NTRD Program Disclaimers

1. Disclaimer of Endorsement:

The posting herein of progress reports and final reports provided to TCEQ by its NTRD Grant Agreement recipients does not necessarily constitute or imply an endorsement, recommendation, or favoring by TCEQ or the State of Texas. The views and opinions expressed in said reports do not necessarily state or reflect those of TCEQ or the State of Texas, and shall not be used for advertising or product endorsement purposes.

2. Disclaimer of Liability:

The posting herein of progress reports and final reports provided to TCEQ by its NTRD Grant Agreement recipients does not constitute by TCEQ or the State of Texas the making of any warranty, express or implied, including the warranties of merchantability and fitness for a particular purpose, and such entities do not assume any legal liability or responsibility for the accuracy, completeness, or usefulness of any information,apparatus, product, or process disclosed, or represent that its use would not infringe privately owned rights.

New Technology Research & Development Program
Grant Contract 582-5-70807-M023

Task 2 & 3 Deliverable Report
Final Report

The preparation of this report is based on work funded in part
by the State of Texas through a Grant from the
Texas Commission on Environmental Quality.

West Virginia University
National Research Center for Alternative Fuels, Engines, and Emissions

Gregory J. Thompson, Ph.D.
West Virginia University
Department of Mechanical and Aerospace Engineering
P.O. Box 6106
Morgantown WV 26506-6106
Phone: (304) 293-3111 ext. 2481; Fax: (304) 293-6689

North Texas Bio-energy, LLC Emissions Tests

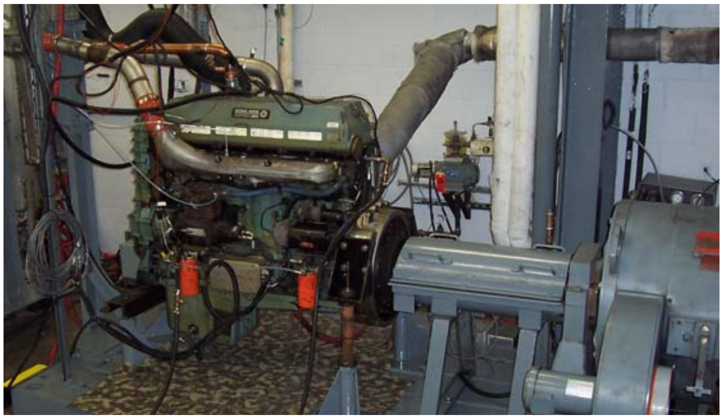
TCEQ Proof of Concept

Presented to:

Lance Lankford
President/CEO
North Texas Bio-energy, LLC
211 Cowboys Parkway, Suite 201
Irving, Texas 75063
phone: 214.561.6749
fax: 214.561.6786
llankford@nabiofuels.net

Prepared by:

Gregory Thompson
West Virginia University



July 5, 2006

Introduction

The West Virginia University (WVU) Engine and Emissions Research Laboratory (EERL) evaluated the emissions from a 1992 Detroit Diesel Corporation Series 60 diesel engine for an EPA diesel fuel (termed Base D2a) and the same EPA diesel (Base D2a) fuel blended with 6% and 12%, by volume, Cetane Enhancer (termed CE), and these fuels were termed “D2a 6%” and “D2a 12%,” respectively. In addition, the Cetane Enhancer was run neat against the Base D2a reference map. The emissions from a second EPA diesel fuel (termed Base D2b) were evaluated against the same EPA diesel (Base D2b) blended with 20%, by volume, biodiesel (D2b B20) and further blended with 6% and 12%, based on the D2b B20 blend by volume, Cetane Enhancer, and these fuels were termed “B20 6%” and “B20 12%,” respectively. The objective of this study was to examine the emissions benefits of the blended Cetane Enhancer fuels relative to the base diesel fuels. The regulated brake-specific mass emissions of oxides of nitrogen (NOx), total particulate matter (TPM), carbon monoxide (CO), and total hydrocarbons (THC), and the unregulated emissions of carbon dioxide (CO_2) and non-methane hydrocarbons (NMHC) along with fuel consumption (FC) were measured with the engine exercised over the Federal Test Procedure (FTP) cycle. The evaluation of the fuels followed the procedures outlined in the Code of Federal Regulations (CFR) Title 40 Part 86 [1]. For each test run, a cold start and three hot start tests were used throughout. In order to perform at least two sets of fuel evaluations per day, a forced cool-down procedure was implemented for the engine.

The preparation of this report is based on work funded in part by the State of Texas through a Grant from the Texas Commission on Environmental Quality (TCEQ).

Laboratory Description

Evaluation of the emissions was conducted using a 1992 Detroit Diesel Corporation Series 60 engine connected to a 550 hp GE dynamometer located in the EERL at WVU. The engine model number was 6067GU60 and engine serial number was 06R0105610.

Engine exhaust was ducted to a full-scale dilution tunnel (18 inches in diameter and 20 feet long) based on the critical flow venturi-constant volume sampler (CFV-CVS) concept. Three feet from the tunnel entrance was a 10-inch diameter orifice. This ensured that the dilute exhaust was thoroughly mixed by the time it reached the sampling zone, ten diameters downstream of the orifice. The exhaust was mixed with air and the quantity of diluted exhaust was measured precisely using critical flow venturis. These venturis were placed upstream of a blower that pulled the diluted air at constant mass flowrate once the venturis were under sonic or choked flow conditions at a nominal 2400 scfm. Temperature in the venturi was measured with an exposed fast-respond thermocouple and pressure was measured by an absolute pressure transducer. Heated sampling probes and lines conducted diluted exhaust to a number of different gas analysis instruments. The engine test cell was equipped with a pre-conditioning system for intake air. Microprocessor controlled heated probes and sampling lines were used to draw gaseous samples into the gas analysis bench.

Continuous sampling and analysis of the exhaust stream was done by non-dispersive infrared (NDIR) analyzers for CO and CO_2; a wet chemiluminescent analyzer for NOx; and a heated flame ionization detector (HFID) for THC. A Varian 3600 gas chromatograph was used to measure the NMHC concentrations from gas sample bags taken during the testing [2]. The gas analysis bench was equipped with exhaust sample conditioning and analysis systems following CFR 40 Part 86 requirements. Data from the exhaust analyzers, sampling trains, double dilution tunnel, and the engine were acquired and archived at a rate of 5 Hz.

A double dilution system was used to measure TPM. A proportional sample was drawn from the main dilution tunnel into a stainless steel 4-inch diameter by 30-inch long secondary dilution tunnel. The dilute TPM sample was pulled through a stainless steel filter holder that contained two Pallflex 70mm diameter Model T60A20 fluorocarbon-coated glass microfiber filters in series. Two filters, a primary and a secondary in series, were used in the filter holder to maximize filter trapping efficiency. The diluted sample stream was maintained at temperatures below 125 ºF and measured at the inlet of the TPM filter holder. The sample filters were conditioned in an environmentally controlled room to a nominal 22 ºC dry bulb, 9.5 ºC dew point, and 45% relative humidity, in compliance with requirements as specified in CFR 40 Part 86, and weighed before and after sample collection using a Mettler Toledo UMX2 microbalance. All dilution air was HEPA filtered to minimize the background particulate contribution entering the tunnel. Two HEPA filters, each at a 2400 cfm capacity, were placed in parallel to provide up to 4800 cfm dilution air capacity to the primary tunnel.

Calibration procedures and intervals were followed according to CFR 40 Part 86 requirements. A laboratory checkout following the procedures listed in CFR 40 Part 86 was performed prior to the collection of the data.

Additionally, the engine was instrumented for speed, torque, throttle position, manifold air pressure, air intake restriction, total exhaust backpressure, manifold intake temperature, coolant temperature, oil temperature, and exhaust temperature according to CFR 40 Part 86 requirements.

