason, the NOx emissions were substantially lower at the end of the test than at the beginning. At this time we do not know the reason for this drop, but we believe it is a change in measurement conditions. We do not believe it is attributable to the fuel additive.

Figure 2. #1 and #2 Diesel Fuels with Soybean Oil, Methyl Soyate, or Fuel Additives

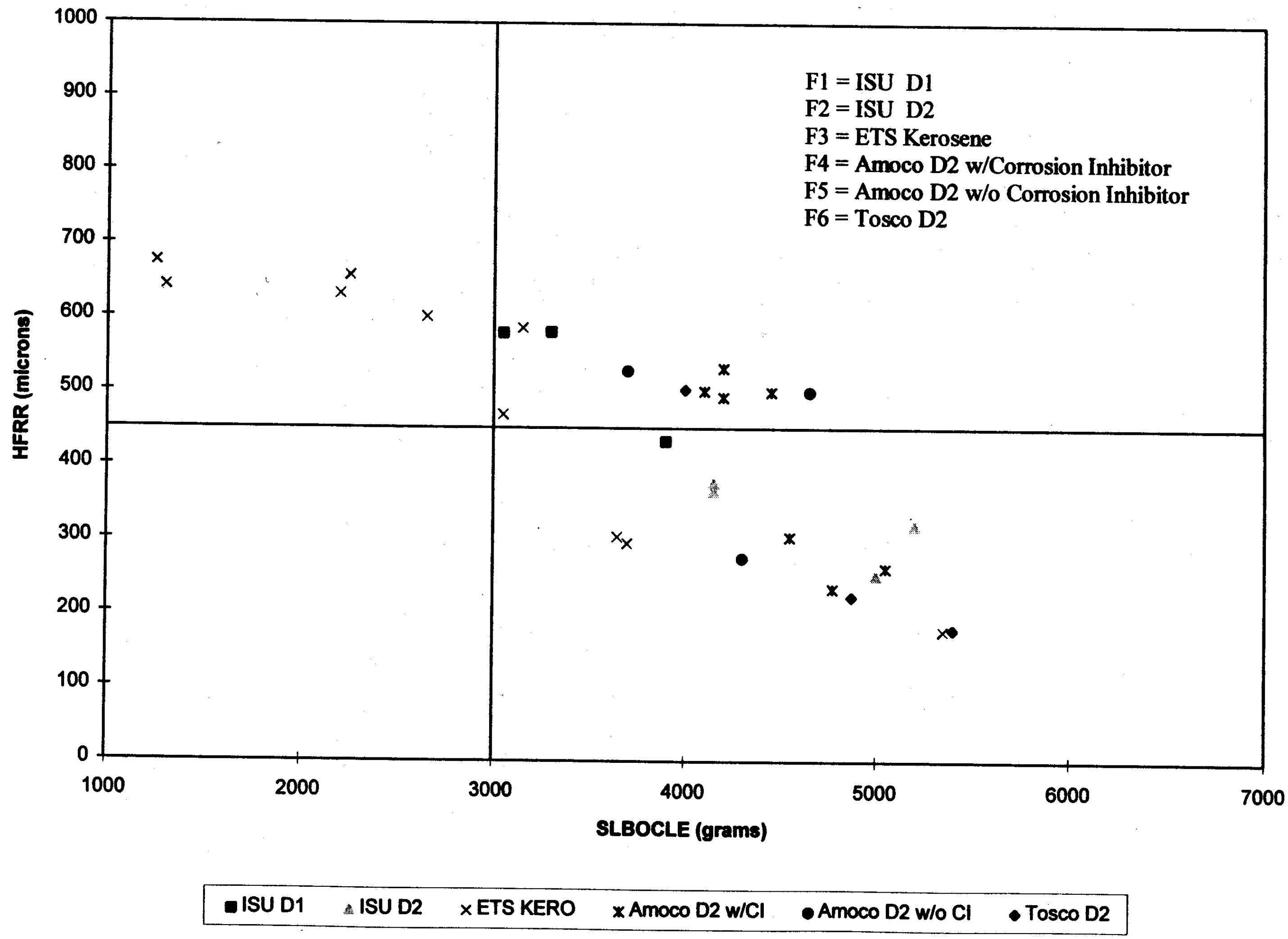

Table 2. Emission Data for John Deere 4276T Engine.

Test Conditions	Species	Initial	Final
1400 rpm/220 ft-lb	NOx, ppm	2600	1810
	CO, ppm	129	101
	CO_2, %	8.0	8.3
	HC, ppm C_6	32.6	31.6
	Smoke (BSN)	1.77	1.83
2100 rpm/187 ft-lb	NOx, ppm	2803	2045
	CO, ppm	95	85
	CO_2, %	7.5	7.3
	HC, ppm C_6	27.9	24.8
	Smoke (BSN)	0.67	0.73
1200 rpm/30 ft-lb	NOx, ppm	606	394
	CO, ppm	252	268
	CO_2, %	2.9	2.1
	HC, ppm C_6	55.9	51.2
	Smoke (BSN)	0.63	0.60

Conclusions

This project investigated the effectiveness of several soybean-based diesel fuel lubricity additives. One additive was tested for its effect on engine operation. Soybean oil was found to be an effective lubricity additive although amounts of 1% or more will probably be required to bring the poorest lubricity fuels into compliance with the recommendations of the Engine Manufactures Association. Methyl soyate was also tested and the results confirmed the observations of other researchers that it is an effective lubricity additive. The methyl soyate appeared to be slightly more effective than soybean oil for equal treatment rates.

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Although the process to produce the ILI additive is proprietary, so its cost cannot be estimated, the additive would appear to have significant commercial value. ILI has stated that they intend to proceed with commercialization and are conducting further testing with this intent. While the amount of soybean oil used may appear to be small, (at the highest treatment rate, 1 gallon of additive for 2000 gallons of diesel fuel) the market is still large due to the amount of diesel fuel consumed in this country. Most of this fuel is additized with a lubricity additive. There does not seem to be any reason why it could not be a soybean-based additive.