Biodiesel Emissions Data From Series 60 DDC Engines

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Introduction

Biodiesel was first used in the late 1800s by Rudolph Diesel as he demonstrated the compression engine that he had designed- the diesel engine. Petroleum based diesel fuel has been the fuel of choice for the compression ignition engine designed by Mr. Diesel for many years. However, methyl esters of animal and vegetable oils (biodiesel), due to their cleaner burning tendencies in the compression ignition engine, are again being evaluated for use as a fuel for modern diesel engines.

Purpose and Objectives

The purpose of this study was to analyze and draw comparisons concerning the fueling of Series 60 DDC engines that have been fueled with blends of biodiesel and petroleum diesel fuel. Specifically, two National Biodiesel Board sponsored research efforts were examined to gain a deeper understanding of: 1) regulated EPA exhaust emissions, 2) selected fuel related properties, and 3) power/performance characteristics.

Detroit Diesel Series (DDC) 60 engines were tested in transient test cells at the Southwest Research Institute (SwRI), San Antonio, Texas and the Colorado Institute for Fuels and High Altitude Engine Research (CIFER), Denver, Colorado. The DDC Series 60 engine chosen for this testing is a modern four stroke engine with 1991 calibration. The hardware is typical of current on-road engine technology and has been extensively used for emission studies. The impact of various fuel compositions on emissions from the Series 60 is well established. The 1991 Series 60 is also the engine specified by the California Air Resources Board for California diesel fuel certification.

Methods

EPA regulated emissions, oxides of nitrogen (NOx), total hydrocarbons (THC), carbon monoxide (CO), and particulate matter (PM) were recorded for five blends using CFR 40 transient testing procedures. Variables such as air and fuel temperature and relative humidity were carefully monitored and controlled. CIFER performed 1 hot and 3 cold transient tests for 0, 20, 35, 65, and 100 percent blends of biodiesel. SwRI performed 4 hot transient tests for 0 and 20 percent blends of biodiesel. All testing was performed against the reference diesel map. Although this does not conform with the Code of Federal Regulations which requires a separate map for each fuel for engine certification purposes, this has become an accepted way to examine the effect of fuel properties on emissions by the EPA and state agencies like CARB (CIFER, 1994).

Reference Number 2 diesel fuel was secured from Colorado Petroleum, Inc (CIFER) and Phillips Petroleum Company (SwRI). The biodiesel was secured from Midwest Biofuels. The chemical composition of the base fuels can be found in Table 1. The cetane numbers reported by CIFER in Table 1 for the biodiesel blends were measured by Core Laboratories in Houston, Texas.

Other CIFER fuel analyses were conducted by Hauser Laboratories, Boulder, Colorado. Hauser determined the oxygen content directly using oxidative coulometry. The oxygen content of the blends, however, were determined by extrapolation which was based on the oxygen content of the base fuels (diesel fuel and biodiesel) and the known weight percent of each stock in a given blend (CIFER, 1995). CIFER did not analyze the 100% neat biodiesel. Rather, they relied upon an analysis of the fuel made by Proctor and Gamble, the manufacturer of the biodiesel. SwRI analyzed the blends for their testing at SwRI.

The fuels were blended volummetrically by weight to 20%, 35%, and 65% levels at each research facility. For example, a B20 blend represents 20 percent biodiesel and 80 percent petroleum diesel on a volume per volume basis.

At each change of fuel, the fuel filter was changed and the fuel lines were drained. The engine was warmed up on the new fuel to purge any of the remaining previous test fuel from the engine's fuel system. The engine was then torque-mapped and prepared for transient testing. Although a torque-map was run at each fuel change to evaluate engine performance, all testing was run using a transient cycle generated from the first torque-map conducted using the base 2-D fuel on the first day of testing. This was done to minimize day-to-day variability and allow for better comparison between test fuels.

The engine tested was a 1991 DDC Series 60, four-stroke, turbocharged, six-cylinder engine of in-line configuration. The test engine was a 12.7 liter, directed injected engine capable of producing 370 horsepower at 1800 rpm. Peak torque was 1450 lb-ft at 1200 rpm. The engine electronic control system was a standard DDEC II electronic control module used with the Series 60 engine.

Results

Because of the greater energy density of petroleum diesel fuel, the engine is capable of generating both the greatest torque and greatest horsepower while fueled with reference diesel at wide open throttle. As such, running the blends using a different torque-map would reduce the researcher’s ability to make equal (as is possible) comparisons between blends. The candidate fuel is not able to generate the same power at wide open throttle as the reference diesel fuel, but all intermediate load set points were met. As noted in Table 2, small differences in power produced per horsepower-hour were noted with B35 and lower blends. Blends greater than 65 percent biodiesel, due to the energy differences previously noted, were unable to produce the same level of power as petroleum diesel.

Table 2. Series 60 power observations in horsepower-hour for biodiesel blend research

conducted at Southwest Research Institute and the Colorado Institute for Fuels and High Altitude Engine Research.