Test Fuels and Oil

North Texas Bio-energy, LLC supplied the base diesel fuel in two 55 gallon drums and the Cetane Enhancer in four 30 gallon drums. The neat biodiesel was purchased by WVU from a local supplier in a 55 gallon drum. It was discovered during the testing that the base diesel fuel in the two drums were not a homogeneous supply. In order to proceed with the program, it was decided by North Texas Bio-energy, LLC to evaluate the Cetane Enhancer blends against the first drum of diesel, Base D2a, and evaluate the B20 with Cetane Enhancer blends against the second drum of diesel, Base D2b. The B20 was made from the Base D2b fuel. It is noted that WVU personnel did measure the specific, or API, gravity of each fuel with hydrometers in order to obtain the gravity information to convert the volume-based ratios to a mass-based ratios and for reporting the fuel consumed measurements.

For the emissions testing phase of the fuels, the base diesel fuel was, when needed, transferred from the original 55 gallon drum and into a 16 gallon stainless steel drum and transferred to the engine dynamometer test cell. The blended fuels were, when needed, made by transferring from the original drums and into an empty 30 gallon drum that was purged with the base diesel fuel. This drum was used to measure the components on a scale to obtain the desired blend ratios. It is noted that WVU personnel performed this blending and that no representatives of North Texas Bio-energy, LLC, or any other organization, were present for the mixing or the testing. The blended diesel fuel was, when needed, were transferred from the 30 gallon drum and into a 16 gallon stainless steel drum and transferred to the engine dynamometer test cell.

The engine's fuel system was directly connected to the relevant 16 gallon drum for the fuel under test. The engine's fuel filters were changed prior to the start of this study. Multiple fuel samples of each fuel were collected from the 16, 30, or 55 gallon drums; these samples were retained at WVU for future analysis, if warranted. The engine oil and oil filters were also changed prior to the commencement of this study. Typical 15W-40 diesel specification engine oil was used as the oil for the oil change that occurred prior to the commencement of this study. WVU personnel did collect and retain an oil sample but did not have the oil analyzed.

Test Procedure

Evaluation of the emissions was conducted using the 1992 Detroit Diesel Corporation Series 60 engine described above and was inspected prior to use in this study. The inspection included visual examination and measurement of engine parameters and review of data from the engine control unit. A Nexiq Technologies Prolink Plus monitor was used to display the engine control unit data and to display any potential problems (error codes) during this testing. In addition, the continuous broadcast of the public messages from the SAE J1708/1587 data link were captured using B&B Electronics VIA HPV100A1 protocol adaptor. There were no error codes generated during this entire testing campaign.

The engine operating parameters were set to within the specifications listed in CFR 40 Part 86 or listed by the engine manufacturer for engine dynamometer testing. An ascending speed engine map (lug curve) was then generated using the fuel being tested. It is noted that the last Base D2a fuel cycle/engine map run on Day 0 of testing was used for all subsequent tests for the Base D2a Cetane Enhancer blends and that the last Base D2b fuel cycle/engine map run on Day 2 of testing was used for all subsequent tests for the Base D2b B20 Cetane Enhancer blends.

The engine description is listed in Table 1 and the engine map used for the engine load setpoint is shown in Figure 1. The average and one standard deviation of the measured torque for each fuel for each day are shown in Table 2 for three consecutive lug curves. As seen in Table 1 and Figure 1, the torque (and power) for the Base D2a fuel was higher (~60-70 ft-lb) than the torque curve for the Base D2b fuel. Additionally, the neat Cetane Enhancer lug curve was lower (~40-50 ft-lb) than the Base D2a fuel but higher (~20 ft-lb) than the Base D2b fuel lug curve. The addition of the 6 and 12% Cetane Enhancer in the Base D2a fuel and the addition of the B20 with 6 or 12% Cetane Enhancer did not impact the lug curve significantly from their respective base diesel fuels.

Table 1 Test engine specifications.

Engine Manufacturer	Detroit Diesel Corp.
Engine Model	Series 60
Model Year	1992
Displacement (liters)	12.7
Power Rating (hp)	360 @ 1810 rpm
Configuration	Inline 6
Bore (in.) x Stroke (in.)	5.12 x 6.30
Induction	Turbocharger with Aftercooler
Fuel Type	Diesel
Engine Strokes per Cycle	Four
Injection	Direct, Electronic

Table 2 Lug curve torque for each test day and fuel. All values are the average of three consecutive lug curves (ascending 8 rpm/s maps). Values in parentheses are one standard deviation of the three tests at that speed.

	Base D2a	D2a w/ 6% CE	D2a w/ 12% CE	Cetane Enhancer (CE)	Base D2b	D2b B20 w/ 6% CE	D2b B20 w/ 12% CE
Speed	Day 0	Day 1	Day 1	Day 1	Day 2	Day 2	Day 2
rpm	ft-lb	ft-lb	ft-lb	ft-lb	ft-lb	ft-lb	ft-lb
600	660 (2)	654 (3)	650 (0)	627 (3)	619 (3)	621 (2)	635 (2)
700	709 (2)	701 (6)	693 (5)	658 (2)	651 (2)	653 (8)	661 (2)
800	688 (2)	677 (4)	673 (1)	643 (2)	640 (1)	653 (0)	655 (2)
900	864 (2)	845 (4)	843 (2)	799 (2)	781 (2)	792 (4)	817 (2)
1000	1067 (3)	1041 (5)	1035 (4)	968 (3)	936 (7)	953 (12)	985 (2)
1100	1229 (2)	1231 (3)	1234 (1)	1174 (2)	1137 (5)	1148 (7)	1170 (4)
1200	1366 (1)	1360 (2)	1358 (3)	1305 (1)	1288 (4)	1299 (2)	1304 (3)
1300	1343 (2)	1337 (1)	1336 (2)	1278 (1)	1251 (1)	1259 (3)	1269 (1)
1400	1303 (3)	1297 (1)	1293 (0)	1240 (1)	1217 (2)	1223 (3)	1228 (1)
1500	1292 (3)	1285 (7)	1284 (1)	1228 (2)	1205 (3)	1214 (3)	1212 (2)
1600	1237 (2)	1227 (5)	1226 (2)	1172 (3)	1150 (1)	1151 (2)	1156 (1)
1700	1161 (0)	1165 (2)	1154 (2)	1097 (1)	1075 (1)	1081 (1)	1094 (1)
1800	1100 (2)	1098 (2)	1094 (0)	1040 (1)	1010 (2)	1021 (0)	1019 (2)
1900	435 (1)	435 (0)	437 (0)	383 (1)	381 (1)	392 (0)	388 (1)

