

1000-Hour Durability Evaluation of a Prototype 2007 Diesel Engine with Aftertreatment Using B20 Biodiesel Fuel

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ABSTRACT

A prototype 2007 ISL Cummins diesel engine equipped with a diesel oxidation catalyst (DOC), diesel particle filter (DPF), variable geometry turbocharger (VGT), and cooled exhaust gas recirculation (EGR) was tested at Southwest Research Institute (SwRI) under a high-load accelerated durability cycle for 1000 hours with B20 soy-based biodiesel blends and ultra-low sulfur diesel (ULSD) fuel to determine the impact of B20 on engine durability, performance, emissions, and fuel consumption. At the completion of the 1000-hour test, a thorough engine teardown evaluation of the overhead, power transfer, cylinder, cooling, lube, air handling, gaskets, aftertreatment, and fuel system parts was performed.

The engine operated successfully with no biodiesel-related failures. Results indicate that engine performance was essentially the same when tested at 125 and 1000 hours of accumulated durability operation. Emission data indicate that THC, CO, and PM levels were not significantly different between the B20 and ULSD fuel, and as expected, the emission-grade B20 fuel resulted in higher NO_x than the ULSD fuel. Within the expected range, fuel consumption was observed to be higher with B20 than 2007 certified ULSD. There were no failures found on the engine components that

were attributable to running B20 biodiesel. The wear and deposits found were normal and consistent with findings from parts that ran with ASTM D975 #2 fuel in similar tests.

INTRODUCTION

With the current focus in the United States on reduction of petroleum imports and emissions of greenhouse gases, there has been renewed interest in the use of alternative diesel fuels, especially biodiesel. Biodiesel is made from lipid feedstocks such as vegetable oil, waste cooking oil, or animal fat by reaction with methanol to form methyl esters in a process called transesterification. Biodiesel is primarily used as a blending component with diesel fuel. Reductions of particulate matter (PM), carbon monoxide (CO), and total hydrocarbon emissions (THC) can be achieved with biodiesel use [1]. Based on life-cycle analysis, the use of biodiesel produces real reductions in petroleum consumption and carbon dioxide (CO₂) emissions [2]. Energy content per gallon is slightly lower, resulting in minor reductions in peak torque and fuel economy for B20, but thermal efficiency is unchanged [3].

In the United States production levels of biodiesel have increased steadily since the introduction of a biodiesel blending tax credit late in 2005. Production in 2008 is

estimated at 690 million gallons [4]. Biodiesel can contain a number of impurities that, if present at excessively high levels, might impact engine durability. These include unreacted oil feedstock, unreacted methanol, partially reacted di- and mono-glycerides, as well as phosphorus (P) from phospholipids that might be present in the feedstock and metals that are residues of the production process (Na, K, Ca, and Mg). To protect end-users, biodiesel sold in the United States must meet the quality requirements of the ASTM D6751 specification, which limits all of these components – as does the European specification, EN14214. These specifications also require a minimum level of oxidation stability to limit the formation of gums, deposits, peroxide and acid. A recent quality survey found that 90% of the production volume in the United States was meeting the D6751 quality requirements [5].

A number of engine durability studies were conducted in the early 1990's [6-11]. At that time there was no ASTM specification for B100 quality; thus, the biodiesel used in these older studies was of significantly lower quality than the biodiesel used today. Problems encountered in several of these studies were almost certainly caused by higher levels of impurities than those in biodiesel as currently produced. A recent light-duty engine and catalyst durability test operated the engine to twice full useful life and found no evidence of biodiesel-related wear or mechanical deterioration [12]. However, there have been few public heavy-duty engine durability studies in recent years. The effect of B20 on heavy-duty engine durability has been assessed in several field studies [13-17]. Field tests generally find no increase in engine wear or engine/fuel system maintenance costs but sometimes note an increase in fuel filter plugging in cold weather for B20.

The introduction of EGR and DPF over the past few years has created a need to again test the impact of biodiesel on engine durability. This will likely require several different types of studies to be conducted, but as an initial step towards this goal Cummins, Inc., the National Biodiesel Board, and the National Renewable Energy Laboratory collaborated on a 1000-hour durability test conducted at SwRI with B20 fuel consumed in a prototype 2007 model year Cummins ISL engine. The objective of this study was to determine if B20 caused operational problems or engine component wear outside of the normally expected range.

APPROACH

The overriding objective of this project was to gain an understanding of the durability impact of B20 biodiesel blends on a transit bus engine. The approach selected for that purpose was to conduct an accelerated endurance evaluation in a test cell under controlled conditions so that biodiesel-specific related issues could be identified.

