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Regulated Emissions from Biodiesel Tested in Heavy-Duty Engines Meeting 2004 Emission Standards

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ABSTRACT

Biodiesel produced from soybean oil, canola oil, yellow grease, and beef tallow was tested in two heavy-duty engines. The biodiesels were tested neat and as 20% by volume blends with a 15 ppm sulfur petroleum-derived diesel fuel. The test engines were the following: 2002 Cummins ISB and 2003 DDC Series 60. Both engines met the 2004 U.S. emission standard of 2.5 g/bhp-h NO_x+HC (3.35 g/kW-h) and utilized exhaust gas recirculation (EGR). All emission tests employed the heavy-duty transient procedure as specified in the U.S. Code of Federal Regulations. Reduction in PM emissions and increase in NO_x emissions were observed for all biodiesels in all engines, confirming observations made in older engines. On average PM was reduced by 25% and NO_x increased by 3% for the two engines tested for a variety of B20 blends. These changes are slightly larger in magnitude, but in the same range as observed in older engines. The cetane improver 2-ethyl hexyl nitrate was shown to have no measurable effect on NO_x emissions from B20 in these engines, in contrast to observations reported for older engines. The effect of intake air humidity on NO_x emissions from the Cummins ISB was quantified. The CFR NO_x/humidity correction factor was shown to be valid for an engine equipped with EGR, operating at 1700 m above sea level, and operating on conventional or biodiesel.

INTRODUCTION

Biodiesel is an oxygenated fuel or blending component made from vegetable oils, waste cooking oil, or animal fats by reaction of the triglyceride fats with methanol to form methyl esters via transesterification. Life cycle analysis indicates that biodiesel is highly renewable and its use, therefore, produces real reductions in petroleum consumption and carbon dioxide emissions [1]. Biodiesel is well known to cause a reduction in particulate matter (PM) emissions and to slightly increase oxides of nitrogen (NO_x) emissions in most engines relative to petroleum diesel [2,3].

The United States Environmental Protection Agency (EPA) produced a review of published biodiesel emissions data for heavy-duty engines. The results for NO_x, PM, carbon monoxide (CO), and total hydrocarbons (HC) are summarized in Figure 1, taken from that report [3]. The chart shows that, on average, substantial reductions in PM, CO, and HC can be obtained through use of biodiesel. However there is also an increase in NO_x emissions, by approximately 2% for B20 (20% biodiesel by volume) blends and 10% for neat biodiesel (B100), on average. Engine model year and technology exhibited a large influence on NO_x emissions with the change in NO_x for B20 ranging from roughly +8% to –6%, but averaging +2%. The NO_x increase may limit the use of biodiesel in non-attainment areas and is therefore a significant barrier to market expansion for this new fuel. Notably the studies reviewed by EPA did not include engines that meet the U.S. 2004 on-road standard of 2.5 g/bhp-h NO_x+HC (3.35 g/kW-h).

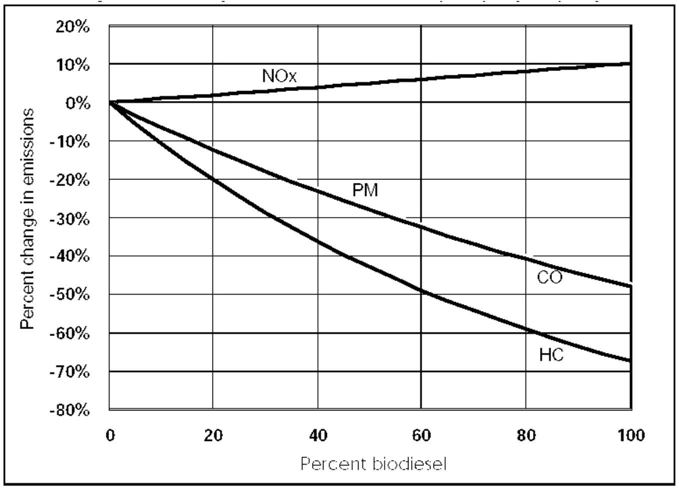

Figure 1. Summary of United States EPA evaluation of biodiesel impacts on pollutant emissions for heavy-duty engines (note PM and CO curves overlap).

In this study biodiesel from several sources was tested in two engines meeting the 2004 U.S. heavy-duty emission requirements using the heavy-duty transient test. Neat biodiesels as well as various blends were tested in a 2002 Cummins ISB. Twenty percent biodiesel blends (B20) were tested in a 2003 DDC Series 60. Earlier work in a 1991 engine demonstrated that B20 NO_x emissions could be lowered to a level equivalent to that of conventional diesel by blending of several thousand ppm of 2-ethyl hexyl nitrate (EHN) [4]. The use of EHN for NO_x reduction was also investigated in this study.

METHODS

FUELS AND FUEL PROPERTY MEASUREMENTS

The baseline diesel fuel used both for comparison to the biodiesel fuels and as the diesel blend stock is a 15 ppm sulfur fuel manufactured by BP and commonly referred to as BP15. Biodiesels meeting the ASTM D6751 specification were acquired from various sources. Biodiesels from the following feedstocks were tested: soybean oil, canola oil, yellow grease, and beef tallow. Two separate batches of soy biodiesel were used at different points in the study as noted in the results section. Appendix A-1 presents important property data for these fuels. Biodiesel blends (primarily B20) were prepared gravimetrically to achieve specific volume percentages. Cetane number for the B20 blends is reported in Appendix A-2. Cetane number results were acquired using both D613 (engine test) and D6890 (derived cetane number from constant volume combustion experiment), there is close agreement in cases were data from both methods are available. Additionally, a B20 soy-biodiesel blend with 2-ethyl hexyl nitrate added at four or five thousand ppm, and targeted at increasing cetane number by 10 units, was tested in both engines.

