FUELING DIRECT INJECTED DIESEL ENGINES WITH 2% BIODIESEL BLEND

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ABSTRACT. *The Agricultural Engineering Department at the University of Missouri−Columbia has monitored the fueling of a 1996 Dodge pickup truck equipped with a 5.9−L (360−in.^{3}) Cummins engine with a 2% blend of methyl−ester soybean oil (soydiesel/biodiesel) and petroleum diesel fuel (B2) for more than 65,352 km (40,608 miles). The pickup averaged 7.91 km/L (18.61 mile/gal). Analysis of engine lubrication oil suggested that the engine was wearing at a normal rate. Exhaust emissions were measured at Iowa State University. The black exhaust smoke normally observed when a diesel engine accelerates was reduced each time the engine was fueled with B2, but CO, HC, and NO_x were not affected.*

Keywords. *Biofuels, Biodiesel, Methyl−Ester, Horsepower, Exhaust Emissions, Transesterification.*

Previous research conducted with diesel engines during the early 1990s in Idaho and Missouri has indicated that diesel engines can be fueled with neat biodiesel fuel and with blends of biodiesel and petroleum diesel fuel (Schumacher et al., 1991; Peterson et al., 1995). However, little research has been conducted using low−level blends of biodiesel and petroleum diesel fuel. This work was a preliminary investigation with the objective of determining the effect of a 2% blend (B2) on engine exhaust emissions and engine oil analysis. A secondary objective was to determine if these quantities would differ after a full year of operation.

This study was intended to identify any serious drawbacks or problems associated with the use of low−level blends of biodiesel and petroleum diesel fuel. It will be followed by a more detailed evaluation of the specific fuel system components that are likely to be affected by biodiesel fueling.

MATERIALS AND METHODS

A 1996 Dodge pickup equipped with a direct−injected turbocharged 5.9−L (360−in.^{3}) diesel engine was the vehicle used in these tests. Specifically, the engine was a 6BTAA, 134−kW (180−hp), Cummins diesel engine. The pickup engine was initially fueled with diesel fuel by the Michigan Soybean Promotion Committee (MSPC). Fueling with a 2% blend of methyl−ester of soybean oil (soydiesel/biodiesel) and 98% petroleum diesel fuel (B2) began after 64,898 km (40,326 miles) of operation. Results of the fuel analysis for the biodiesel and the reference diesel fuel used for emissions testing at Iowa State University are presented in table A1. Three laboratories assisted with the fuel analysis. System Lab Services of Kansas City, Kansas, analyzed the Philips 66 low sulphur certification fuel according to ASTM D975 (ASTM, 1984). NOPEC Corporation of Lakeland, Florida, analyzed the 100% neat biodiesel using guidelines that were used when developing ASTM D6751 [ASTM, 2001 (formerly ASTM PS 121, 1999)], and Cleveland Technical Center (Kansas City, Kans.) analyzed the B2. The data provided for B2 is based on a composite sample of fuel collected from the vehicle at various times throughout the test period. The fuel samples were mixed together so that the fuel analysis would represent the "average" fuel that was used to fuel the engine.

The engine was not modified for use with B2. Polyurethane ester grade tubing and a shut−off valve were installed in the return fuel line. This allowed MSPC personnel to sample fuel that was in the vehicle fuel system without siphoning or pumping fuel directly from the on−board fuel tank.

The pickup engine lubricating oil (Quaker State 15W−40) was changed at approximately 4800−km (3000−mile) intervals. Engine lubricating oil was sampled at 1600−km (1000−mile) intervals and analyzed by Cleveland Technical Center using standard ASTM test procedures for glycol, perchloric base number, oxidative stability, water and sediment, and viscosity tests. Cleveland Technical Center used bispectral analysis to identifying additives, contaminants, and wear metals in the oil. A computer−generated report provided a breakdown of wear metals, contaminants, water and sediment, glycols, oil additives, perchloric base number, soot, oxidative stability, and nitrogen. The levels of wear metals from the 1998 Dodge were compared with oil samples drawn from engines that had been fueled with 100% diesel fuel engines that had been fueled with 100% biodiesel using Microsoft Excel 2000 statistical procedure ANOVA (α = 0.05). Statistical t−tests were subsequently used to determine statistical differences between means (α = 0.05).

