PROJECT UPDATE: FUELING 5.9L CUMMINS ENGINES WITH 100% BIODIESEL

Leon. G. Schumacher

Steven C. Borgelt

William G. Hires

Mark D. Russell

University of Missouri-Columbia

Columbia, MO 65211

and

Juergen G. Krahl, Ph. D., wissenschaftlicher Mitarbeiter

Institut of Biosystems Engineering, Federal Agricultural Research Centre

Braunschweig, Germany D-38116

Abstract

The Agricultural Engineering Department at the University of Missouri-Columbia has fueled a 1991 and a 1992 Dodge pickup Cummins engine with 100 % methyl-ester soybean oil (biodiesel) for more than 172,545 km (107,215 mile). The 1991 pickup has been driven 89,888 km (55,854 mile) and the 1992 pickup has been driven approximately 82,658 km (51,361 mile). Fueling the 5.9 L (360 in3) engines with 100% biodiesel initially increased engine power by 3% (1991 engine) and reduced power by 7% (1992 engine). However, both pickups produced less power while fueled on biodiesel during the latest series of chassis dynamometer testing. The pickups averaged 6.9 km/L (16.6 mile/gal). Analysis of engine lubrication oil showed that the engines were wearing at a normal rate. Black exhaust smoke normally observed when a diesel engine accelerates was reduced when the diesel engine was fueled with 100% biodiesel. Increased EPA exhaust emissions requirements for diesel engines have created much interest in the use of biodiesel as a fuel for diesel engines.

Introduction

Much of the biodiesel research conducted within the United States since 1990 has used a blend of biodiesel and petroleum diesel fuel. The National Biodiesel Board has proactively researched the environmental and performance effects of fueling compression ignition engines with a 20 % blend (BD20). A small number of engines have been fueled with 100% biodiesel (BD100) (Peterson et al., 1994; National Biodiesel Board, 1995), a fuel that is biodegradable, lower in toxicity than fossil fuels, and a renewable agricultural commodity. Although the University of Idaho is fueling two 5.9L engines with BD100, very little analysis of engine wear and exhaust emissions have been conducted on over-the-road (OTR) vehicles fueled with BD100. This research provides much needed information for niche markets (such as the fueling of marine vessels on pristine waters) that will benefit by the fueling of compression ignition engines with BD100

Related Literature

Ziejewski et al. (1984), Reece et al. (1993), Scholl et al. (1993), and Schumacher et al. (1992, 1993) reported reductions in smoke density when fueling with biodiesel or biodiesel as compared to #2 diesel. Reece et al. (1993) also noted reductions in smoke density when fueling with a 20% biodiesel/80% #2 diesel blend. Ziejewski fueled with sunflower derived biodiesel and Reece fueled with rapeseed derived biodiesel. Scholl and Schumacher used soybean derived biodiesel. Srinivasa et al. (1991), however, noted increases in smoke density when fueling with karanja based biodiesel.

Marshall (1993), Schumacher et al. (1992), Mittelbach et al. (1985), Mittelbach et al. (1988), and Scholl and Sorenson (1993) noted reductions in hydrocarbons and carbon monoxide. Schumacher and Scholl and Sorenson fueled with soybean derived biodiesel. Mittelbach fueled with rapeseed derived biodiesel in 1985, but used waste cooking oil during the 1988 investigation. Marshall used animal derived fats as his source of biodiesel. Niehaus (1985), however, noted increases in carbon monoxide and hydrocarbon exhaust emissions. Niehaus also noted decreases in oxides of nitrogen exhaust emissions.

Ziejewski et al. (1984), Niehaus et al. (1985), Schumacher et al. (1992), Reece and Peterson (1993), and Marshall (1993) observed reductions in power ranging from one to seven percent. Schumacher observed increased power (3%) using a 1991 Cummins 5.9L DI turbocharged engine. Increased power was observed by Feldman and Peterson (1992) during a 200 hour EMA test using a 3 cylinder, DI, naturally aspirated diesel engine with the injection timing advanced 2 degrees.