EMISSIONS TESTING

All emission tests were conducted according to CFR Title 40 Part 86 Subpart N, the heavy-duty transient. The baseline fuel engine-torque curve was used to generate the transient test for all fuels. Repeat hot-start tests were performed on each fuel with control test runs on the reference fuel included on every test day to minimize the effect of day-to-day variability on the fuel comparisons.

The Cummins ISB engine was tested at NREL's ReFUEL laboratory and the Detroit Diesel Corporation (DDC) Series 60 was tested at SwRI. Both laboratories employed the full-scale dilution tunnel method with constant volume sampling for mass flow measurement. Gaseous emissions of NO_x, HC, CO and CO_2 were continuously sampled and analyzed using standard methods. PM emissions were collected on filters using double-dilution with a secondary dilution ratio of roughly 2-to-1. A class 1000 clean room with precise environmental controls was used for all filter handling, conditioning and weighing at ReFUEL. PM filter handling was performed in HEPA filtered temperature and humidity controlled chambers at SwRI. Intake and dilution tunnel air were conditioned for humidity and temperature, and then passed through a HEPA filter to eliminate background particulate matter. All emissions data were corrected for background, analyzer span and humidity in accordance with CFR recommendations. The NO_x humidity correction factor (40 CFR 86.1342-94(d)(8)(iii)) was applied to the real time data to correct to an absolute humidity of 75 grains/lb. Experiments were performed to confirm the validity of the CFR humidity correction factor for petroleum-based diesel and neat biodiesel in the Cummins ISB at Denver's altitude (1700 m), as described in the Results.

Properties of the test engines are shown in Table 1. Both engines are direct injection, inter-cooled with cooled high-pressure EGR, employ a variable geometry turbocharger, and electronic control. The 2002 Cummins ISB employs a high-pressure common rail fuel injection while the 2003 DDC Series 60 features high-pressure electronic unit injectors (EUI).

Table 1. Test engine specifications.

	Cummins ISB	DDC Series 60
Serial Number	56993170	06R0773118
Displacement, L	5.9	14
Cylinders	6	6
Rated Power, kW	224@ 2500 rpm	373@ 1800 rpm
Rated Torque	895 N-m@ 1600 rpm	2237 N-m@ 1200 rpm
Bore x Stroke	10.2x12 cm	13.3x16.8 cm
Compression Ratio	16.5:1	16.0:1
Fuel System	Common Rail	EUI
Intake Restriction, kPa	4.47	3.97
Exhaust Backpressure, kPa	7.95	8.10

RESULTS

Emission results for both engines and all fuels are summarized as percent change in emissions in Figure 2. Biodiesel shows a trend towards reductions in HC and CO. However, for B20 and lower blends these changes are generally not statistically significant. This is in contrast to the results shown in Figure 1 where CO emission reductions closely tracked PM emission reductions and where HC emission reductions are large and measurable. At higher blend levels both HC and CO are reduced. The trends for NO_x and PM shown in Figure 2 are similar to those in Figure 1, however changes in emissions are larger. NO_x emissions increased in an approximately linear manner with blend level. For B20 and lower blend levels the PM reduction may exceed that predicted by a linear fit of the data.

Table 2 compares average percent change in emissions for B20 from the EPA study of 1997 and older engines [3] with those measured for the two engines tested here.

The average change in HC for this study is not significantly different from zero and represents the error inherent in measuring the very low levels of total hydrocarbon emitted by modern diesel engines. CO emissions were reduced on average for the 2004 engines, but the percent reduction is less than for older engines. The NO_x emission increase for B20 appears somewhat higher than observed in the older engines. However, both studies found a broad range of changes in NO_x and the results for the 2004 engines fall well within the range observed in the EPA study. The large variability in percent change in NO_x is caused by the use of biodiesels from a variety of feedstocks, as discussed below. PM reductions for the two engines are on average more than twice as large as observed in older engines. Note that the effect of biodiesel on emissions was shown to be sensitive to base diesel properties [3]. The EPA study results listed in Table 2 are averages for a wide range of base fuels.

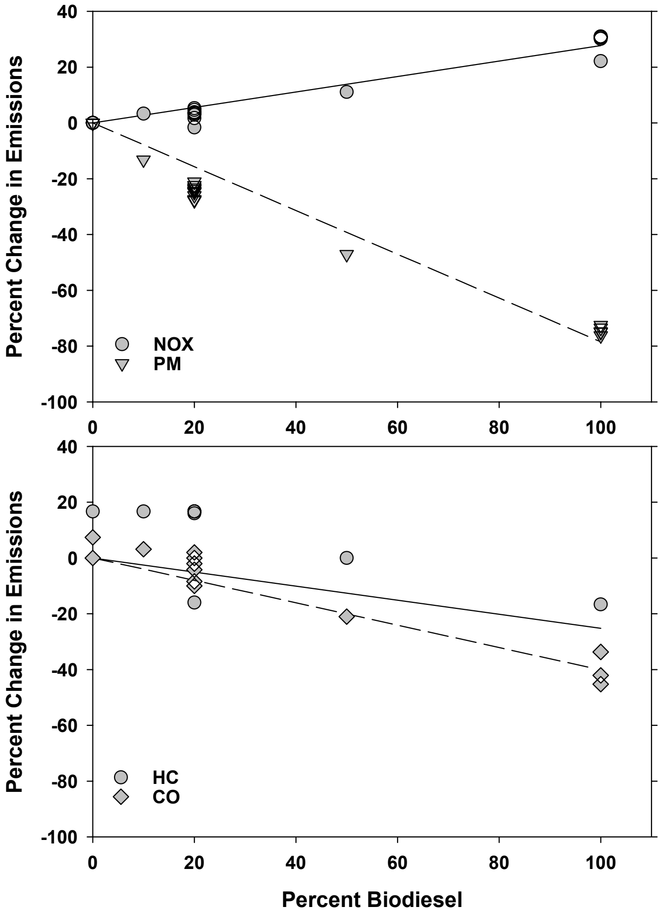

Figure 2. Effect of biodiesel on changes in pollutant emissions for all fuels and both engines.