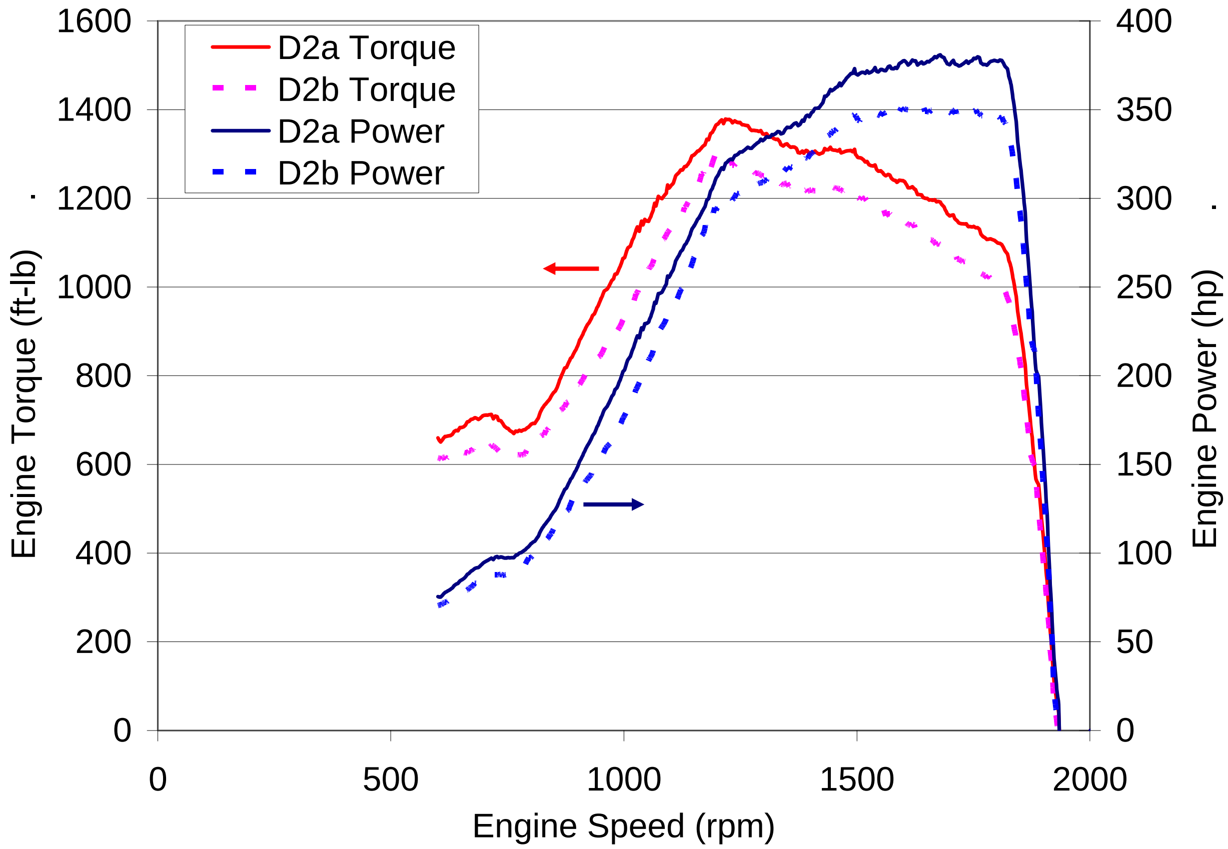


Figure 1 1992 DDC S60 engine lug curve. Note that the last base diesel fuel (Base D2a) engine map during day 0 of testing and the last base diesel fuel (Base D2b) engine map during day 2 of testing were used to generate these curves and that these curves were used for all subsequent FTP evaluations for that base diesel fuel.

Prior to the start of the first FTP for each fuel evaluation, the analyzers were zeroed and spanned. At the end of each FTP test, the analyzers were checked for zero and span readings. The post test zero and span readings were recorded in the test data sheet prior to adjusting, if required, the analyzers' zero and or span value. It is noted that there were no significant (greater than two percent) drift problems encountered in the analyzers or sampling system during this study.

At the completion of each test day a 20-minute tunnel TPM background was collected to correct the TPM test data. It is noted that the HEPA filters significantly reduced the ambient TPM contribution. However, HEPA filters are only 99.97% efficient at 0.3 μm and their efficiencies at other particle sizes are dependant upon the filter loading history. Also, tunnel shedding and hydrocarbon outgassing does still occur and is most likely the largest contributor to the tunnel background.

When the fuel was switched from one fuel to another, the laboratory's fuel system was purged. The laboratory incorporated a Max Machinery 710 fuel meter system. This system incorporated a primary loop to circulate fuel from the 16 gallon supply drum and a secondary loop to circulate fuel to the engine. The fuel transferred from the primary to secondary side was the measured fuel to the engine. The primary loop was purged by pulling approximately two gallons of fuel that was being tested at the time from the supply drum and returning it to a waste drum. After the primary side was purged, the return line was placed into the fuel to be tested that was located in the 16 gallon supply drum. The secondary loop was purged in a similar manner in that the return line to the fuel meter was diverted and the fuel emptied into a waste container. However, for the secondary loop, a bypass system around the engine's lift pump was incorporated from the outlet of the primary fuel filter to the inlet of the secondary fuel filter. During testing, this bypass was disengaged from the fuel system with a quarter-turn valve located at the secondary filter inlet. After approximately two gallons of fuel was extracted from the secondary loop, the return line to the fuel meter was connected. The engine was then started and run to insure that the fuel system was functioning properly and any remaining fuel from the previous run(s) was sufficiently purged.

The order of the evaluation and a description of the testing as performed are given in Table 3. It is noted that additional hot starts were performed for the D2a, D2a 6%, and D2b 12% due to data quality issues.

Table 3 Test history.

Day	Fuel	Description
0	Base D2a	Set intake and exhaust, mapped engine, and ran practice test.
1	Base D2a	Cold and four hot starts.
	D2a w/ 6% Cetane Enhancer	Cold and four hot starts.
	D2a w/ 12% Cetane Enhancer	Cold and three hot starts.
2	Neat Cetane Enhancer	Cold and three hot starts.
	Base D2b	Cold and three hot starts.
	D2b B20 w/ 6% Cetane Enhancer	Cold and three hot starts.
3	D2b B20 w/ 12% Cetane Enhancer	Cold and four hot starts.

In order to perform more than one set of one cold and three hot start tests in a day, a forced cool down procedure was implemented. The requirements for performing a cold start FTP after an engine has been forced to cool are given in CFR 40 Part 86. The procedure to cool the engine down between fuel evaluations consisted of cooling the engine coolant and engine oil using external heat exchangers. After the fuel system was flushed, the engine was started and operated under full-load conditions to bring the engine to normal operating temperature. Once the engine's coolant and oil reached operating conditions, the engine was mapped four times, with the last three maps reported in Table 2. Once the last map was performed, the engine was motored and the temperature of the intake and exhaust system was lowered with the engine then being used as a pump to force ambient air through the intake and exhaust. The engine coolant and oil temperatures were reduced during the motoring. To reduce the oil and coolant to the required temperature, two pumps were used to circulate the engine coolant and engine oil through external heat exchangers. Valves were used to open these circuits during the cool-down procedure. The coolant circuit pumped the coolant through the engine, bypassing the thermostat. The existing coolant heat exchanger was used to remove the heat from the engine's coolant. The oil circuit removed the oil from the crankcase, pumped it through an external heat exchanger, and sent it back through the engine. It required about two hours to cool the engine to the required temperature each time. After the cool down procedure was completed, the valves were shut closed for the next set of tests.