Engine exhaust emission tests were conducted at Iowa State University using a Clayton roll−type chassis dynamometer equipped with 200−mm (8−in.) rolls. The engine was

Article was submitted for review in June 2002; approved for publication by the Power & Machinery Division of ASAE in May 2004. Presented at the 1998 ASAE Annual Meeting as Paper No. 986084.

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tested using four test cycles: the Arterial Bus Cycle, the Central Business District Test Cycle (CBD), the Urban Driving Dynamometer Schedule (UDDS), and a 64−km/h (40−mph) steady state condition.

Each test cycle is designed to replicate conditions encountered under specific operating conditions. The UDDS is designed to test light duty cars and trucks. This test is by far the most difficult to conduct, as the vehicle is accelerated over a predetermined time and power sequence with speeds approaching 97 km/h (60 mph). The CBD test cycle was designed to test city buses. The CBD accelerates the vehicle quickly to 32 km/h (20 mph) and then decelerates to 0. This procedure is repeated every 30 s. This cycle repeats 20 times (10 min.) after which time the emissions profile is calculated. The Arterial Bus Cycle rapidly accelerates the vehicle to 64.4 km/h (40 mph). This speed is maintained for 25 s, then the vehicle is de−accelerated to 0 mph, for a 10−s idle period. This procedure is repeated four times for a duration of 370 s. This steady state test involved maintaining a speed of 64 km/h (40 mile/h) until engine power, speed, and operating temperatures have stabilized. Exhaust emissions readings were recorded during this “stable period.”

The vehicle test cell at Iowa State University was capable of conducting the Environmental Protection Agency (EPA) UDDS transient test cycle, but emission measurements approximated the EPA procedure due to the fact that a constant volume exhaust sampling system was not available. The pollutant flow rates were calculated using instantaneous exhaust concentration measurements and instantaneous engine air flow rate measurements. These pollutant flow rates were integrated over the cycle and then divided by the total distance traveled during the cycle to obtain g/km emissions data.

Results and Discussion

Fuel efficiency fluctuated depending on how the pickup was operated. The overall fuel economy was 8.2 km/L (18.6 mile/gal). Comparisons between fueling logs made prior to B2 fueling and after B2 fueling revealed that B2 fuel efficiency was similar to that obtained when the engine was fueled with diesel fuel.

Mixing only 2% biodiesel with the petroleum diesel fuel had no effect on cold weather operation. Under normal conditions, neat biodiesel will gel at 0°C (32°F). The MSPC personnel noted no gelling problems. This was to be expected as an analysis of the B2 revealed a pour point of −36°C (−34°F).

Table 1 presents an abbreviated version of the engine oil analysis data. These data were compared with engine lubricating oil samples taken from diesel−powered farm tractor engines in 1991, a 1991 Dodge ¾−ton pickup and a 1992 ¾−ton Dodge pickup fueled on 100% biodiesel (Schumacher et al., 1991). These data were compared to normal levels of diesel engine lubricating oil wear metals data developed by the Minnesota Valley Testing Laboratory. The engine oil samples taken from tractors that had greater than 90 h of use were excluded from this analysis. These samples were excluded since none of the pickup oil samples that were pulled from the pickups had been used in excess of 90 h.

Table 1. Anova P−Values and statistical differences for wear metals found in used engine−lubricating oil grouped by tractor and pickup. (t−test, α = 0.05).

Wear Metal		N	Mean (ppm)	Standard Deviation (ppm)	F−Value Probability	Statistical Differences
Iron	(D) [a]	46	44.26	26.44	0.0001	D≠B100, D≠B2
	(B100)	40	7.57	8.03		
	(B2)	36	9.08	2.80		
	(M)		10−40			
Lead	(D)	46	9.09	8.12	0.0001	D≠B100, D≠B2
	(B100)	40	1.37	2.78		
	(B2)	36	1.11	0.89		
	(M)		1−12			
Copper	(D)	46	10.22	34.42	0.2428	
	(B100)	40	2.00	2.14		
	(B2)	36	6.41	5.46		
	(M)		3−15			
Chromium	(D)	46	3.28	4.20	0.0003	D≠B100, D≠B2
	(B100)	40	2.80	5.86		
	(B2)	36	0.48	0.49		
	(M)		0.5−8			
Silicon	(D)	46	4.91	2.81	0.0003	D≠B100
	(B100)	40	1.75	1.70		
	(B2)	36	4.44	3.93		
	(M)		0−12			