The engine selected had to be representative of the current trend on transit bus powertrains. The original plan was to use an 11 liter Cummins ISM engine that is typical of transit bus applications, but it was later decided to use a 9 liter ISL engine instead, reflecting the increased demand for this engine by transit bus operators. As a result, a pre-production engineering 2007 ISL engine was made available in June 2006 by the Cummins Product Development Engineering team for this project.

A 1000-hour test cycle was selected to represent accelerated endurance conditions. The particular test cycle selected is used extensively during engine development activities at Cummins, including the 2007 ISL, and therefore provides an excellent baseline when comparing the end of test results of biodiesel B20 against diesel fuel.

Engine testing was performed at SwRI in San Antonio, Texas, while the pre-build measurements and post-test teardown analysis were conducted at the Cummins Technical Center in Columbus, Indiana. The engine was evaluated for performance and emissions throughout the test. The impact on durability was assessed at the end of the test by components review and comparison to the database from operation on straight ASTM D975 #2 diesel fuel.

Since the engine was a pre-production unit, all changes/events during the test were documented, but only those related to biodiesel operation would be analyzed and reviewed in detail.

TEST PROCEDURE – A prototype 2007 model year Cummins ISL engine, shown in Figure 1, was provided by Cummins Inc. for the biodiesel durability and emissions test program. The 8.9 liter heavy-duty, on-highway diesel engine produced 268 kW on B20 fuel. The inline 6-cylinder engine had a rated speed of 2100 rpm and peak torque of 1708 N•m at 1400 rpm with emissions-grade B20 fuel. The engine was equipped with a DOC followed by a catalyzed DPF that used diesel fuel post injection (in-cylinder) for active regeneration. The engine was also equipped with a blow-by filtration system allowing the filtered blow-by stream to be vented to the atmosphere. The engine had a VGT and a high-pressure EGR with an EGR cooler.

The Cummins engine was operated over a 1,000-hour durability sequence using commercially available B20 biodiesel fuel. Regulated emissions were evaluated at 125 hours and 1,000 hours of operation using B20 fuel as well as ULSD fuel. Lube oil samples were taken every 50 hours of operation for analysis.

Durability operation was performed in a steady-state durability test cell. The durability test cell was computer-controlled and incorporated a number of automated safety functions that allowed the test cell to operate

continuously. The engine was shut down every 25 hours to check engine lube oil levels and test cell hardware. The engine lube oil and lube oil filter were changed

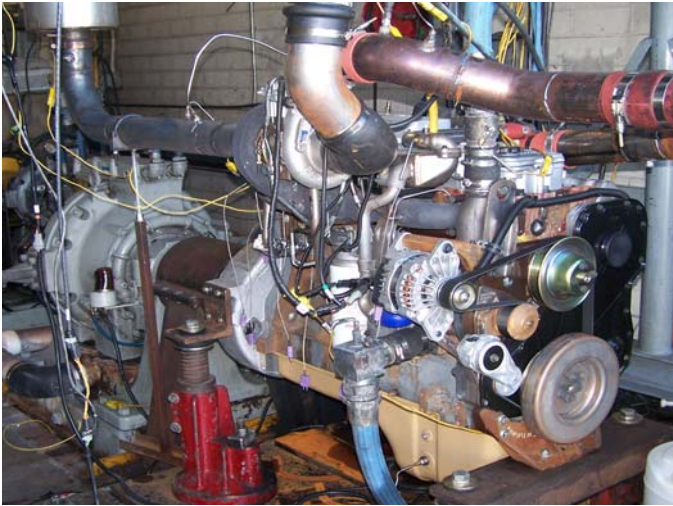


Figure 1. Cummins ISL diesel engine operating in a durability test cell

every 250 hours of accumulated durability operation. The engine lube oil used during the program was Valvoline Premium Blue, SAE 15W-40, API Services CJ-4, CI-4, CH-4, and DF/SL.

During durability testing, the engine was operated over a proprietary high-load, accelerated, transient durability cycle. The cycle consists of more than 70% of its time at full load, and was repeated for the duration of the 1000-hour durability test (Figure 2).