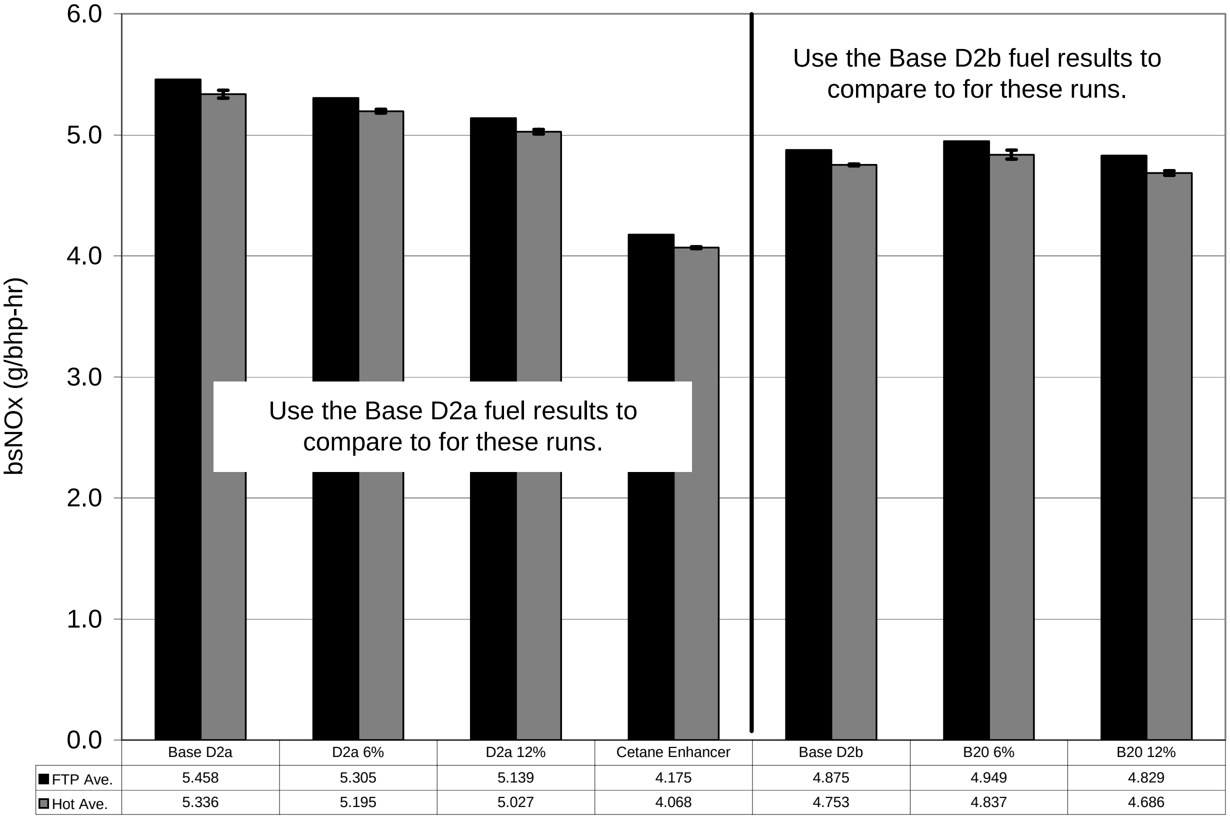
Results

The results for the evaluation are summarized in the graphs below and in tabular format in Appendix A. The tables in the Appendix contain the test number, test date, test time, start type, comments, integrated work, fuel consumption, brake specific fuel consumption (BSFC), THC, NMHC, CO, CO_2, NOx, TPM, hot-start average, hot start standard deviation, and the coefficient of variation (COV) for each set of tests. Table 4 to Table 10 contain the summary data for the test runs.

The emissions data will be compared based on the base diesel fuel used in the blending. That is, the emissions from the Base D2a fuel will be compared against the Base D2a with 6% Cetane Enhancer fuel, Base D2a with 12% Cetane Enhancer fuel, and the neat Cetane Enhancer fuel since these runs all used the Base D2a set point file. Likewise, the emissions from the Base D2b fuel will be compared against the Base D2a B20 with 6% Cetane Enhancer fuel and the Base D2a B20 with 12% Cetane Enhancer fuel since these runs all used the Base D2b set point file. In addition, the comparison of the data will only examine the hot-start tests since there is a larger variation with cold start data.

The primary constituent of interest is NOx and is illustrated in Figure 2 as the FTP (1/7 cold+6/7 hot start) and average of the hot start test for each fuel. The bars on the hot start data represent one standard deviation of the three (or four) hot start data for each test. As illustrated in this figure, as the concentration of the Cetane Enhancer increases, the hot start emissions of NOx decreased by 2.6% for the 6% Cetane Enhancer blend ratio and decreased by 5.8% for the 12% Cetane Enhancer blend ratio. This is an approximate reduction rate of one-half percent NOx reduction per one percent of Cetane Enhancer addition for the Base D2a fuel at the 6% and 12% blend ratios. The neat Cetane Enhancer showed a 23.8% reduction in the NOx compared to the Base D2a fuel. Based on the finite NOx reduction with the Cetane Enhancer, there is a limit to which the NOx can be reduced with a diesel fuel blended with Cetane Enhancer. For the Base D2b fuel comparison, the Base D2b B20 with 6% Cetane Enhancer showed a 1.8% increase in the NOx value over the Base D2b fuel. An increase of 3-5% is typical for this engine with a soy-derived B20 blend compared to the base diesel fuel. Therefore, the 1.8% increase with the Base D2b B20 with 6% Cetane Enhancer is consistent with the NOx gain (3-5%) from the soy-derived biodiesel and the reduction (~2.6% based on the Base D2a 6% Cetane Enhancer data) from the Cetane

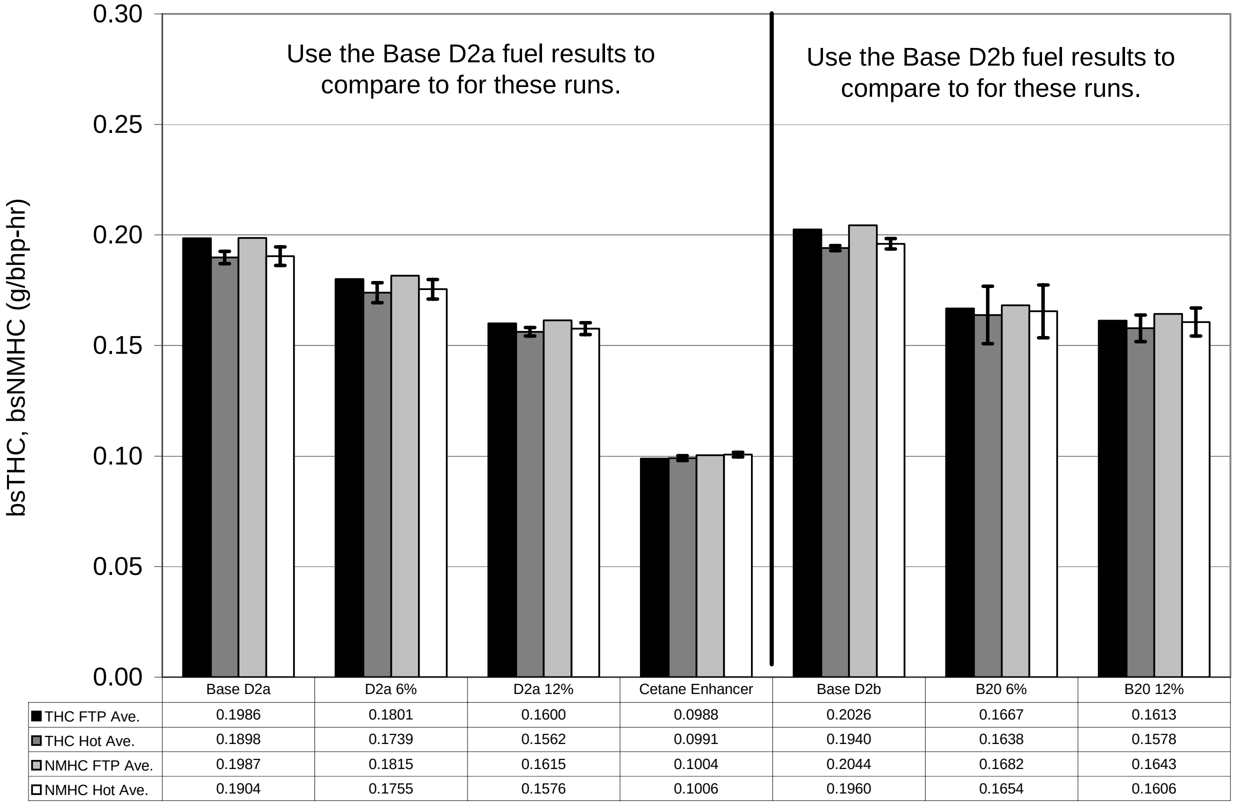
Enhancer. The Base D2b B20 with 12% Cetane Enhancer showed a 1.4% decrease in the NOx value over the Base D2b fuel. Based on these results, it is estimated that a 9% Cetane Enhancer blend with soy-based biodiesel will result in an equivalent NOx emissions value as the base diesel fuel used to make the B20 blend.



	Base D2a	D2a 6%	D2a 12%	Cetane Enhancer	Base D2b	B20 6%	B20 12%
■ FTP Ave.	5.458	5.305	5.139	4.175	4.875	4.949	4.829
▨ Hot Ave.	5.336	5.195	5.027	4.068	4.753	4.837	4.686

Figure 2 FTP and hot start average NOx values. Bars represent one standard deviation of the hot start data for that set of tests.