Lab	DF	B20	B35	B65	B100
SwRI	25	25.1	-	-	-
% Change	N/A	+0.4			
CIFER	22.29	22.35	22.23	22.13	21.94
% Change	N/A	+0.3	-0.3	-0.71	-1.57

The engine exhaust emissions analyzers were calibrated using the same set of span gases during the test programs. The results of the testing are in general agreement with biodiesel studies that have been conducted on other two and four stroke diesel engines. As the biodiesel blend concentration increased, the oxides of nitrogen (NOx) emissions increased, while the total hydrocarbons (THC), carbon monoxide (CO) and particulate matter (PM) decreased. Each targeted EPA emission (NOx, THC, CO, & PM) are discussed and compared independently in the text that follows.

The Series 60 engine at SwRI produced higher THC when fueled on B20 at SwRI when compared to B20 fueling at CIFER. Two of the hot runs, however, were significantly different from the other two test runs. Careful review of the raw data found in the final report clearly substantiates this premise. A value of .149 and .1 were observed on the first day of testing as compared to values of .08 and .075 on the second day of testing. Averages computed for the second day of testing parallel the data reported by CIFER. The data reported by CIFER more closely follows the data that has been reported in the literature (Schumacher, et al., 1992, Borgelt, et al., 1994). (Table 3)

The trends observed concerning CO when testing the Series 60 engine clearly indicate that as the level of biodiesel in the blend increases, that CO levels emitted by the engine decline. The data recorded at both labs were quite similar concerning this EPA targeted emissions variable. As noted in Table 4, CO reductions ranged from approximately 7 - 40 percent when fueling with biodiesel and biodiesel blends. These observations are based on data reported in Table 4.

Table 3. Series 60 Total Hydrocarbon engine exhaust emissions for biodiesel blend research conducted at Southwest Research Institute and the Colorado Institute for

Fuels and High Altitude Engine Research. (Note: units are in grams per brake horsepower-hour)

Lab	DF	B20	B35	B65	B100
SwRI (hot only)	0.077	0.095	-	-	-
% Change	N/A	+23.4			
CIFER (hot only)	0.154	0.130	0.139	0.110	0.085
CIFER (composite)	0.164	0.143	0.148	0.120	0.092
% Change (composite)	N/A	-12.8	-10.4	-26.8	-43.9

Table 4. Series 60 Carbon Monoxide engine exhaust emissions for biodiesel blend research conducted at Southwest Research Institute and the Colorado Institute for Fuels and High Altitude Engine Research. (Note: units are in grams per brake horsepower-hour)

Lab	DF	B20	B35	B65	B100
SwRI (hot only)	2.258	2.052	-	-	-
% Change	N/A	-9.1			
CIFER (hot only)	4.270	3.868	3.477	3.005	2.242
CIFER (composite)	4.458	4.141	3.668	3.178	2.633
% Change (composite)	N/A	-7.1	-17.7	-28.7	-40.9

Oxides of nitrogen emissions followed that which is reported in the literature. B20 and B35 blends were not significantly different from baseline diesel, but were approximately one percent higher than the baseline diesel. Blends greater than B35, however were statistically different from baseline diesel and would require engine and/or fuel modifications to meet EPA regulations. As noted in Table 5, the increase in NOx ranged from 1 to 11.5 percent, depending on the blend that was tested.

Table 5. Series 60 Oxides of Nitrogen engine exhaust emissions for biodiesel blend research conducted at Southwest Research Institute and the Colorado Institute for Fuels and High Altitude Engine Research. (Note: units are in grams per brake

horsepower-hour).

Lab	DF	B20	B35	B65	B100
SwRI (hot only)	4.679	4.626	-	-	-
% Change	N/A	-1.1			
CIFER (hot only)	4.577	4.629	4.625	4.789	5.106
CIFER (composite)	4.635	4.688	4.680	4.848	5.166
% Change (composite)	N/A	+1.1	+1.0	+4.6	+11.5

Reductions in PM were substantial when testing an unmodified Series 60 engine. As noted in Table 6, fueling with a B20 blend produced a 9 - 19 percent reduction in PM, depending on which lab did the testing. The 19 percent reduction reported by CIFER has been observed in the literature. The 60 percent reduction noted, although extremely good, is not commonly reported in the literature. The testing at the higher blend levels in the Series 60 must be replicated to substantiate these data. These comments are based on the data reported in Table 6.

Table 6. Series 60 Particulate Matter engine exhaust emissions for biodiesel blend research conducted at Southwest Research Institute and the Colorado Institute for Fuels and High Altitude Engine Research. (Note: units are in grams per brake horsepower-hour).