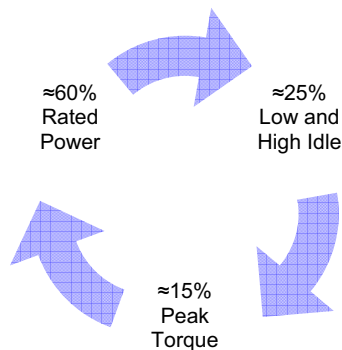


Figure 2. Cycle used during the 1000-hour durability test

After 125 hours and again after 1,000 hours of accumulated durability operation, the Cummins ISL engine was removed from the durability test cell and installed in a transient emissions test cell. The engine was tested according to procedures outlined in the Code of Federal Regulations (CFR) Title 40 Part 86 Subpart N for heavy-duty on-highway engines. The test sequence conducted on the engine included one cold-start transient federal test procedures (FTP) test, three hot-

start transient FTP tests, and one supplemental emissions test (SET) ramped modal cycle (RMC). This sequence of tests was performed using both the emissions-grade B20 biodiesel fuel as well as the 2007 certification ULSD fuel. All measurements were made using dilute sampling techniques with a full flow CVS dilution tunnel. Regulated emissions of HC, CO, NOx, and PM were measured for each test. While all gaseous emissions measurements were conducted in accordance with CFR Part 86, Subpart N, the PM measurement was done in accordance with CFR Part 1065 using a 47-mm Teflon membrane filter downstream of a PM2.5 cyclone, heated to a filter face temperature of $47^{\circ}\text{C} \pm 5^{\circ}\text{C}$. Furthermore, all emissions testing was conducted with the blow-by stream routed to the exhaust stream downstream of the DPF. No changes were made to the calibration as far as aftertreatment; thus, any regeneration of the aftertreatment was driven by the delta pressure sensors. Since this was a fairly high load test, it would have required active regeneration less than that of an equivalent engine in the field. However, active regeneration was not prevented from taking place.

Engine lube oil analysis for metals (ASTM D 5185), TBN (ASTM D 4739), viscosity (ASTM D 445), soot, and fuel dilution was performed on samples collected every 50 hours of durability operation. A modified version of ASTM D3524 was used to measure the amount of diesel fuel in the oil, and a Thermo-Nicolet 6700 mid-FTIR instrument was used for the calculation of the biodiesel portion. Using a 0.05-mm fixed path length potassium bromide (KBr) transmission cell, the peak area of the region from 1720–1780 wave numbers is integrated and compared with a calibration curve generated with lab prepared standards ranging from 0% to 25% fatty acid methyl esters (FAME) by mass. Using a fresh oil of a similar type to the used oil, the fresh oil absorption spectrum is subtracted from the sample using the spectral subtraction function of the instrument software to account for any absorption in the region of interest typical to oil of the type being tested. The spectral subtraction is not essential to the analysis, but it aids in determining the best baseline to use for peak integration. The calibration curve using this method has been found to be strictly linear, and R-squared values of 0.9999 are typical.

FUELS – Four different fuels were used during the engine testing (Table 1). The B100 neat soy-based biodiesel, referred to as (A), was obtained from Sun Coast Resources, Inc. and was used to make the B20 blends. The 2007 certification ULSD fuel, referred to as (B), which met the 2007 EPA specifications, was obtained from Haltermann Products. The third fuel was a blend of fuel (A) and fuel (B), referred to as (A+B), which was an emission-grade B20 blended by SwRI. The fourth fuel consisted of durability-grade B20, which is referred to as (C), a blend of (A) and Texas commercially available ULSD blended by Sun Coast Resources, Inc.

Fuel batch (C) was used during the durability testing, and fuel batches (B) and (A+B) were used during the emissions testing (Table 2). Fuel analyses (Table A-1) were performed by SwRI for fuels (A), (A+B), and (C), while the Certificate of Analysis from Haltermann Products was used for fuel (B).

RESULTS

DURABILITY RESULTS – The 1,000-hour durability testing with soy-based B20 biodiesel fuel was successful. Other than the exceptions listed below, the engine showed no significant changes in operation or performance throughout the test. With the high load durability cycle, DPF active regeneration started and ended with no problems.

Table 1. Test fuel labels, type, and description

	Fuel Type	Description
A	Neat Biodiesel (B100)	B100 soy-based biodiesel from Sun Coast Resources, Inc.
B	2007 Certified ULSD	Emission grade ULSD #2 (<15-ppm sulfur) which met 2007 EPA specifications obtained from Haltermann Products
(A+B)	Emission-Grade B20	Blend of 2007 certified ULSD and neat biodiesel blended by SwRI used only during emissions testing
C	Durability-Grade B20	B20 blend of neat soy-based biodiesel and Texas commercially available ULSD blended by Sun Coast Resources, Inc.

Table 2. Type of fuel used during engine test cycle

Hours	Test	Fuel
0-125	Durability	C
125	Emissions	B
125	Emissions	(A+B)
125-1000	Durability	C
1000	Emissions	B
1000	Emissions	(A+B)

At 150 hours of durability operation, the engine began leaking lube oil from the filler cap on the valve cover. It was also observed that there was no blow-by flow from the open crankcase ventilation system even at high load operation, although blow-by flow had been evident earlier in the program. Furthermore, an engine fault code related to the crankcase pressure became active. Removal of the crankcase ventilation system filter remedied the problems described above.