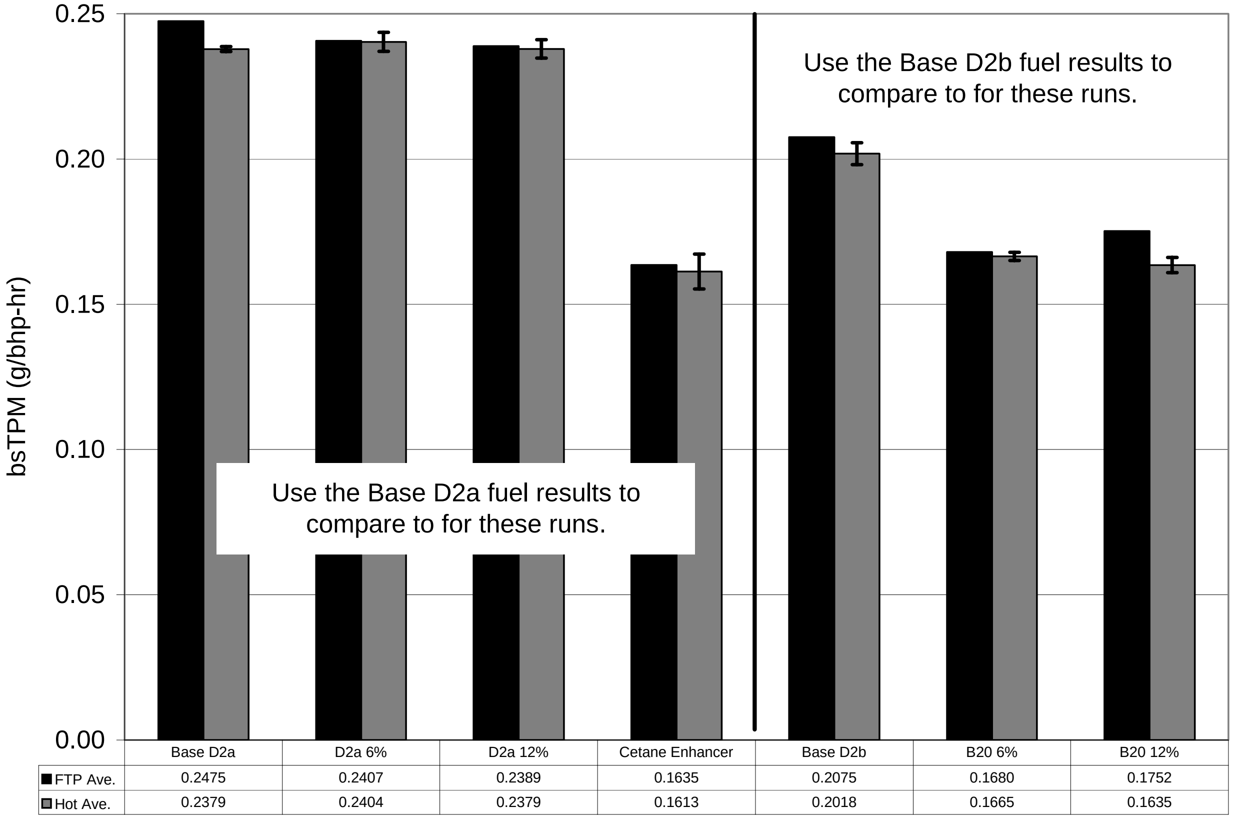
The results for THC and NMHC are shown in Figure 3 as the FTP (1/7 cold+6/7 hot start) and average of the hot start test for each fuel. The bars on the hot start data represent one standard deviation of the three (or four) hot start data for each test. It is noted that the THC data was recorded from the continuous HFID analyzer while the NMHC data was inferred from the bag samples using the gas chromatograph and using the SAE J1151 procedure. As illustrated in this figure, as the concentration of the Cetane Enhancer increases, the hot start emissions of THC decreased by 8.4% for the 6% Cetane Enhancer blend ratio and decreased by 17.7% for the 12% Cetane Enhancer blend ratio. This is an approximate reduction rate of 1.4 percent THC reduction per one percent of Cetane Enhancer addition for the Base D2a fuel for the 6% and 12% blend ratios. The neat Cetane Enhancer showed a 47.8% reduction in the THC compared to the Base D2a fuel. Based on the finite THC reduction with the Cetane Enhancer, there is a limit to which the THC can be reduced with a diesel fuel blended with Cetane Enhancer. For the Base D2b fuel comparison, the Base D2b B20 with 6% Cetane Enhancer showed a 15.6% reduction in the THC value over the Base D2b fuel. A decrease is typical for this engine with a B20 blend compared to the base diesel fuel. Therefore, the 15.6% reduction with the Base D2b B20 with 6% Cetane Enhancer is consistent with the THC reduction from the biodiesel. The Base D2b B20 with 12% Cetane Enhancer showed an 18.7% decrease in the THC value over the Base D2b fuel. The THC and NMHC data generally match to within the standard deviation for each set of tests. The THC and NMHC values should be equivalent for a compression ignition engine using a conventional No. 2 diesel fuel, bio-derived fuel, or their blends.



	Base D2a	D2a 6%	D2a 12%	Cetane Enhancer	Base D2b	B20 6%	B20 12%
■ THC FTP Ave.	0.1986	0.1801	0.1600	0.0988	0.2026	0.1667	0.1613
▩ THC Hot Ave.	0.1898	0.1739	0.1562	0.0991	0.1940	0.1638	0.1578
▨ NMHC FTP Ave.	0.1987	0.1815	0.1615	0.1004	0.2044	0.1682	0.1643
□ NMHC Hot Ave.	0.1904	0.1755	0.1576	0.1006	0.1960	0.1654	0.1606

Figure 3 FTP and hot start average THC and NMHC values. Bars represent one standard deviation of the hot start data for that set of tests.

The results for TPM are shown in Figure 4 as the FTP (1/7 cold+6/7 hot start) and average of the hot start test for each fuel. The bars on the hot start data represent one standard deviation of the three (or four) hot start data for each test. As illustrated in this figure, as the concentration of the Cetane Enhancer increases, the hot start emissions of TPM do not show any significant change for the 6% or 12 % Cetane Enhancer blend ratio for the Base D2a blend. The neat Cetane Enhancer did show a 32.2% reduction in the TPM compared to the Base D2a fuel. There appears to be a Cetane Enhancer blend ratio above 12% that may result in a TPM reduction. For the Base D2b fuel comparison, the Base D2b B20 with 6% Cetane Enhancer showed a 17.5% reduction in the TPM value over the Base D2b fuel. A decrease is typical for this engine with a B20 blend compared to the base diesel fuel. Therefore, the 17.5% reduction with the Base D2b B20 with 6% Cetane Enhancer is consistent with the TPM reduction from the biodiesel. The Base D2b B20 with 12% Cetane Enhancer showed a 19.0% decrease in the TPM value over the Base D2b fuel; this reduction is consistent with the Base D2a fuel results where the TPM reduction at the 6% and 12% blend ratios are due to the biodiesel.