The review of these data and a study conducted by Krahl et al. (1994) suggest that trends in engine exhaust emissions and performance exist when the engine is fueled on 100 % biodiesel. Shifting the timing as performed by Feldman and Peterson appears to be an appropriate and acceptable method that should be used to optimize the compression ignition engine for biodiesel fueling.

Purpose and Objectives

The purpose of this investigation was to determine the effects of fueling a diesel engine with 100% biodiesel as compared to fueling the engine with petroleum diesel fuel. Specific objectives that were investigated included: fuel efficiency, engine wear, power, and exhaust emission levels.

Materials and Methods

A 1991 and a 1992 Dodge pickup equipped with Cummins, six-cylinder, direct injected turbocharged, 5.9 L (360 in3) diesel engines were the OTR vehicles used in these tests. The engines were fueled with diesel fuel during the first months of operation. Fueling with biodiesel began after 4,827 km (3,000 mile) of operation for the 1991 pickup and after 2,413.5 km (1,500 mile) of operation for the 1992 pickup. Note the fuel analysis below.

Table 1. Fuel properties of Biodiesel and Reference Diesel fuel.

Fuel Property	ASTM Test Procedure	Fuel Biodiesel Low Sulfur Reference Diesel	
Density g/L	D1298	0.86-0.90	0.8466
Gross Heat Value MJ/Kg	D2382	37.2	42.4
Cloud Point 0C	D2500	3.3C (38o F) Max.	-14C (+60F)
Pour Point oC	D97	-2.2C (28 F) Max.	-23C (-100F)
Flash Point oC	D92	149C (300 F) Min.	67C (1520F)
Viscosity @ 40oC	D445	4.00-5.50Cst	2.7Cst
Sulfur	D129	0.02% Max.	0.033%
Carbon Residue	D524	0.1% Max	86.8%
Cetane Number	D613	48 Min.	46.7
Ash	D482	0.02% Max.	N/T

Free Glycerine	G.C.	0.03% Max	N/Ap.
Total Glycerine	G.C.	0.2% Max	N/Ap.
% Ester	G.C.	97.5% Min	N/Ap.
Distillation in 0C		264 (5080F)	187 (3690F)
IBP		327 (6220F)	213 (4160F)
5		331 (6280F)	222 (4310F)
10		N/T	233 (4510F)
20		335 (6360F)	244 (4710F)
30		337 (6380F)	264 (5070F)
50		340 (6440F)	285 (5450F)
70		N/T	298 (5680F)
80		343 (6500F)	314 (5970F)
90		350 (6620F)	328 (6220F)
95		351 (6640F)	338 (6400F)
End			

N/T = Not tested, **N/Ap** = Not applicable, **G.C.** = Gas Chromatograph

Power determinations were made using a Super Flow Corporation model SF-601 chassis dynamometer. The engine was tested for power at 1700, 1900, 2100, 2300, 2500, and 2700 rpm. The chassis dynamometer was used to load the engine to peak pound foot ratings as determined by Cummins Engine Company. The pickup was operated for six minutes at each rpm. The load was then reduced by the dynamometer operator, allowing the engine to accelerate to the next rpm interval as designated by the SAE power test procedures.

Initially, the 1991 pickup engine lubricating oil (15w-40) and the engine lubricating oil filter were changed at approximately 4,023 km (2,500 mile) intervals. Engine lubricating oil was sampled at 805 km (500 mile) intervals and analyzed by MFA Oil Inc. laboratories. Analysis showed no indication of lube oil dilution, therefore, oil sampling interval and the oil change interval were subsequently lengthened to 1,609 km (1,000 mile) and 4,827 km (3,000 mile) respectively. The 1992 pickup engine lubricating oil sampling procedures and change intervals have been maintained at 1,609 km (1,000 mile) and 4,827 km (3,000 mile) intervals.

The biodiesel analysis was conducted by Cleveland Technical Center, Kansas City, MO for Interchem Environmental, Inc. The low sulfur diesel fuel was analyzed by Phillips Chemical Company.

Internal parts of the engine were visually examined using a boroscope on three separate occasions by MU technicians. MFA technicians used an atomic absorption spectrophotometer to analyze the lubricating oil samples for wear metal content.