The maintenance interval for replacement of the crankcase ventilation filter is 80,000 miles or 2,000 hours of field operation. Due to the high-load accelerated

durability cycle, the filter was not expected to have to be replaced until 975 hours of durability operation. A newer design replacement crankcase ventilation filter was supplied and installed on the engine. The new replacement filter is the one used in current production engines, and the failed filter was a prototype design. The new replacement filter was used throughout the remaining 850 hours of durability operation without any crankcase-related problems.

At approximately 950 hours of accumulated durability operation, the engine began surging when operated at rated speed and full load. An engine fault code also activated, stating the injector metering pressure was below normal. It became apparent that the fuel filter had not been changed during the project. The Cummins-specified maintenance interval for the fuel filter replacement is 500 hours of field operation. Due to the high-load accelerated durability cycle, the fuel filter should have been replaced every 250 hours. After replacing the fuel filter, the engine resumed normal operation and the active engine fault cleared. Because the failed fuel filter had operated well past the specified maintenance interval, it was not confirmed if this problem was fuel-specific.

EMISSION RESULTS – After installation in a transient emissions test cell, the engine settings were verified and a power validation procedure was performed by operating the engine at full load and at rated speed and peak torque speed with emissions-grade B20 biodiesel fuel. Using an 8 rpm per second speed sweep, a full load torque map was generated. Figure 3 shows the full load torque and power maps for the Cummins ISL engine when operated on emissions-grade B20 fuel at the 125-hour and 1,000-hour test intervals.

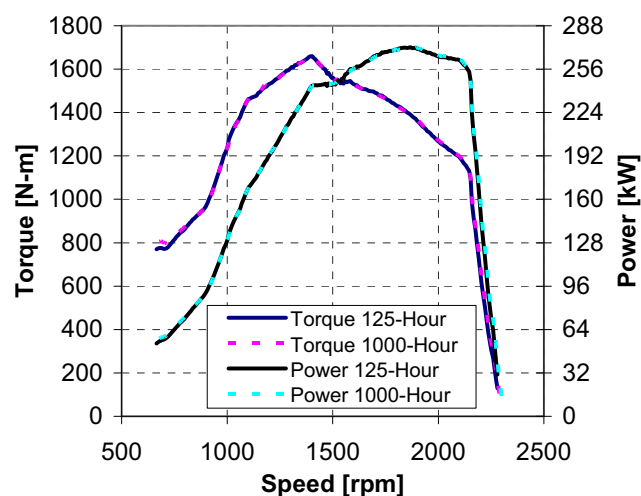


Figure 3. Full load torque and power map for the 8.9 liter Cummins ISL diesel engine when operated with B20 fuel at 125 and 1,000 hours of accumulated durability operation

As shown from the torque and power traces, engine performance was essentially the same when tested at 125 and 1,000 hours of accumulated durability operation. The B20, 125-hour, full load torque map was used to generate the transient FTP test cycle and the ramped modal cycle (RMC) test cycle. In order to keep testing consistent between fuels and between the 125-hour and 1,000-hour test intervals, the same command cycles generated with the emissions-grade B20 fuel at the 125-hour test were used throughout the program. After emission tests were performed with emissions-grade B20, the test fuel was changed to 2007 EPA certification ULSD. The fuel change was performed by removing the fuel supply and return hoses from the engine and purging the system with ULSD fuel. Engine and laboratory fuel filters were also replaced. After the fuel system was reassembled, the engine was operated at rated power for approximately one hour with ULSD fuel to further purge the system.

Because the ISL engine is a pre-production prototype and not a fully certified production engine, only normalized emission results are presented. Furthermore, emission results from the 125-hour and 1,000-hour testing are isolated, showing no comparison between the initial and final testing. Therefore, the only evaluations performed were between the B20 biodiesel fuel and ULSD fuel at the 125-hour and 1,000-hour emission tests. It should be noted that the engine met the emission standard for all four pollutants at 125 and 1000 hours when operating on certification diesel.