[a] D = oil samples from farm tractors, operated on 100% diesel fuel.
B100 = oil samples from 1991 and 1992 Dodge pickups, operated on 100% biodiesel.
B2 = oil samples from 1994 Dodge (Michigan) pickup, operated on 2% biodiesel.
M = rule of thumb averages developed by Minnesota Valley Testing Laboratories.
N = number of samples analyzed.

A review of these analyses showed no indication of abnormal wear. The levels of chromium, copper, silicon, and iron were either below or the same as expected when fueled on diesel fuel. It was interesting to note that statistically different (α = 0.05), levels of lead, chromium, and iron were noted for B2 fueled engines as compared to diesel engines that were fueled on 100% diesel fuel. In all cases, the levels of wear metals (ppm) for B2 fueled engines were slightly lower than when the diesel−fueled engines (tractors) were fueled with petroleum diesel fuel.

The 1996 Dodge pickup had 64,898 km (40,326 miles) when the first (pre) emissions and performance tests were conducted. The second (post) emissions and performance test was conducted after the engine had logged 63,820 km (39,656 mile) on B2. This information is presented in table 2.

An Arterial Bus Cycle, the Central Business District Test Cycle, and the Urban Driving Dynamometer Schedule transient chassis dynamometer tests and the steady state dynamometer tests were conducted by the Department of Mechanical Engineering at Iowa State University. Each of the numbers listed is a composite average of a cold−start test and a hot start test, except for the steady state test, which was conducted after the engine was fully warmed. The hot start measurement used for the transient tests was the average of three or four separate tests. The diesel fuel used was EPA emissions certification fuel and the B2 fuel was a 2% blend of biodiesel and the certification fuel.

The carbon monoxide (CO) measurement indicates very little change as the fuel was switched from diesel fuel to B2. There were significant differences between the CO levels measured between the two test dates. The CO levels measured at the second test date are 15% to 40% lower than the first date. While these changes could be due to changes in the engine emissions, it should also be noted that a different CO measurement instrument was used for the two tests. Part of the difference may be due to differences in the instrument response.

The oxides of nitrogen (NOx) emissions did not appear to be significantly affected by switching from diesel fuel to B2. The NOx increased slightly for some tests when B2 was used and decreased for others. Again, there are some differences between the data collected on the two test dates, although the differences are smaller than observed with CO. The NOx data were corrected for humidity, but the differences in ambient conditions on the two test days may have contributed to the variation in the data.

The hydrocarbons emissions (HC) data taken during the first test appear to show a small but consistent reduction in HC when the engine was operated on B2. All four test cycles show this behavior. However, during the second test period, three of the four test cycles showed a small increase in HC when operated on B2. We have concluded that the changes in HC are due to measurement variation.

The data shown for soot emissions was collected by measuring the exhaust smoke level using an opacity meter and then converting the percent opacity levels to instantaneous exhaust soot levels. These instantaneous soot levels were converted to soot flow rates using the measured intake air flow rate and then integrated to give the total emitted for the cycle. The soot emissions measurement is strongly influenced by the rate of acceleration of the vehicle and therefore is more prone to test variation than the other emission quantities. There was a consistent reduction of the measured soot emissions when the engine was operated on B2. The low level of biodiesel used makes it difficult to understand why the soot would decrease by the amounts shown. However, the consistency and size of the reduction indicate that further testing in this area would be justified.

Conclusions

Although the findings from the vehicle were far from conclusive, the results from this study were positive concerning the use of B2 as a fuel for diesel engines. The following conclusions were drawn from the investigation:

- The amount of wear metals for iron, chromium, and lead noted in the engine lubricating oil samples were significantly different when compared to an engine fueled with petroleum diesel fuel.
- Regardless of which emissions test procedure that was used the level of soot (black smoke) and carbon monoxide was reduced when the engine was fueled with B2 as compared to petroleum diesel fuel.

Recommendations

The findings from this investigation cannot be considered conclusive, because the study was very limited in scope. Interpretations made from the data must be done with caution.