The engines were not modified. Fuel storage and fuel delivery systems were modified. An aftermarket fuel tank was installed for biodiesel fueling. An electric fuel valve (and switch) was installed to permit the operator to switch between biodiesel and petroleum diesel fuel. Stainless steel heat exchangers were installed to warm the fuel during cold weather operation. Rubber based components in the original fuel lines and in the 1991 injection pump deteriorated when exposed to biodiesel. These components were replaced with either viton (fluorinated rubber), steel, aluminum, or nylon reinforced tubing.

Results and Discussion

Fuel efficiency during biodiesel fueling fluctuated, depending on how the pickup was operated. The overall fuel economy for the 1991 pickup was 7.0 km/L (16.9 mile/gal) and for the 1992 pickup was 6.8 km/L (16.3 mile/gal). The highway fuel economy while the vehicles were operating on 100% biodiesel as compared to diesel fuel was 9.5 km/L (22.8 mile/gal) vs 9.9 km/L (23.9 mile/gal). Biodiesel fuel economy was nearly identical to that obtained when the engine was fueled with diesel fuel under comparable conditions. These data are summarized in Table 2.

Table 2. Operational data of the 1991 and 1992 Dodge pickups equipped with Cummins 6BT & 6BTA, 5.9L, direct injected engines fueled with Biodiesel.

	1991	1992
Cummins Engine	6BT 5.9L	6BTA 5.9L
Fuel Economy Range	5.0-10.3 km/L (12-24.8 mile/gal)	3.7-9.5 km/L (8.9-23 mile/gal)
Total Pickup Travel Distance	89,888.0 km (55,854.0 mile)	82,658.0 km (51,361.0 mile)
Travel Distance on Biodiesel	85,060.0 km	80,243.5 km

	(52,854.0 mile)	(49,861.0 mile)
Engine Run Time	1524.8 h	1259.3 h
Total Fuel Consumption	10,450.4 L (2,760.7 gal)	9,562.3 L (2,526.1 gal)
Fuel Economy	7.0 km/L (16.9 mile/gal)	6.8 km/L (16.3 mile/gal)
Fuel Flow	7.2 L/h (1.9 gal/h)	8.3 L/h (2.2 gal/h)

The engine lubricating oil analyses indicated that engine wear was normal. The levels of chromium, copper, silicon, and iron were either below or the same as expected when fueled on diesel fuel. No abnormal coking was noted on the injectors, on top of the pistons, on cylinder walls or on the valve stems when the engine was visually examined using a boroscope. The engine did not appear to be wearing at an accelerated rate.

Table 3 presents the engine oil analysis. These data were compared with engine lubricating oil samples taken from diesel powered farm tractor engines (Schumacher et al., 1991). As noted by Schumacher et al. (1995), the analysis of the oil samples for the 1991 and 1992 5.9L engines was not statistically different. Data from the pickups were subsequently combined and analyzed to determine if differences existed between the pickup engines and farm tractor engines. The tractor engine oil samples that had greater than 113 h of use were excluded from this analysis. These samples were excluded since none of the pickup oil samples had been used in excess of 113 h. Note that the number of hours on the lubricating oil is not statistically different between groups. As noted by Schumacher in previous analysis, chromium and copper engine wear metals were not significantly different. Levels of iron, lead, and silicon were statistically different when compared to the oil samples that were taken from engines that had been fueled with diesel fuel.

Table 3. T-test analysis between engines grouped by tractor and pickup.

Wear metal		N	Mean (ppm)	StDev. (ppm)	t-value	t-prob.
Iron	(T)	62	39.40	26.47	8.24	0.000
	(P)	90	9.77	12.11		

Lead	(T)	62	10.10	10.47	5.84	0.000
	(P)	90	1.99	3.82		
Copper	(T)	62	9.44	29.98	1.29	0.200
	(P)	90	4.33	9.72		
Chromium	(T)	62	3.16	3.74	1.96	0.052
	(P)	90	1.90	4.12		
Silicon	(T)	62	4.82	2.79	8.42	0.000
	(P)	90	1.50	1.66		
Hours on oil	(T)	62	55.97	34.24	0.67	0.506
	(P)	90	52.52	26.47		

T) Oil samples from farm tractors, operated on 100% diesel fuel.