Lab	DF	B20	B35	B65	B100
SwRI (hot only)	.220	.200	-	-	-
% Change	N/A	-9.1			
CIFER (hot only)	0.295	0.248	0.216	0.158	0.098
CIFER (composite)	0.322	0.259	0.222	0.165	0.102
% Change (composite)	N/A	-19.6	-31.1	-48.8	-68.3

One of two major differences observed in the chemical make-up of biodiesel and biodiesel blends is that oxygen is present in the fuel. The oxygen noted in the blends ranged from 2.4 to 7.2 percent by weight. The addition of oxygen to diesel fuel is believed to be responsible for the reductions in the solid portion of PM.

The second of two major differences concerning the chemical make-up of biodiesel and biodiesel blends is the cetane value of the fuel. Since the chemical make-up of biodiesel and biodiesel blends differs from petroleum diesel fuel, the cetane index is not appropriate to calculate the cetane number of the fuel. Rather, a cetane engine must be used to determine the cetane number of the fuel. Both SwRI and CIFER used a cetane engine to calculate the cetane number of the fuel. As noted in Table 7, the addition of biodiesel to the baseline diesel consistently improved the cetane value of the fuel.

Table 7. Oxygen content and cetane numbers for diesel, biodiesel, and biodiesel blends used to fuel Series 60 engines during engine testing conducted by Southwest Research Institute and the Colorado Institute for Fuels and High Altitude Engine Research.

Item	DF	B20	B35	B65	B100
% Oxygen (SwRI)	0.0	2.2	-	-	-
% Oxygen (CIFER)	0.21	2.4	4.0	7.2	11.1
Cetane (SwRI)	45.8	48.1			
Cetane (CIFER)	46.2	50.2	52.2	54.5	56.4

Summary and Conclusions

As noted previously, the results of the testing are in general agreement with biodiesel studies that have been conducted on other two and four stroke diesel engines. Specifically, as the biodiesel blend concentration increased, the oxides of Nitrogen (NOx) emissions increased, while the total hydrocarbons (THC), carbon monoxide (CO) and particulate matter (PM) decreased. The neat biodiesel exceeded the 1991-1994 NOx emission standard of 5 grams per brake horsepower-hour, however the 1994 PM standard was met using the neat fuel. In general, the amount of PM reductions noted were proportional to the total weight percent of oxygen present in the fuel. CO showed a similar relationship with varying oxygen content.

The increase in THC that were observed within the SwRI data may be an anomaly within the data. The data observed while testing the same engine one month earlier using a high sulfur, high aromatic fuel followed the trends reported by CIFER. In this study Callahan, (1993) reported a 7% reduction in THC when fueling with B20.

An analysis of the PM revealed that the reduction was entirely due to a reduction in insolubles that are primarily composed off carbon soot. However, one should note that a slight increase in the soluble organic fraction of the PM was observed.

Although power remained consistent with the lower level blends (B35 or lower), the pounds of fuel used per brake horsepower-hr increased as the concentration of biodiesel increased. Fueling with B20 increased fuel consumption by 1.3%, B35 by 2.3%, B65 by 7.1%, and B100 by 12.7%. When one compares this data with that reported in the literature, this increase in fuel consumption was normal and expected. Engine efficiency (not to be confused with fuel efficiency) was found to be the same for biodiesel and biodiesel blends as for the reference fuel. Fuel consumption for biodiesel blends should therefore be able to be calculated from diesel fuel economy data based on these findings.

The researchers reported that future research should focus on activities that allow one to better understand the relationship between fuel composition and emissions in the Series 60 engine. The aromatic content and the cetane number of the fuel should receive further testing. Fuels that have been oxygenated by different oxygenates should be tested and compared with biodiesel blends. The pursuit of these efforts will help develop a deeper understanding of how the diesel engine might best utilize the chemical properties of biodiesel and biodiesel blends.

Table 1. Fuel properties of diesel, biodiesel, and biodiesel blends as reported by the Colorado Institute for Fuels and High Altitude Engine Research and Southwest Research Institute when testing a Series 60 Detroit Diesel engine.

Fuel Variable	DF- SwRI	DF-CIFER	B20 - SwRI	B100- SwRI
Carbon, WT%	N/A	86.64	N/A	76.5
Hydrogen	N/A	12.80	N/A	12.5
Oxygen	N/A	0.21	2.2	11.0
Nitrogen	N/A	0.11	N/A	N/A
Sulfur	0.032	0.032	0.024	0.003
Saturates, Vol %	56.0	64.4	N/A	N/A
Olefins	8.3	1.3	N/A	N/A
Aromatics	35.7	34.3	N/A	N/A
API Gravity	35.7	35.6	34.2	28.0
IBP, F	367	387	373	606
IBP, 10%	429	429	433	626
IBP, 50%	507	527	533	638
IBP, 90%	598	632	627	650
EBP, 100%	638	677	647	664
Flash Point, F	172	N/A	177	307
Viscosity, CST, @ 40 C	2.59	N/A	2.83	4.11
Cetane number	45.8	46.2	48.1	N/A

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