Table 2. Average change in emissions for B20, 95% confidence interval shown for results from this study.

	EPA 2002 [3]	This study
HC	-21.1	+3±8
CO	-11.0	-4±3.3
NO_x	+2.0	+3±1.5
PM	-10.1	-25±1.7

CUMMINS ISB

Average transient test results for each fuel tested in the Cummins ISB are tabulated in Appendix A-3. These data represent results for three or more hot-start transient tests. Work with this engine includes tests of all five biodiesels as B100 and B20. Additionally, soy biodiesel was tested as B10 and B50, and as B20 with 4000 ppm of EHN. Both Soy 1 and Soy 2 were used at different stages of the study. Comparison of the results for these two fuels as B100 or B20 shows no significant difference in emissions performance.

Figures 3 and 4 show NO_x and PM results for testing of B100 and B20, respectively, in the ISB. Both B100 and B20 produce reductions in PM that are independent of biodiesel feedstock. NO_x emissions increase significantly for B100 and the increase varies with biodiesel feedstock. Note that B100 has approximately 10% lower energy content per volume than conventional diesel resulting in about 3% lower cycle work. This effect is insignificant for B20. For B20 the NO_x increase is evident for all biodiesels but the effect of feedstock is much less pronounced.

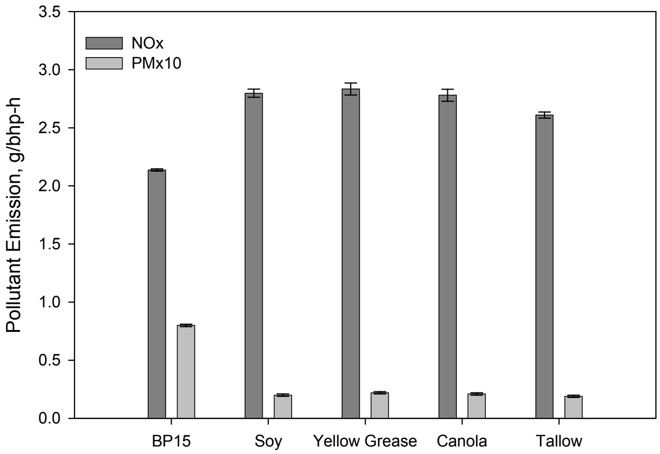

Figure 3. NO_x and PM emission results for testing of B100 fuels in the Cummins ISB.

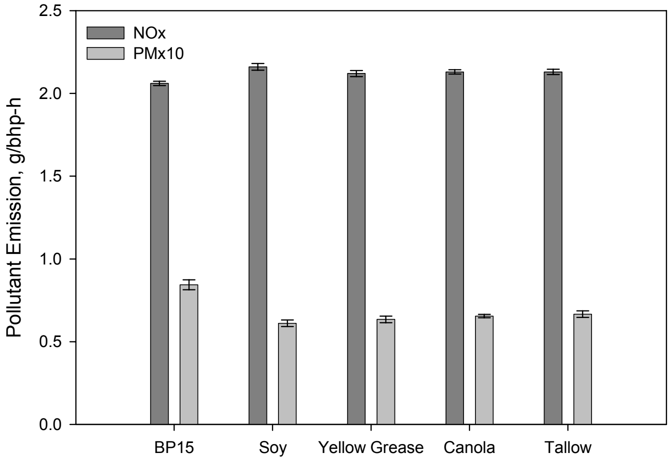

Figure 4. NO_x and PM emission results for testing of B20 fuels in the Cummins ISB.

DDC SERIES 60

Average transient test results are tabulated in Appendix A-4. The data in this table represent an average of three hot-start tests. This engine was tested with B20 blends using biodiesel made from soy (Soy 1), yellow grease, and tallow. A B20 was prepared using 10% soy and 10% tallow to investigate the potential for blending of more saturated biodiesel as a NO_x reduction strategy. Also, a soy biodiesel was tested as B20 with 5000 ppm of EHN.

NO_x and PM results are shown in Figure 5. A significant reduction in PM emissions is observed independent of feedstock. NO_x emissions increased significantly for soy B20, but were statistically unchanged for the yellow grease biodiesel and increased only marginally for beef tallow. In an attempt to lower NO_x emissions, fuel was prepared from 10% soy, 10% tallow, and 80% baseline diesel. Testing of this fuel shows a small but statistically insignificant reduction in NO_x as compared to the soy only B20 tests.

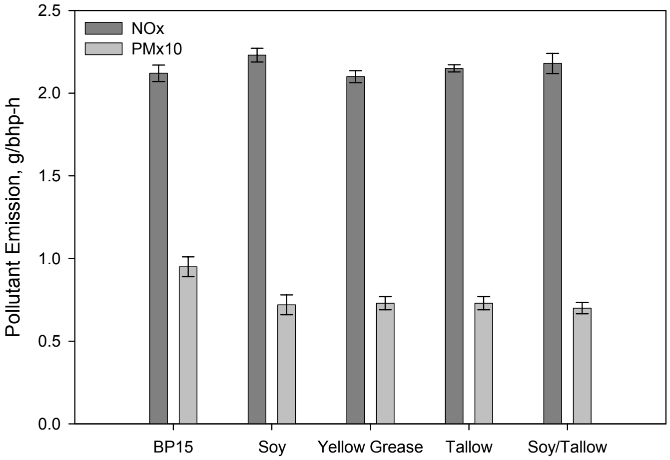

Figure 5. NO_x and PM emission results for testing of B20 fuels in the DDC Series 60.