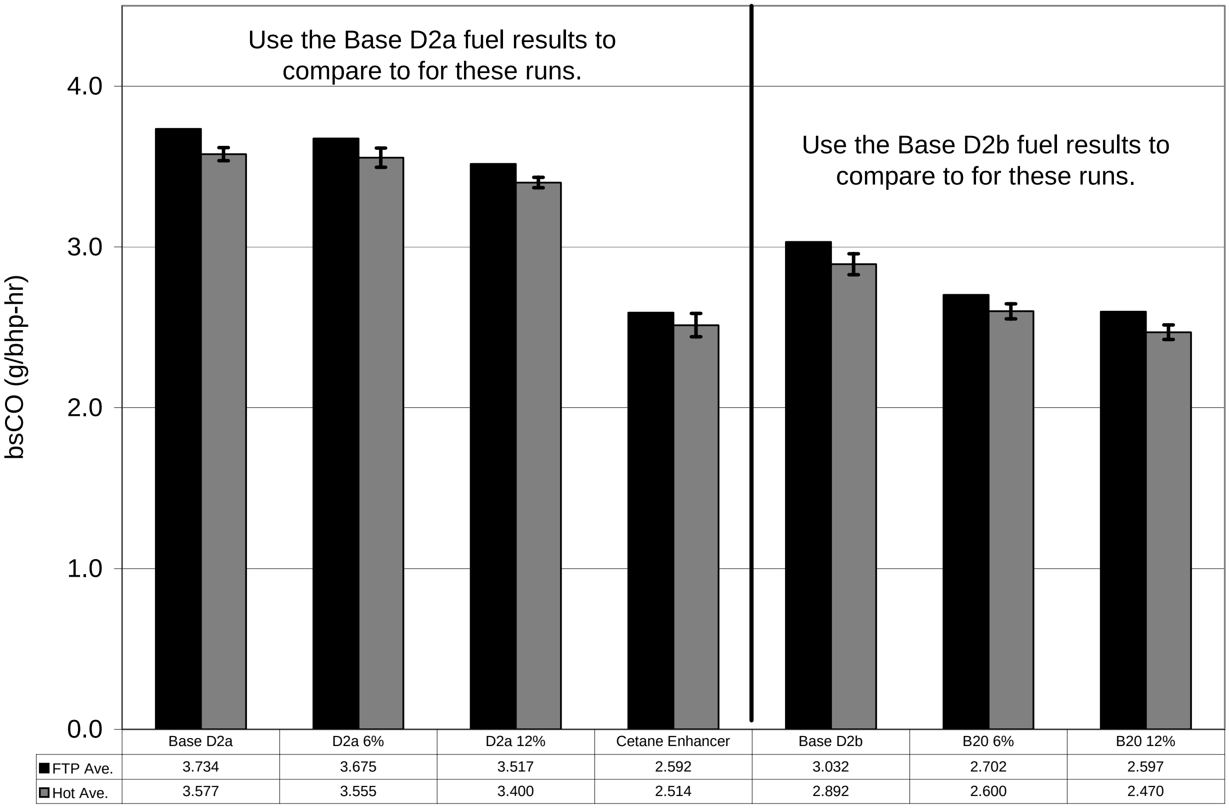
Use the Base D2b fuel results to compare to for these runs.

Use the Base D2a fuel results to compare to for these runs.

	Base D2a	D2a 6%	D2a 12%	Cetane Enhancer	Base D2b	B20 6%	B20 12%
■ FTP Ave.	0.2475	0.2407	0.2389	0.1635	0.2075	0.1680	0.1752
▨ Hot Ave.	0.2379	0.2404	0.2379	0.1613	0.2018	0.1665	0.1635

Figure 4 FTP and hot start average TPM values. Bars represent one standard deviation of the hot start data for that set of tests.

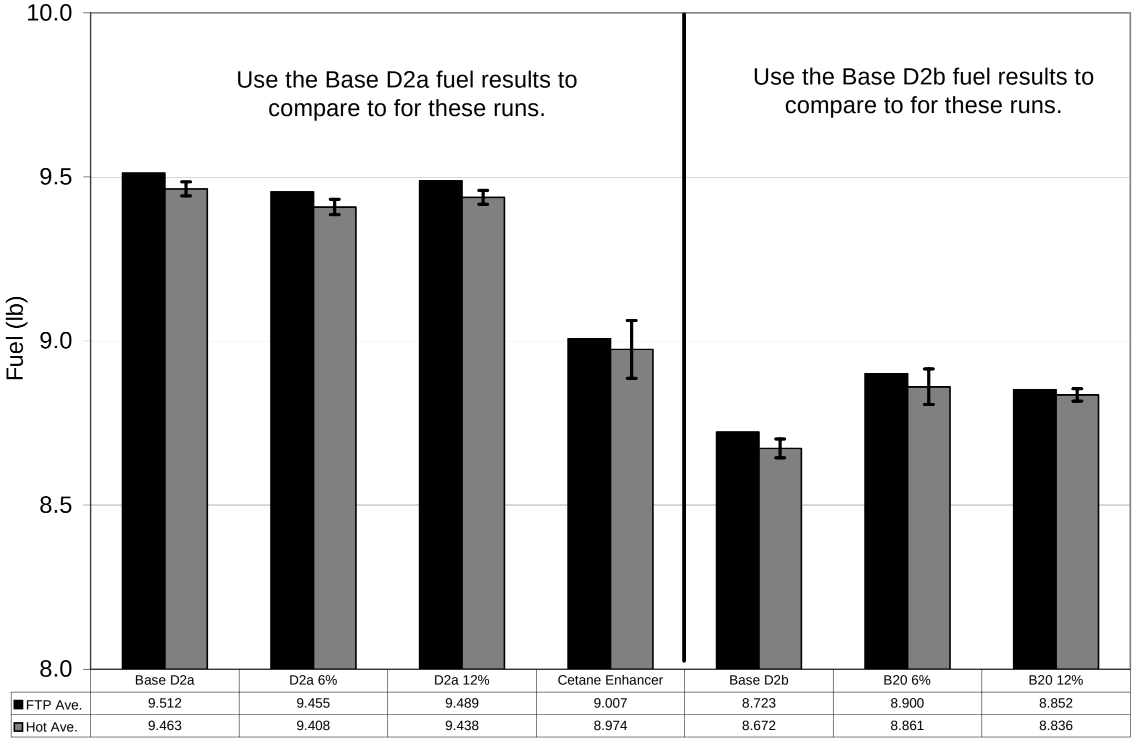
The results for CO are shown in Figure 5 as the FTP (1/7 cold+6/7 hot start) and average of the hot start test for each fuel. The bars on the hot start data represent one standard deviation of the three (or four) hot start data for each test. As illustrated in this figure, as the concentration of the Cetane Enhancer increases, the hot start emissions of CO show small changes for the 6% or 12 % Cetane Enhancer blend ratio for the Base D2a blend. The neat Cetane Enhancer did exhibit a 29.7% reduction in the CO compared to the Base D2a fuel. There appears to be a Cetane Enhancer blend ratio above 12% that may result in a CO reduction. For the Base D2b fuel comparison, the Base D2b B20 with 6% Cetane Enhancer showed a 10.1% reduction in the CO value over the Base D2b fuel. A decrease is typical for this engine with a B20 blend compared to the base diesel fuel. Therefore, the 10.1% reduction with the Base D2b B20 with 6% Cetane Enhancer is consistent with the CO reduction from the biodiesel. The Base D2b B20 with 12% Cetane Enhancer showed a 14.6% decrease in the CO value over the Base D2b fuel; this reduction is consistent with the Base D2a fuel results where the CO reduction at the 6% and 12% blend ratios are mainly due to the biodiesel.