P) Oil samples from Dodge pickups, operated on 100% methyl-ester soybean oil.

The date and hours on each engine at the time of each chassis dynamometer test can be found in Tables 4 and 5. Power (kw and hp) comparison tests were measured at 1700, 1900, 2100, 2300, 2500, and 2700 rpm. The engines were loaded at peak torque rpm and then the load was reduced allowing the engine to increase speed (at 200 rpm intervals) until the engine reached 2700 rpm. Fueling the engines with BD100 initially increased engine power by 3% (1991 engine) and reduced power by 7% (1992 engine). Both pickups produced less power, however, during the January 1995 series of chassis dynamometer testing. This information is found in Tables 4 and 5.

Table 4. Power tests produced by a 1991 5.9 L turbocharged, direct injected, Cummins diesel engine.

Engine Speed Test (rpm) Date	Power #2 Diesel kw hp	Power Biodiesel kw hp	% Change from #2 Diesel
1700 A	87.9 118.0	93.2 125.0	+5.9
B	77.7 104.2	78.8 105.7	+1.4

C	96.2 129.1	95.2 127.7	-1.1
1900 A	96.9 130.0	102.2 137.0	+5.4
B	88.2 118.3	89.3 119.8	+1.3
C	103.4 138.6	104.7 140.4	+1.3
2100 A	106.6 143.0	110.4 148.0	+3.5
B	99.6 133.6	99.2 133.0	-0.4
C	113.4 152.1	110.5 148.2	-2.6
2300 A	114.1 153.0	116.3 156.0	+2.0
B	110.1 147.7	104.2 139.7	-5.4
C	121.9 163.5	116.3 156.0	-4.6
2500 A	114.8 154.0	120.1 161.0	+4.5
B	108.4 145.3	104.1 139.6	-3.9
C	121.9 163.5	120.0 160.9	-1.6
2700 A	56.7 76.0	55.2 74.0	-2.6
B	45.7 61.3	42.7 57.2	-6.7
C	74.2 99.5	68.4 91.7	-7.8

A) Dyno test on 5/29/92, 507 hours on engine.

B) Dyno test on 2/2/94, 1155 hours on engine.

C) Dyno test on 1/4/95, 1436 hours on engine.

Table 5. Power tests produced by a 1992, 5.9 L turbocharged. direct injected, aftercooled, Cummins diesel engine.

Engine Speed Test	Power #2 Diesel	Power Biodiesel	% Change from #2 Diesel

(rpm) Date	kw hp	kw hp	
1700 A	85.8 115.0	79.8 107.0	-7.0
B	66.1 88.7	56.5 75.9	-14.4
C	8.9 05.8	0.8 108.4	+2.5
1900 A	96.9 130.0	89.5 120.0	-7.7
B	81.1 108.8	71.0 95.2	-12.5
C	90.9 121.9	88.9 119.2	-2.2
2100 A	105.9 142.0	101.4 136.0	-4.2
B	90.1 120.8	74.0 99.2	-17.9
C	96.6 129.5	95.5 128.1	-1.1
2300 A	106.6 143.0	102.9 138.0	-3.5
B	97.9 120.8	83.9 112.5	-14.3
C	99.5 133.4	94.8 127.1	-4.7
2500 A	104.4 140.0	96.9 131.0	-7.1
B	95.7 131.3	82.2 110.2	-14.1
C	97.3 130.5	93.3 125.1	-4.1
2700 A	60.4 81.0	57.4 77.0	-4.9
B	44.3 59.4	44.3 59.4	0.0
C	50.5 67.7	48.5 65.0	-4.0

A) Dyno test on 5/29/92, 5 hours on engine.

B) Dyno test on 2/2/94, 790 hours on engine.

C) Dyno test on 1/10/95, 1145 hours on engine.

Exhaust emission levels were analyzed by MU personnel in conjunction with the most recent dynamometer testing. A Nova Model 7550P5B engine exhaust analyzer (calibrated using appropriate span gases) was used for this analysis. Variables tested include CO, CO2, HC, NOx, O2, and opacity. Several test values were recorded for each variable at each test point rpm. The values at each rpm were then averaged to determine an overall level for each variable during the test. These results, as well as the results from the emissions testing on February 2, 1994, are summarized in Tables 6 and 7.