EFFECT OF CETANE IMPROVER

Earlier work has shown that cetane-increasing additives, specifically EHN and di-tert butyl peroxide, are effective for reducing NO_x emissions from B20 blends in older engines [4,5,6]. McCormick and coworkers tested these additives at different blend levels and showed that a treat rate of approximately 5000 ppm produces a NO_x equivalent B20 when testing in a 1991 DDC Series 60 engine. This EHN treat rate typically produces an increase of ten cetane units. Engines meeting the 2.5 g/bhp-h NO_x + HC standard such as those tested here have much more highly retarded injection timing and are therefore much less sensitive to the effect of cetane number [7], thus it was of interest to examine the effect of cetane improvers on NO_x emissions for these engines.

Results of testing with EHN are shown in Figures 6 and 7 for the ISB and Series 60, respectively. The ISB was tested with B20+4000 ppm of EHN producing a cetane number increase of 8 units. The Series 60 was tested with B20+5000 ppm of EHN producing a cetane number increase of 10 units (see Appendix A-2). In both cases addition of EHN had no measurable (i.e. statistically significant) effect on NO_x, confirming the cetane insensitivity of NO_x emissions in engines meeting this NO_x emission standard, as has been noted by others [7]. Additionally, the cetane improver had no impact on emissions of other pollutants either.

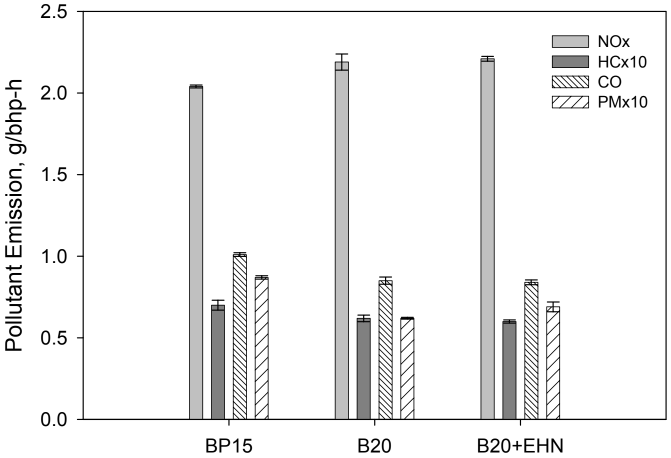

Figure 6. Results for testing of soy B20 containing 4000 ppm of EHN in the Cummins ISB engine.

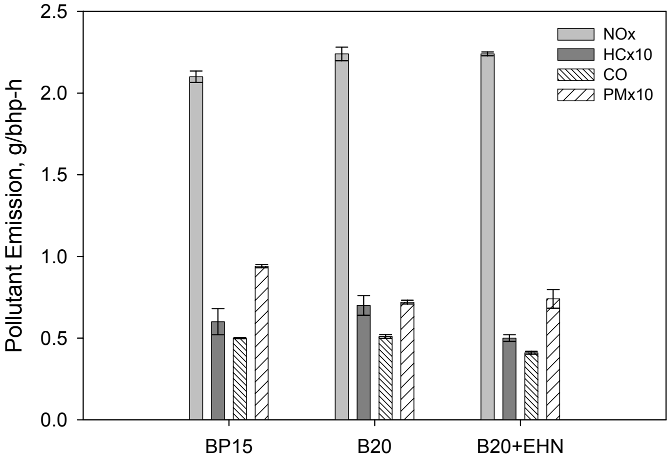

Figure 7. Results for testing of soy B20 containing 5000 ppm of EHN in the DDC Series 60 engine.

EFFECT OF INTAKE AIR HUMIDITY

Tests were conducted to demonstrate the influence that intake air humidity has on NO_x emissions for the Cummins ISB engine. Figures 8 and 9 show the relationship between humidity and NO_x for both baseline diesel and B100 Soy 2. The uncorrected data show a nearly linear relationship between intake air humidity and NO_x levels. The CFR NO_x humidity correction factor was applied to correct all data to an inlet humidity of 75 grains/lb. This yielded NO_x averages of 2.10 g/bhp-hr for baseline diesel and 2.75 g/bhp-hr for B100. This is consistent with results from previous testing; confirming the validity of applying the CFR correction factor to an EGR engine, fueled with either ultra-low sulfur diesel or biodiesel, and operated at altitude (1700 m).

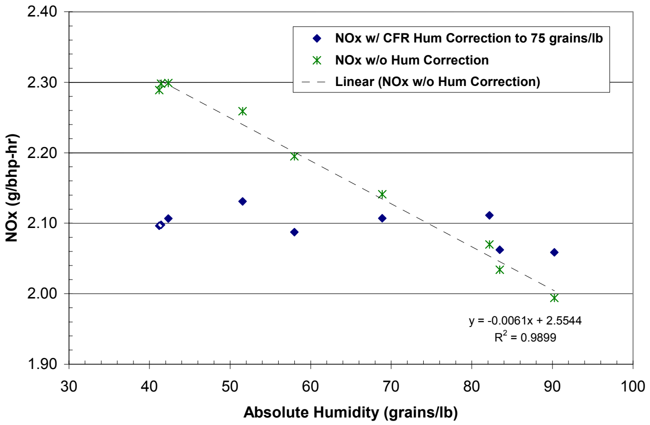

Figure 8. Effect of intake air humidity and application of the NO_x correction factor on emissions from baseline diesel fuel.

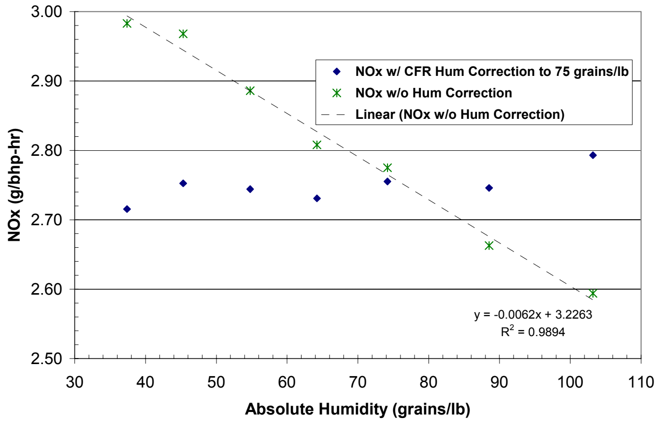

Figure 9. Effect of intake air humidity and application of the NO_x correction factor on emissions from B100 Soy 2.