Table 2. Hot start engine exhaust emissions produced by a 1996, 5.9−L turbocharged, intercooled, direct injected Cummins diesel engine using four chassis dynamometer testing procedures.[a]

Arterial Bus Cycle−Hot Start Data								
Date	05/20	02/25	05/20	02/25	05/20	02/25	05/20	02/25
Fuel	CO		NOx		HC		Soot	
D[b]	0.893	0.653	2.965	3.641	5.468	3.41	0.254	0.186
B2[c]	0.935	0.566	2.906	3.624	4.309	3.554	0.196	0.144
Central Business District Cycle− Hot Start Data								
Date	05/20	02/25	05/20	02/25	05/20	02/25	05/20	02/25
Fuel	CO		NOx		HC		Soot	
D	1.393	0.947	4.38	5.584	6.826	4.595	0.782	0.452
B2	1.37	0.958	5.106	5.699	5.953	4.702	0.578	0.313
Urban Dynamometer Driving Schedule−Hot Start Data								
Date	05/20	02/25	05/20	02/25	05/20	02/25	05/20	02/25
Fuel	CO		NOx		HC		Soot	
D	1.427	0.706	3.222	4.382	6.736	3.989	1.53	0.241
B2	1.24	0.639	3.81	4.278	5.884	3.861	1.304	[d]
Steady State−Hot Start Data								
Date	05/20	02/25	05/20	02/25	05/20	02/25	05/20	02/25
Fuel	CO		NOx		HC		Soot	
D	0.611	0.496	1.867	2.14	2.533	2.299	0.299	0.447
B2	0.599	0.461	1.888	2.232	2.502	2.405	0.257	0.239

[a] All units are expressed as g/km.
[b] D = emissions tests conducted using 100% low sulphur diesel fuel.
[c] B2 = emissions tests when the pickup truck engine was operated on 2% biodiesel.
[d] Data not available due to equipment failure.

Based on these observations and the conclusions that were drawn, the following recommendations were made:

- Due to the fact that this study logged data on only one engine, an experimental research design should be determined that will quantify the amount of wear metals found in engine lubricating oil samples for comparison of engines fueled with B2 and petroleum diesel fuel.
- This experimental research design should be used to evaluate the performance of several engine families and designs.
- Additional engine exhaust emissions testing should be conducted with different engines to determine if the lower levels of soot (black smoke) and carbon monoxide that were noted can be generalized to other types of diesel engines.

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APPENDIX A. FUEL PROPERTIES

Table A1. Fuel analysis of Biodiesel, #2 diesel fuel, and B2 used to test the 1996 Cummins Engine Company 6BTAA, 134−kW (180−hp), automotive rated engine for exhaust emissions.

		Fuel[a]		
Fuel Property	ASTM Test Procedure[b]	Biodiesel	Low Sulfur Reference Diesel	B2 Blend
Gross heat value	D2382	N/T	N/T	38,546 kJ/L
Color	D1500	N/T	L 1.5	N/T
Corrosion	D130	1A	1A	1A
Cloud point	D2500	0°C	−15°C	−17°C
Pour point	D97	−3°C	−23°C	−36°C
Flash point	D92	141°C	75°C	63°C
Viscosity	D445	4.8 cS@40°C	2.791cS@40°C	N/T
Sulphur	D129	0.01%	0.0257%	N/T
Carbon residue	D524	N/T	0.13	N/T
Carbon residue	D4530	0.03%	N/T	N/T
Cetane index	D976	N/T	47.7	47.8
Ash	D482	0.001%	N/T	N/T
Free glycerine	G.C.	0.033%	N/Ap.	N/Ap.
Total glycerine	G.C.	0.295%	N/Ap.	N/Ap.
Acid number	D664	0.25 mg KOH/g	N/T	N/T
Water and sediment	1796/4807	0.0%	N/T	N/T
Distillation				
IBP		N/T	176°C	175°C
10		N/T	225°C	214°C
20		N/T	236°C	N/T
50		N/T	261°C	264°C
90		N/T	313°C	315°C
End		N/T	338°C	335°C

[a] N/T = not tested.
N/Ap. = not applicable.
[b] G.C. = gas chromatograph.