	Base D2a	D2a 6%	D2a 12%	Cetane Enhancer	Base D2b	B20 6%	B20 12%
■ FTP Ave.	3.734	3.675	3.517	2.592	3.032	2.702	2.597
▨ Hot Ave.	3.577	3.555	3.400	2.514	2.892	2.600	2.470

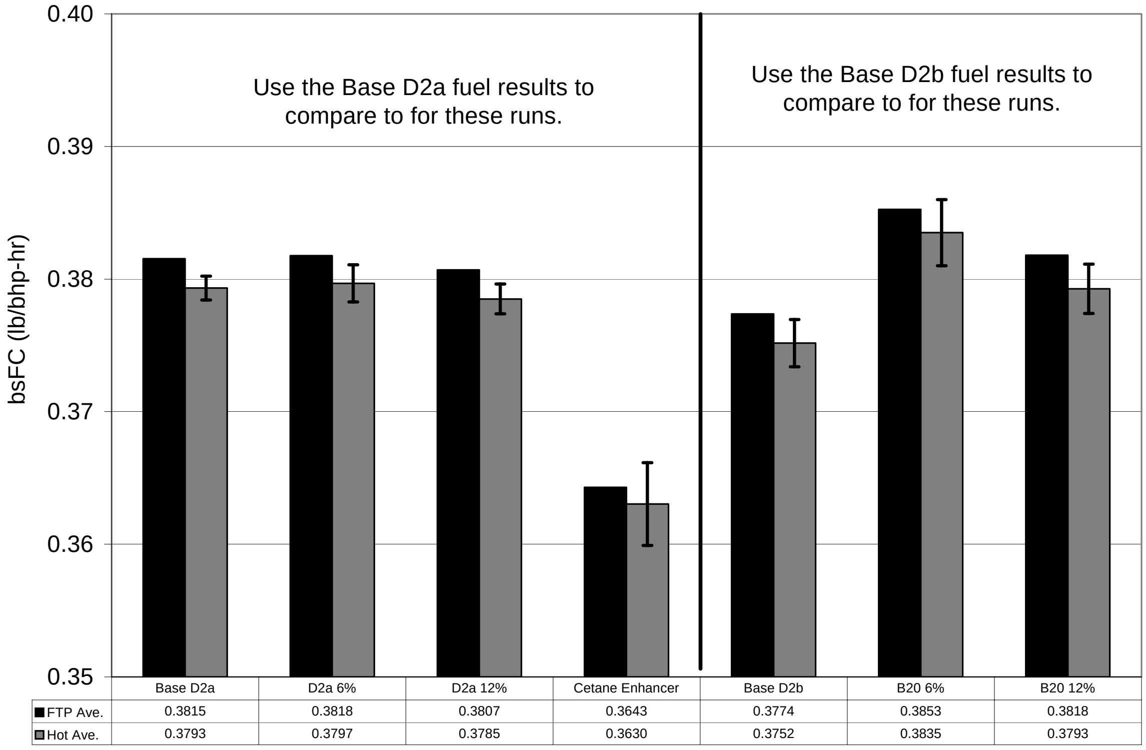
Figure 5 FTP and hot start average CO values. Bars represent one standard deviation of the hot start data for that set of tests. Note the expanded axis.

The results for fuel consumption are shown in Figure 6 and the results for BSFC are shown in Figure 7. The bars represent one standard deviation of the data for each test for each noted day. The fuel consumed values were the direct measurement from the fuel meter. The BSFC values use the consumed measurement and the integrated work from the dynamometer. The data uses specific or API gravity to determine the fuel consumed values; the gravity values were measured at WVU. As shown in the fuel consumption and BSFC data, there was no significant difference in the amount of fuel required to exercise the engine over hot-start FTP cycles between the Base D2a and Base D2a at a 6% or 12% blend ratio. The neat Cetane Enhancer did exhibit lower fuel consumption by 4.3% compared to the Base D2a fuel. There was an increase in the amount of fuel required to exercise the engine over hot-start FTP cycles between the Base D2b and Base D2a B20 at a 6% or 12% blend ratio by 1 to 2%. It is noted that there was no significant difference (<1%) in the overall average integrated work value between the base diesel fuels and the blended fuels. However, there was a significant difference (24.95 hp-hr for the Base D2a fuel and 23.12 bhp-hr for the Base D2b fuel) between the two base diesel fuels.



	Base D2a	D2a 6%	D2a 12%	Cetane Enhancer	Base D2b	B20 6%	B20 12%
■ FTP Ave.	9.512	9.455	9.489	9.007	8.723	8.900	8.852
▨ Hot Ave.	9.463	9.408	9.438	8.974	8.672	8.861	8.836

Figure 6 FTP and hot start average fuel consumption values. Bars represent one standard deviation of the hot start data for that set of tests. Note the expanded axis.



	Base D2a	D2a 6%	D2a 12%	Cetane Enhancer	Base D2b	B20 6%	B20 12%
■ FTP Ave.	0.3815	0.3818	0.3807	0.3643	0.3774	0.3853	0.3818
▨ Hot Ave.	0.3793	0.3797	0.3785	0.3630	0.3752	0.3835	0.3793

Figure 7 FTP and hot start average bsFC values. Bars represent one standard deviation of the hot start data for that set of tests. Note the expanded axis.

Conclusions

The emissions from a base diesel fuel was compared to the same base diesel fuels blended with 6 and 12% Cetane Enhancer. The emissions from a second base diesel fuel was compared to the second base diesel fuels blended with 20% biodiesel (B20) and then blended with 6% and 12% Cetane Enhancer. The emissions of NOx, THC, NMHC, CO, and TPM were compared between the fuels. The results show that the Cetane Enhancer addition reduces NOx, THC, and NMHC while not impacting the work or fuel economy. The results also show that the increase in NOx from a B20 blend using the D2b base fuel can be neutralized with approximately 9% Cetane Enhancer while benefiting from the THC, NMHC, CO, and TPM reduction with the B20 blend.

References

1 *Title 40 Code of Federal Regulations, Part 86,* U.S. Government Printing Office, Washington, DC, 2000.
2 *Methane Measurement Using Gas Chromatograph,* Society of Automotive Engineers, Recommended Practice SAE J1151, Warrendale, PA, 1991.

Appendix A – Emissions Summary Tables

Table 4 Summary of the Base D2a fuel emissions data.

Fuel: **Base D2a**				Work	Fuel Cons	bsFC	bsTHC	bsNMHC	bsCO	bsCO2	bsNOx	bsTPM
Date	Time	Test No.	Start Type	bhp-hr	lb	lb/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
4/7/06	7:59	E01027-01	Cold	24.83	9.803	0.3948	0.2511	0.248	4.674	583.2	6.191	0.3052
4/7/06	8:39	E01027-02	Hot	24.97	9.493	0.3803	0.1862	0.184	3.636	558.7	5.385	0.2384
4/7/06	9:19	E01027-03	Hot	24.91	9.457	0.3797	0.1929	0.193	3.572	557.9	5.315	0.2325
4/7/06	10:00	E01027-04	Hot	24.96	9.461	0.3791	0.1901	0.193	3.544	557.3	5.323	0.2384
4/7/06	10:40	E01027-05	Hot	24.96	9.442	0.3782	0.1900	0.191	3.557	556.0	5.321	0.2369
			FTP Average	24.93	9.512	0.3815	0.1986	0.20	3.734	561.1	5.458	0.2475
			Hot Start Average	24.95	9.463	0.3793	0.1898	0.19	3.577	557.5	5.336	0.2379
			Hot Start Std Dev	0.03	0.021	0.0009	0.0028	0.00	0.041	1.1	0.033	0.0008
			COV (%)	0.11	0.23	0.24	1.45	2.19	1.14	0.21	0.62	0.36

Comments:

TPM filter for E01027-03 mishandled. Extra hot start run to obtain three valid tests for TPM. All other hot start data are for the four hots.

Table 5 Summary of the Base D2a with 6% Cetane Enhancer fuel emissions data.

Fuel: **D2a 6%**				Work	Fuel Cons.	bsFC	bsTHC	bsNMHC	bsCO	bsCO2	bsNOx	bsTPM
Date	Time	Test No.	Start Type	bhp-hr	lb	lb/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
4/7/06	14:46	E01029-01	Cold	24.69	9.735	0.3943	0.2170	0.218	4.393	581.2	5.964	0.2426
4/7/06	15:26	E01029-02	Hot	24.74	9.418	0.3806	0.1799	0.181	3.640	558.4	5.189	0.2446
4/7/06	16:06	E01029-03	Hot	24.80	9.398	0.3789	0.1742	0.175	3.546	554.9	5.177	0.2413
4/7/06	16:46	E01029-04	Hot	24.76	9.435	0.3811	0.1691	0.171	3.533	557.8	5.202	0.2376
4/7/06	17:27	E01029-05	Hot	24.81	9.381	0.3781	0.1724	0.175	3.500	555.3	5.213	0.2380
			FTP Average	24.77	9.455	0.3818	0.1801	0.18	3.675	560.1	5.305	0.2407
			Hot Start Average	24.78	9.408	0.3797	0.1739	0.1755	3.555	556.6	5.195	0.2404
			Hot Start Std Dev	0.03	0.024	0.0014	0.0045	0.0044	0.060	1.7	0.016	0.0033
			COV (%)	0.13	0.25	0.37	2.60	2.51	1.69	0.31	0.30	1.36

Comments:

Table 6 Summary of the Base D2a with 12% Cetane Enhancer fuel emissions data.