DISCUSSION

Considerable effort has been devoted to determining the reason that biodiesel increases NO_x emissions. One theory holds that the cause of the NO_x increase is a shift in fuel injection timing caused by different mechanical properties of biodiesel [8, 9]. Because of the higher bulk modulus of compressibility (or speed of sound) for biodiesel there is a more rapid transfer of the fuel pump pressure wave to the injector needle, resulting in earlier needle lift or effectively a small advance in injection timing. Sybist and Boehman have recently examined this effect in more detail [10]. They found that soy B100 produces a 1° advance in injection timing but a nearly 4° advance in the start of combustion. This bulk modulus effect appears to be applicable, at least theoretically, to pump-line nozzle and unit injection systems, but would not appear to be relevant to high-pressure common rail systems where “rapid transfer of a pressure wave” does not occur.

It was observed in earlier studies on a 1991 engine equipped with electronic unit injectors that biodiesel produced from more saturated feedstocks (lower iodine number) such as animal fats produced lower NO_x emissions [1]. The bulk modulus of compressibility was also shown to be correlated with iodine value and to be lower for biodiesel produced from more highly saturated feedstocks [8], as shown in Figure 10. Thus, in the discussion that follows iodine number will be used as a surrogate for bulk modulus of compressibility.

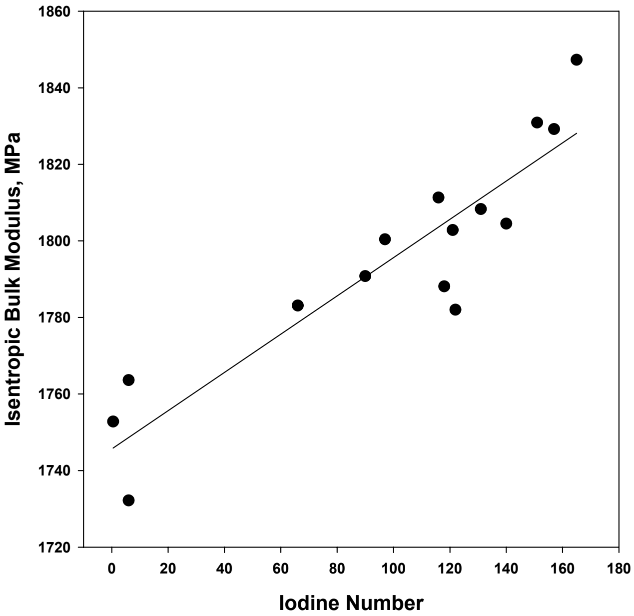

Figure 10. Relationship between isentropic bulk modulus of compressibility and iodine number for a range of biodiesel fuels (r^2=0.83), data taken from reference 8 for 40°C and 20 MPa.

Figure 11 shows results from this earlier study, along with results of B100 testing in the ISB engine, in terms of brake specific NO_x emissions as a function of fuel iodine value (a measure of the degree of saturation or number of double bonds per mass of sample). For the 1991 engine data the slope of the regression line is significant at greater than 99% confidence. For the ISB engine the slope is also statistically significant, although the effect is much smaller than observed in the older engine. This smaller effect of fuel saturation suggests that the bulk modulus effect discussed above is less important for common rail injection systems.

B20 blends were tested in engines with both common rail and electronic unit injection systems. While the NO_x increase is much smaller for B20 blends, making feedstock effects more difficult to observe, we have examined these data in terms of iodine number in Figure 12. A significant effect of biodiesel iodine value on NO_x was observed for B20 blends in the 1991 engine [11]. NO_x emissions from the newer engines are less than half the emissions from the 1991 engine, and while error bars (one standard deviation) are typically 2% to 3% of the mean, it is not possible to observe an effect for iodine value with a high degree of statistical significance for blends. Nevertheless, for the most unsaturated fuels (highest iodine value) NO_x emissions are significantly higher for the electronic unit injection engine (Series 60) than for the common rail engine. Thus it seems possible that a saturation (or bulk modulus) effect is occurring for the unit injection system but is too small to be accurately quantified for B20 blends. Testing with a series of B100 fuels might reveal a significant effect given the much higher levels of emissions.

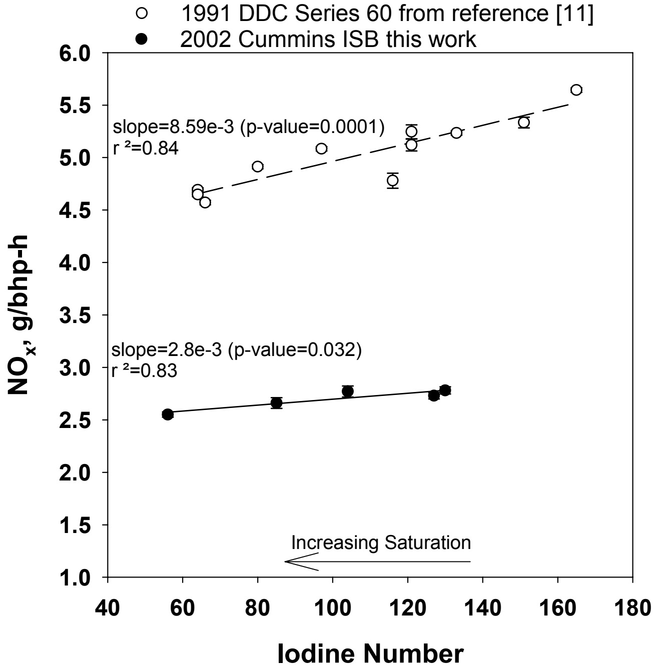

Figure 11. Effect of biodiesel degree of saturation on B100 NO_x emissions (iodine number via ASTM D1959).