The 1991 truck performed as expected. CO, CO2, and opacity were all reduced while NOx increased. The measured HC values for the January 1995 testing were unchanged. This was attributed to the emissions analyzer. Except for CO, the 1992 truck also performed as expected. CO2 emissions were similar to those noted previously in the literature. Opacity fluctuated significantly during the February 1994 testing. As noted in Table 7, this variance was believed to be a result of measurement error. The reduction in opacity noted during the January 1995 testing was similar to data reported in the literature. As with the 1991 truck, the measured HC values did not change. Oxides of NOx levels and CO levels for the 1992 truck increased. While the oxides of NOx increase was expected, the CO increase was not. The CO increase was quite small and was not significantly different.

Table 6. Exhaust emissions produced by a 1991 5.9L turbocharged, direct injected Cummins diesel engine (2/2/94 and 1/4/95) while fueled with 100 % biodiesel and 100 % low sulfur diesel fuel.

	2/2/94			1/5/95		
Variable	Diesel	BD20	%Change	Diesel	BD20	%Change
Carbon Monoxide %	0.025	0.013	-47.2%	0.029	0.022	-24.4%
Carbon Dioxide	7.2	7.1	-0.8%	7.8	7.8	-0.5%
Hydrocarbons, ppm	6.6	5.4	-17.4%	10.0	10.0	0%
Nitrogen oxides, ppm	639.7	768.6	20.1%	967.0	106.3	9.9%
Oxygen, %	10.7	10.9	1.2%	10.3	10.5	2%
Opacity, %	3.3	1.4	-58.2%	2.8	1.8	-35.8%

Table 7. Exhaust emissions produced by a 1992 5.9L turbocharged, direct injected, aftercooled, Cummins diesel engine (2/2/94 and 1/10/95) while fueled with 100 % biodiesel and 100 % low sulfur diesel fuel.

	2/2/94			1/10/95		
Variable	Diesel	BD20	%Change	Diesel	BD20	%Change
Carbon Monoxide %	0.015	0.019	25.0%	0.023	0.024	4.3%

Carbon Dioxide	6.6	6.4	-4.1%	7.4	6.9	-6.4%
Hydrocarbons, ppm	6.3	4.3	-31.0%	10.0	10.0	0%
Nitrogen oxides, ppm	635.7	681.1	7.1%	671.0	709.2	5.8%
Oxygen, %	11.3	11.8	5.0%	11.9	11.0	8.5%
Opacity, %	1.9	2.4	27.2%	1.4	1.2	-15.4%

*This data point is believed to be a result of measurement error.

Conclusions

The following conclusions were drawn from the investigation:

1. The fueling of compression ignition engines on 100 % biodiesel slightly reduced the power when compared to the power developed when fueled with fossil diesel fuel. This was also noted in our review of literature.

2. The specific power developed by a compression ignition engine fueled on 100 % biodiesel will vary depending on engine design and fuel delivery. Differences in the test results of the two engines continue to surface during each subsequent test.

3. Nitrile rubber OEM fuel lines and other fuel line components made out of nitrile rubber deteriorate rapidly when fueling an engine with 100% biodiesel.

4. CO, HC, particulate matter, and smoke exhaust emissions tend to be lower when fueled on biodiesel than when fueled on diesel fuel. NOx exhaust emissions tend to be higher when fueled on 100% biodiesel.

5. Materials from engine wear were found to be lower in the analysis of the engine lubricating oil (Fe, Pb, Si) when the engine was fueled on 100% biodiesel as compared to petroleum diesel fuel.

Recommendations

1. Nitrile rubber OEM fuel lines and other rubber fuel line components should be replaced before fueling an engine with 100% biodiesel.

2. Additional research is needed to examine fuel line component compatibility with 100% biodiesel.

3. Research should be conducted to determine the most efficient means of reducing NOx exhaust emissions when fueling with 100% biodiesel. As noted by Feldman and Peterson, an adjustment of the timing of the engine was beneficial when optimizing the engine for

biodiesel fueling. Fuel injection timing should be evaluated closely as a means of reducing NOx emissions.