Fuel: **D2a 12%**				Work	Fuel Cons.	bsFC	bsTHC	bsNMHC	bsCO	bsCO2	bsNOx	bsTPM
Date	Time	Test No.	Start Type	bhp-hr	lb	lb/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
4/7/06	20:41	E01031-01	Cold	24.86	9.792	0.3938	0.1830	0.185	4.215	584.2	5.815	0.2448
4/7/06	21:21	E01031-02	Hot	24.92	9.445	0.3791	0.1543	0.155	3.431	559.2	5.047	0.2344
4/7/06	22:01	E01031-03	Hot	24.94	9.455	0.3792	0.1582	0.160	3.403	556.6	5.019	0.2388
4/7/06	22:41	E01031-04	Hot	24.96	9.414	0.3772	0.1561	0.157	3.367	556.3	5.014	0.2405
			FTP Average	24.93	9.489	0.3807	0.1600	0.16	3.517	561.2	5.139	0.2389
			Hot Start Average	24.94	9.438	0.3785	0.1562	0.1576	3.400	557.4	5.027	0.2379
			Hot Start Std Dev	0.02	0.021	0.0011	0.0020	0.0027	0.032	1.6	0.018	0.0031
			COV (%)	0.08	0.23	0.30	1.25	1.70	0.94	0.29	0.35	1.32

Comments:

Table 7 Summary of the neat Cetane Enhancer fuel emissions data.

Fuel: **Cetane Enhancer**				Work	Fuel Cons.	bsFC	bsTHC	bsNMHC	bsCO	bsCO2	bsNOx	bsTPM
Date	Time	Test No.	Start Type	bhp-hr	lb	lb/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
4/8/06	8:20	E01033-01	Cold	24.76	9.206	0.3719	0.0975	0.099	3.062	555.6	4.818	0.1771
4/8/06	9:00	E01033-02	Hot	24.75	9.074	0.3666	0.0996	0.102	2.592	532.6	4.074	0.1661
4/8/06	9:40	E01033-03	Hot	24.72	8.940	0.3617	0.0998	0.100	2.500	529.2	4.060	0.1632
4/8/06	10:21	E01033-04	Hot	22.34	8.087	0.3621	0.1162	0.122	2.669	531.4	4.195	0.1687
4/8/06	11:01	E01033-05	Hot	24.69	8.909	0.3608	0.0978	0.100	2.449	529.1	4.071	0.1546

FTP Average	24.73	9.007	0.3643	0.0988	0.10	2.592	533.9	4.175	0.1635
Hot Start Average	24.72	8.974	0.3630	0.0991	0.1006	2.514	530.3	4.068	0.1613
Hot Start Std Dev	0.03	0.088	0.0031	0.0011	0.0010	0.072	2.0	0.007	0.0060
COV (%)	0.12	0.98	0.86	1.11	1.03	2.88	0.37	0.18	3.72

Comments:

Test E01033-04 test invalid - engine power dropped out ~720 to ~760 seconds, extra hot start run to replace test.

Table 8 Summary of the Base D2b fuel emissions data.

Fuel: **Base D2b**				Work	Fuel Cons.	bsFC	bsTHC	bsNMHC	bsCO	bsCO2	bsNOx	bsTPM
Date	Time	Test No.	Start Type	bhp-hr	lb	lb/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
4/8/06	15:04	E01035-01	Cold	23.10	9.025	0.3906	0.2537	0.255	3.867	571.1	5.607	0.2416
4/8/06	15:44	E01035-02	Hot	23.08	8.705	0.3771	0.1937	0.195	2.953	548.8	4.754	0.2037
4/8/06	16:24	E01035-03	Hot	23.11	8.661	0.3748	0.1953	0.199	2.901	545.3	4.745	0.2043
4/8/06	17:05	E01035-04	Hot	23.16	8.651	0.3736	0.1931	0.195	2.823	543.7	4.760	0.1975

FTP Average	23.11	8.723	0.3774	0.2026	0.20	3.032	549.5	4.875	0.2075
Hot Start Average	23.12	8.672	0.3752	0.1940	0.1960	2.892	545.9	4.753	0.2018
Hot Start Std Dev	0.04	0.029	0.0018	0.0011	0.0024	0.065	2.6	0.008	0.0038
COV (%)	0.17	0.33	0.47	0.59	1.21	2.26	0.48	0.16	1.87

Comments:

Table 9 Summary of the Base D2b B20 with 6% Cetane Enhancer fuel emissions data.

Fuel: **B20 6%**				Work	Fuel Cons.	bsFC	bsTHC	bsNMHC	bsCO	bsCO2	bsNOx	bsTPM
4/8/06	20:07	E01037-01	Cold	23.09	9.139	0.3958	0.1846	0.185	3.319	578.1	5.622	0.1770
4/8/06	20:47	E01037-02	Hot	23.10	8.923	0.3863	0.1560	0.159	2.644	552.6	4.880	0.1662
4/8/06	21:27	E01037-03	Hot	23.08	8.835	0.3827	0.1788	0.179	2.604	549.3	4.814	0.1680
4/8/06	22:07	E01037-04	Hot	23.13	8.824	0.3815	0.1565	0.159	2.551	546.7	4.816	0.1653
FTP Average				23.10	8.900	0.3853	0.1667	0.17	2.702	553.6	4.949	0.1680
Hot Start Average				23.10	8.861	0.3835	0.1638	0.1654	2.600	549.5	4.837	0.1665
Hot Start Std Dev				0.03	0.054	0.0025	0.0130	0.0120	0.047	3.0	0.038	0.0014
COV (%)				0.11	0.61	0.65	7.95	7.23	1.79	0.54	0.78	0.83

Comments:

Table 10 Summary of the Base D2b B20 with 12% Cetane Enhancer fuel emissions data.

Fuel: **B20 12%**				Work	Fuel Cons.	bsFC	bsTHC	bsNMHC	bsCO	bsCO2	bsNOx	bsTPM
Date	Time	Test No.	Start Type	bhp-hr	lb	lb/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
4/9/06	8:42	E01039-01	Cold	22.54	8.949	0.3970	0.1820	0.186	3.365	572.0	5.686	0.2451
4/9/06	9:22	E01039-02	Hot	23.25	8.862	0.3811	0.1608	0.163	2.534	546.6	4.796	0.1660
4/9/06	10:02	E01039-03	Hot	23.25	8.832	0.3799	0.1596	0.164	2.461	543.7	4.706	0.1640
4/9/06	10:43	E01039-04	Hot	23.41	8.819	0.3767	0.1489	0.151	2.429	538.8	4.680	0.1598
4/9/06	11:23	E01039-05	Hot	23.27	8.830	0.3794	0.1619	0.165	2.454	541.4	4.671	0.1642
FTP Average				23.19	8.852	0.3818	0.1613	0.16	2.597	546.8	4.829	0.1752
Hot Start Average				23.30	8.836	0.3793	0.1578	0.161	2.470	542.6	4.686	0.1635
Hot Start Std Dev				0.08	0.018	0.0019	0.0060	0.0063	0.045	3.3	0.018	0.0026
COV (%)				0.33	0.21	0.49	3.81	3.94	1.83	0.61	0.39	1.60

Comments:

The post test span for the E01039-02 NOx was high. Although less than post test span drift was less than 2% and this point was not deemed an outlier per the ASTM E178 criteria, the NOx for this run was removed from the data set and an extra hot start run in its place. The other values for this run are valid. Statistics reflect this change.