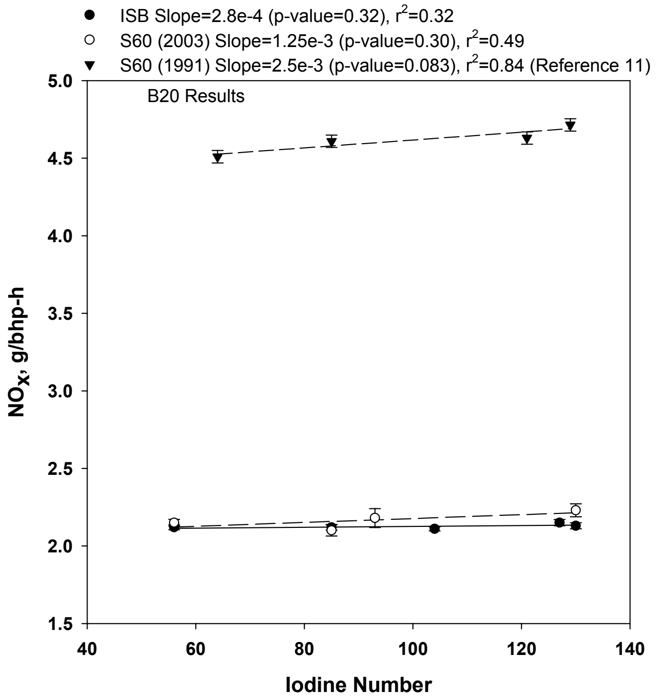

Figure 12. Effect of biodiesel degree of saturation on B20 NO_x emissions (iodine number via ASTM D1959).

Another important property difference between conventional diesel and biodiesel is energy content, with B100 typically having about 10% lower heat of combustion per volume. The modern engines tested in the present study have complex and highly sophisticated controls based on measurement of fuel flow rate, exhaust and EGR loop temperature, EGR flow rate, and other factors. The values of these measured parameters may change significantly when burning a lower energy content fuel such as B100, altering the way the engine operates in unanticipated ways.

CONCLUSIONS

1. In engines meeting the 2004 emission standards NO_x emissions increase by about 3% for B20. This is not statistically different from what is observed in testing of older engines.

2. PM emissions decrease by a significantly larger amount (25% versus 10%), on average, than was observed in older engines.

3. The biodiesel degree of saturation, and by implication bulk modulus of compressibility, had a small effect on NO_x for a common rail injection system (B100), in comparison to the much larger effect observed in older engines. For B20 blends no significant effect of biodiesel degree of saturation on NO_x was observed.

4. Because the results show a significant increase in NO_x for both electronic unit injection and high-pressure common rail systems, the higher fuel bulk modulus for biodiesel is probably not the exclusive cause of the NO_x increase.

5. The addition of a cetane increasing additive, 2-ethyl hexyl nitrate, had no effect on NO_x in either engine.

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ACRONYMS AND ABBREVIATIONS

ASTM – ASTM International, originally known as the American Society for Testing and Materials

BSFC – Brake specific fuel consumption

BP – BP p.l.c. and its subsidiaries and affiliates, formerly known as British Petroleum

Bxx – A volumetric blend of xx% biodiesel in conventional diesel

CFR – United States Code of Federal Regulations

CO – Carbon monoxide

DDC – Detroit Diesel Corporation

EGR – Exhaust gas recirculation

EHN – 2-ethylhexyl nitrate cetane improver additive

EPA – United States Environmental Protection Agency

EUI – electronic unit injector

HC – total hydrocarbon

HEPA – high efficiency particulate air

NO_x – oxides of nitrogen (NO and NO_2)

NREL – National Renewable Energy Laboratory

PM – particulate matter

S60 – DDC Series 60 engine

SwRI – Southwest Research Institute

YG – yellow grease

APPENDIX

Table A-1. Results of fuel property testing for baseline diesel and B100.

Property	Method	Units	Baseline Diesel	Soy Biodiesel Batch 1	Soy Biodiesel Batch 2	Canola Biodiesel	Yellow Grease Biodiesel	Beef Tallow Biodiesel
Cetane Number	D613		51	53	52	58	56	65
Kinematic Viscosity 40C	D445	mm2/s	2.5	4.12	4.07	3.53	4.61	4.71
Cloud Point	D2500	ºC	-12	-2	1	-2	8	14
Flash Point	D93	ºC	64	161	115	150	165	159
Total Sulfur	D5453	ppm	13	1	0	1	5	8
Ash Content	D482	wt%	0.000	--	--	--	--	--
Sulfated Ash	D874	wt%	--	0.001	0.001	0.000	0.000	0.000
Specific Gravity	D4052		0.8371	0.8823	0.8838	0.8816	0.8793	0.8754
Carbon Residue*	D524	wt%	0.04	<0.010	0.015	<0.010	<0.010	<0.010
Corrosion, Copper strip	D130		1A	1A	1A	1A	1A	1A
Water and Sediment	D2709	vol%	0	0	0	0	0	0
Acid Number	D664	mgKOH/g	--	0.34	0.62	0.16	0.52	0.48
Carbon	D5291	wt%	86.04	--	--	--	--	--
Hydrogen	D5291	wt%	13.48	--	--	--	--	--
Phosphorus	D4951	wt%	--	0.0007	0.0000	0.0000	0.0000	0.0004
Aromatics	D1319	%vol	29	--	--	--	--	--
Free Glycerin	D6584	wt%	--	0.001	0.002	0.010	0.005	0.006
Total Glycerin	D6584	wt%	--	0.022	0.166	0.176	0.102	0.058
Distillation T90	D86	ºC	322	351	351	352	351	351
Iodine Value	D1959		--	130	127	104	85	56

*Biodiesel carbon residue measured on total sample rather than 10% bottoms, as required by ASTM D6751.