4. Research should be conducted to determine how HC, CO, and PM emissions change after an engine has been fueled for extended periods of time.

5. Engine lubricating oil analysis data collection should be replicated. Findings over time clearly suggest that lubricating oil samples taken at regular oil change intervals contain low levels of engine wear materials (when compared to standards previously established for petroleum diesel fuel).

References

Feldman, M. E. and C. L. Peterson. 1992. Fuel injector timing and pressure optimization on a DI diesel engine for operation on biodiesel. *Liquid Fuels From Renewable Resources - Proceedings of an Alternative Energy Conference*. Nashville, TN. St. Joseph, MI: ASAE.

Krahl, J. G., G. Vellguth and A.Munack. 1994. Ubersicht von Arbeiten zum Einsatz von Rapsol und Rapsolmethylester als Kraftstoffe unter Berucksichtinung umweltrelevanter Ausirkungen. Institute Fur Biosystemtechnik, Federal Agricultural Research Center, Braunschweig, Germany.

Marshall, W. F. 1993. Effects of methyl esters of tallow and grease on exhaust emissions and performance of a Cummins L10 engine. Itt Research Institute, National Institute for Petroleum and Energy Research, Bartlesville, OK. (Report prepared for Fats and Proteins Research Foundation, Inc, Ft. Myers, Beach, FL)

Mittelbach, M. P., P. Tritthart, and H. Junek. 1985. Diesel fuel derived from vegetable oils, II: emission tests using rape oil methyl ester. *Energy Agriculture*. 4: 208-215.

Mittelbach, M. P. and P. Tritthart. (1988). Diesel fuel derived from vegetable oils, III. Emissions tests using methyl esters of use frying oil. *Journal of the American Oil Chemists' Society*. 65(7): 1185-1187.

Niehaus, R. A., C. E. Goering, L. D. Savage, and S. C. Sorenson. 1985. Cracked soybean oil as a fuel for a diesel engine. ASAE Paper No. 85-1560. St. Joseph, MI: ASAE.

Reece, D. L. and C. L. Peterson. 1993. A report on the Idaho on-road vehicle test with RME and neat rapeseed oil as an alternative to diesel fuel. ASAE Paper No. 93-5018. ASAE, St. Joseph, MI: ASAE.

Scholl, K. w. and S. C. Sorenson. 1993. Combustion of a soybean oil methyl ester in a direct injection diesel engine. SAE paper No. 930934. Warrendale, PA:SAE.

Schumacher, L.G., S.C. Borgelt, and W.G.Hires. 1995. Fueling a diesel engine with methyl-ester soybean oil. *Applied Eng. In Agr.* 11(1):37-40.

Schumacher, L.G., J.C. Frisby and W.G. Hires. 1991. Tractor PTO horsepower, filter maintenance and tractor engine oil analysis. *Applied Eng. in Agr.* 7(5):625-629.

Schumacher, L. G, W. G. Hires, and S. C. Borgelt. 1992. Fueling a diesel engine with methyl-ester soybean oil. *Liquid Fuels From Renewable Resources- Proceedings of an Alternative Energy Conference*. Nashville, TN. St. Joseph, MI: ASAE.

Schumacher, L. G., S. C. Borgelt, W. G. Hires, and J. K. Humphrey. 1993. Biodiesel on the road- A report from Missouri. ASAE paper No. 93-5017. St. Joseph, MI: ASAE.

Schumacher, L. G., S. C. Borgelt, and W. G. Hires. 1993. Soydiesel/Biodiesel Blend Research. ASAE paper No. 93-6523. St. Joseph, MI: ASAE.

Srinivasa, R. P. and K. V. Gopalakrishnan. 1991. Vegetable oils and their methylesters as fuels for diesel engines. *Indian Journal of Technology*. 29: 292-297.

Ziejewski, M., Kaufman, K. R., Schwab, A. W, and Pryde, E. H. (1984). Diesel engine evaluation of an nonionic sunflower oil-aqueous ethanol microemulsion. *Journal of the American Oil Chemists Society*. 61 (10): 1620-1626.