Table 3 shows the normalized emission results for the 125-hour emissions testing. The emission results were normalized using the 125-hour ULSD hot-start mean emission value for each pollutant. With the use of a DPF, the HC, CO, and PM emission levels were very low, causing increased measurement variability. A t-Test comparison was performed on the B20 and ULSD hot-start tests to determine if the mean values were equal. Hot-start t-Test p-values of less than 0.05 indicate there was a 95% chance or greater that the mean values were distinct. Due to the higher variability for the low levels of HC, CO, and PM measurements, the B20 and ULSD hot-start mean values were not significantly different at the 5% significance level. However, the hot-start mean NOx, CO₂, and brake-specific fuel consumption (BSFC) values were significantly different at the 5% significance level. The NOx levels increased 5.9% with the emissions-grade B20 biodiesel fuel as compared with the ULSD fuel over the hot-start triplicate testing. Carbon dioxide increased 0.5% and BSFC increased 2.6% with B20 fuel over hot-start testing. The increase in fuel consumption with the B20 was expected due to the lower energy content of B20 fuel when compared with that of ULSD [18]. Reported on a mass basis, BSFC differences were in line with typical energy differences between ULSD and B20 fuel. The impact of B20 on NOx is well documented in the literature. It can be attributed to changes in fuel properties that impact combustion characteristics and calibration response that may affect NOx formation [19-20].

Table 3. Summary of normalized emission results for a Cummins ISL engine after 125 hours of durability operation with B20 fuel

Fuel	Test	Normalized Brake Specific Results ²					
	Name	HC ¹	CO ¹	NOx	PM ¹	CO ₂	BSFC
125 Hour B20	Cold 1	0.0	6.91	0.98	6.35	1.03	1.05
	Hot 1	0.2	0.57	1.05	1.46	1.00	1.03
	Hot 2	1.1	1.08	1.06	1.41	1.00	1.02
	Hot 3	1.5	0.72	1.06	1.31	1.01	1.03
	RMC	2.7	0.83	0.83	1.85	0.88	0.90
	C/H Comp. ⁴	0.1	1.47	1.04	2.15	1.01	1.03
	Hot Ave.	0.9	0.79	1.06	1.39	1.00	1.03
	Hot COV	75.0%	32.9%	0.6%	5.3%	0.2%	0.2%
125 Hour ULSD	Cold 1	0.0	8.32	0.93	0.69	1.03	1.03
	Hot 1	2.4	1.00	1.00	1.33	1.00	1.00
	Hot 2	0.6	0.76	1.00	0.70	1.00	1.00
	Hot 3	0.1	1.24	1.00	0.97	1.00	1.00
	RMC	2.1	0.95	0.79	1.40	0.89	0.89
	C/H Comp. ⁴	2.0	2.04	0.99	1.24	1.01	1.01
	Hot Ave. ²	1.0	1.00	1.00	1.00	1.00	1.00
	Hot COV	120.0%	24.2%	0.3%	31.4%	0.2%	0.2%
% Diff	RMC	29.0%	-12.6%	4.4%	32.1%	-0.2%	1.9%
	C/H Comp. ⁴	-93.0%	-28.0%	4.7%	74.2%	0.3%	2.4%
	Hot Ave.	-6.1%	-20.8%	5.9%	39.0%	0.5%	2.6%
	Hot t-Test ³	0.944	0.368	0.000	0.101	0.044	0.000

¹ BSHC, BSCO, and BSPM are well below the regulatory standards.

² Test results were normalized using the ULSD hot start average emission values.

³ Values less than 0.05 indicate hot start mean values are significantly different at the five percent significance level.

⁴ Cold-start/hot-start composite (1/7 cold-start + 6/7 hot-start)

Table 4 shows the normalized Cummins ISL 1,000-hour emission results. The results were normalized using the 1,000-hour ULSD hot-start mean emission value for each pollutant. As with the 125-hour test results, it is difficult to quantify changes in HC, CO, and PM emission results due to the very low emission levels and higher variability of the data. For the 1,000-hour test, the mean hot-start NOx level increased 6.5% with B20 fuel as compared with the ULSD test results. The mean hot-start BSFC increased 3.4%, and CO₂ increased 1.7% with B20 biodiesel fuel as compared with the straight ULSD fuel.

LUBRICANT – The lube oil and lube oil filter were changed every 250 hours of accumulated durability operation, and samples were collected every 50 hours of the durability testing. The oil samples were analyzed by SwRI for soot mass, viscosity, total base number, and selected elements (Tables A-2 and A-3). For fuel dilution, biodiesel in the lubricant was measured by the National Renewable Energy Laboratory (NREL) and Cummins Technical Center (CTC), and the diesel portion was measured by CTC. There was a slight increase in soot mass during every oil drain interval throughout the engine test, and the highest percent measured was 1.75 mass percent at the 750-hour mark (Figure 4). The soot mass percent acceptable in the used lubricant oil is between 0 and 3% [21]. Since the soot mass percent did not exceed 3%, this indicates that the amount of soot mass present in the lubricant oil was within acceptable limits.