Table A-2. Cetane Number of B20 Blends

Fuel	Cetane Number D613	Cetane Number D6890
B20 Soy 1	51	52
B10 Soy 2	--	--
B20 Soy 2	--	49
B50 Soy 2	--	53
B20 Yellow Grease	54	53
B20 Canola	--	55
B20 Beef Tallow	57	54
B20 Soy/Tallow	54	--
B20+4000 ppm EHN	--	60
B20+5000 ppm EHN	61	--

Table A-3. Hot-Start Transient Emission Test Results for the Cummins ISB Engine (1 g/bhp-h = 1.341 kW-h).

		Transient Emissions, g/hp-hr				BSFC	Work
Fuel		**HC**	**CO**	**NOx**	**PM**	**lb/hp-hr**	**hp-hr**
Baseline	Mean	0.06	0.90	2.18	0.081	0.402	19.91
5/13/2004	Std. Dev.	0.002	0.007	0.010	0.001	0.000	0.030
	% COV	4.0	0.8	0.5	1.0	0.1	0.2
YG B100	Mean	0.04	0.52	2.83	0.022	0.460	19.35
5/13/2004	Std. Dev.	0.002	0.006	0.051	0.001	0.001	0.005
	% COV	4.5	1.2	1.8	4.6	0.2	0.0
Baseline	Mean	0.06	0.95	2.15	0.078	0.406	19.92
5/19/2004	Std. Dev.	0.003	0.012	0.006	0.002	0.001	0.032
	% COV	4.7	1.3	0.3	2.3	0.2	0.2
Canola B100	Mean	0.04	0.55	2.78	0.021	0.459	19.35
5/19/2004	Std. Dev.	0.001	0.006	0.052	0.001	0.000	0.035
	% COV	2.9	1.1	1.9	3.4	0.1	0.2
Baseline	Mean	0.06	0.96	2.10	0.080	0.404	19.95
5/20/2004	Std. Dev.	0.001	0.021	0.040	0.002	0.000	0.012
	% COV	1.3	2.2	1.9	2.4	0.1	0.1
Tallow B100	Mean	0.04	0.52	2.61	0.019	0.461	19.29
5/20/2004	Std. Dev.	0.002	0.013	0.026	0.000	0.000	0.028
	% COV	4.8	2.6	1.0	1.7	0.0	0.1
Baseline	Mean	0.06	0.97	2.12	0.083	0.405	19.92
5/21/2004	Std. Dev.	0.001	0.004	0.021	0.001	0.001	0.029
	% COV	1.5	0.4	1.0	1.5	0.3	0.1
Soy 1 B100	Mean	0.04	0.55	2.80	0.020	0.462	19.31
5/21/2004	Std. Dev.	0.003	0.011	0.035	0.000	0.000	0.015
	% COV	7.2	1.9	1.3	0.5	0.1	0.1
Baseline	Mean	0.07	1.04	2.04	0.086	0.402	19.97
8/31/2004	Std. Dev.	0.002	0.005	0.016	0.001	0.001	0.019
	% COV	2.8	0.5	0.8	1.2	0.1	0.1
Soy 1 B20	Mean	0.06	0.86	2.16	0.061	0.414	19.87
8/31/2004	Std. Dev.	0.000	0.009	0.012	0.002	0.001	0.027
	% COV	0.6	1.0	0.6	3.0	0.2	0.1
Baseline	Mean	0.07	1.03	2.06	0.083	0.405	19.96
9/1/2004	Std. Dev.	-	-	-	-	-	-
	% COV	-	-	-	-	-	-
Soy 2 B20	Mean	0.07	0.91	2.14	0.061	0.411	19.91
9/1/2004	Std. Dev.	0.001	0.019	0.025	0.002	0.000	0.008
	% COV	1.5	2.1	1.2	2.8	0.1	0.0
Baseline	Mean	0.06	1.02	2.09	0.086	0.403	19.88
9/9/2004	Std. Dev.	0.002	0.011	0.017	0.001	0.000	0.107
	% COV	3.6	1.1	0.8	0.8	0.1	0.5
Soy 2 B20	Mean	0.06	0.91	2.20	0.064	0.413	19.84
9/9/2004	Std. Dev.	0.001	0.007	0.007	0.002	0.001	0.106
	% COV	1.2	0.7	0.3	3.5	0.2	0.5
Baseline	Mean	0.07	1.04	2.06	0.083	0.402	20.00
9/2/2004	Std. Dev.	0.002	0.017	0.033	0.002	0.001	0.005
	% COV	2.8	1.6	1.6	2.5	0.1	0.0
Canola B20	Mean	0.07	0.93	2.13	0.066	0.411	19.93
9/2/2004	Std. Dev.	0.001	0.013	0.013	0.001	0.000	0.024
	% COV	1.6	1.4	0.6	1.6	0.1	0.1

Table A-3. Continued.

		Transient Emissions, g/hp-hr				BSFC	Work
Fuel		HC	CO	NOx	PM	lb/hp-hr	hp-hr
Baseline	Mean	0.07	1.06	2.04	0.085	0.403	19.98
9/3/2004	Std. Dev.	0.001	0.017	0.011	0.000	0.001	0.021
	% COV	1.6	1.6	0.5	0.1	0.2	0.1
Tallow B20	Mean	0.06	0.93	2.13	0.067	0.413	19.88
9/3/2004	Std. Dev.	0.001	0.012	0.016	0.002	0.000	0.015
	% COV	0.8	1.2	0.7	2.7	0.0	0.1
Baseline	Mean	0.07	1.02	2.07	0.082	0.402	20.00
9/7/2004	Std. Dev.	0.002	0.005	0.007	0.001	0.000	0.014
	% COV	2.9	0.5	0.3	1.1	0.1	0.1
YG B20	Mean	0.06	0.87	2.12	0.064	0.411	19.95
9/7/2004	Std. Dev.	0.001	0.010	0.018	0.002	0.001	0.009
	% COV	1.4	1.2	0.9	2.6	0.1	0.0
Baseline	Mean	0.07	1.01	2.11	0.080	0.404	19.98
9/14/2004	Std. Dev.	0.004	0.049	0.024	0.003	0.002	0.025
	% COV	4.8	4.9	1.1	3.3	0.4	0.1
Soy 2 B10	Mean	0.07	0.98	2.17	0.071	0.408	19.92
9/14/2004	Std. Dev.	0.001	0.013	0.010	0.001	0.000	0.004
	% COV	1.8	1.3	0.5	2.0	0.0	0.0
Soy 2 B100	Mean	0.05	0.63	2.75	0.020	0.459	19.39
9/14/2004	Std. Dev.	0.000	0.012	0.021	0.001	0.000	0.042
	% COV	0.1	1.9	0.8	7.1	0.0	0.2
Baseline	Mean	0.070	0.96	2.13	0.079	0.404	19.99
9/15/2004	Std. Dev.	0.001	0.010	0.013	0.001	0.001	0.035
	% COV	1.8	1.0	0.61	1.8	0.31	0.18
Soy 2 B50	Mean	0.06	0.75	2.37	0.042	0.430	19.76
9/15/2004	Std. Dev.	0.003	0.014	0.027	0.001	0.001	0.022
	% COV	5.1	1.9	1.1	3.4	0.2	0.1
Soy 2 B20	Mean	0.07	0.85	2.25	0.062	0.415	19.91
9/15/2004	Std. Dev.	0.002	0.022	0.050	0.000	0.001	0.023
	% COV	3.1	2.5	2.2	0.1	0.2	0.1
Baseline	Mean	0.07	1.01	2.04	0.087	0.406	20.02
9/31/2004	Std. Dev.	0.003	0.011	0.009	0.001	0.001	0.025
	% COV	4.3	1.1	0.4	1.2	0.2	0.1
Soy 2 B20+EHN[1]	Mean	0.06	0.84	2.21	0.069	0.417	19.93
9/31/2004	Std. Dev.	0.001	0.015	0.015	0.003	0.001	0.015
	% COV	1.7	1.8	0.7	4.4	0.2	0.08

[1] Soy B20 plus 4000 ppm of 2-ethyl hexyl nitrate

Table A-4. Hot-Start Transient Emission Test Results for the DDC Series 60 Engine (1 g/bhp-h = 1.341 kW-h).

		Transient Emissions, g/hp-hr				BSFC	Work
Fuel		**HC**	**CO**	**NOx**	**PM**	**lb/hp-hr**	**hp-hr**
Baseline	Mean	0.07	0.53	2.16	0.097	0.404	33.23
8/25/2004	Std. Dev.	0.001	0.010	0.039	0.0011	0.0062	0.056
	% COV	1.5	1.9	1.8	1.1	1.5	0.2
Soy B20	Mean	0.07	0.51	2.24	0.072	0.416	33.12
8/25/2004	Std. Dev.	0.006	0.011	0.042	0.0012	0.0059	0.040
	% COV	8.3	2.1	1.9	1.7	1.4	0.1
Baseline	Mean	0.06	0.49	2.13	0.095	0.402	33.11
8/26/2004	Std. Dev.	0.006	0.020	0.091	0.0013	0.0052	0.036
	% COV	10.5	4.0	4.3	1.3	1.3	0.1
YG B20	Mean	0.06	0.49	2.10	0.073	0.418	33.14
8/26/2004	Std. Dev.	0.011	0.011	0.036	0.0012	0.0040	0.178
	% COV	19.2	2.2	1.7	1.7	1.0	0.5
Baseline	Mean	0.06	0.53	2.12	0.096	0.407	33.25
8/27/2004	Std. Dev.	0.001	0.020	0.006	0.0024	0.0021	0.046
	% COV	1.0	3.8	0.3	2.5	0.5	0.1
Tallow B20	Mean	0.06	0.50	2.15	0.073	0.421	33.05
8/27/2004	Std. Dev.	0.003	0.010	0.022	0.0003	0.0035	0.010
	% COV	4.9	2.1	1.0	0.5	0.8	0.0
Baseline	Mean	0.07	0.50	2.11	0.093	0.409	33.12
8/29/2004	Std. Dev.	0.010	0.001	0.020	0.0007	0.0009	0.044
	% COV	14.4	0.2	0.9	0.8	0.2	0.1
Soy B20+EHN[1]	Mean	0.05	0.41	2.24	0.074	0.420	33.03
8/30/2004	Std. Dev.	0.002	0.009	0.012	0.0008	0.0057	0.035
	% COV	4.7	2.2	0.5	1.1	1.4	0.1
Baseline	Mean	0.05	0.50	2.09	0.095	0.412	33.19
8/31/2004	Std. Dev.	0.006	0.008	0.049	0.0014	0.0017	0.007
	% COV	11.0	1.7	2.3	1.5	0.4	0.0
Baseline	Mean	0.06	0.48	2.07	0.093	0.406	33.17
9/2/2004	Std. Dev.	0.007	0.012	0.039	0.0016	0.0063	0.040
	% COV	12.4	2.4	1.9	1.7	1.5	0.1
Soy+Tallow B20[2]	Mean	0.05	0.45	2.18	0.070	0.417	33.05
9/2/2004	Std. Dev.	0.005	0.008	0.061	0.0001	0.0034	0.026
	% COV	12.0	1.8	2.8	0.2	0.8	0.1
Overall Baseline Mean		0.06	0.50	2.12	0.095	0.406	33.17
Overall Baseline Std. Dev.		0.010	0.024	0.048	0.0020	0.0047	0.067
Overall Baseline % COV		15.8	4.8	2.2	2.2	1.2	0.2

[1] Soy B20 plus 5000 ppm of 2-ethyl hexyl nitrate

[2] B20 prepared from 80% baseline, 10% soy biodiesel and 10% tallow biodiesel