FUELING DIESEL ENGINES WITH METHYL-ESTER SOYBEAN OIL

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ABSTRACT

Two 5.9 liter Cummins engines were fueled for a combined total of more than 80,467 km (50,000 miles). One truck. a 1991 Dodge, has been driven approximately 48,280 km (30.000 miles). The other, a 1992 Dodge, has been driven approximately 32,187 km (20,000 miles). Fueling these engines with soydiesel increase engine power by 3 percent (1991 engine) and reduced power by 6 percent (1992 engine). The pickups averaged more than 7.1 km/L (16.7 mpg). Analysis of used engine oil samples indicated that the engines were wearing at normal rate. The black exhaust smoke normally observed when a diesel engine accelerates was reduced as much as 86 percent when the diesel engine was fueled with 100% soydiesel. Increased EPA exhaust emissions requirements for diesel engines have created much interest in the use of soydiesel as a fuel for diesel engines.

KEY WORDS. Biofuels, Biodiesel, Methyl-ester, Horsepower, Emissions, Fuel efficiency, Transesterification.

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INTRODUCTION

Previous research conducted with diesel engines during the early 1980s in Illinois, Idaho, Missouri, and North Dakota showed that diesel engines could he fueled with vegetable oils (ASAE, 1982). Much of this research, however, was conducted using raw, degummed vegetable oils with engines operating at a constant RPM. An over-the-mad (OTR) diesel engine operates under conditions other than those used in these early tests. Such an engine operates under varying loads. with starts and stops, with acceleration and deaccelention. idling, and variable speeds. Very little engine wear and exhaust emissions analysis have not been investigated for OTR vehicles fueled with methyl-ester soybean oil.

RELATED LITERATURE

Romano (1982), stated that fatty acids react readily with metals such as tin, lead. cobalt and manganese at elevated temperatures. Modem diesel engines operate at temperatures that could promote reactions with these metals which are commonly found in diesel engines. He further cautioned that after 200 to 250 hours of operation the crankcase oil of diesel engines fueled with methyl-ester vegetable oils lost lubrication qualities. According to Romano, (1982. p. 114) "a gelatinous deposit caused the metals to wear out." Hassett and Hasan (1982) expressed concerns about the dilution of the lubricating oils.

Kusy (1982) found engine torque and power dropped five percent when fueled with ethyl-ester soybean oil and that visible smoke was similar to operation on diesel fuel. According to Ventura. Nascimento and Bandel (1982, p.397), recorded engine parameters were normal during engine testing. The engine lubricating system. however, approached collapse since the lubricating oil started to thicken. Preliminary observations suggested that engine exhaust smoke emissions would be lower than predicted by Kusy. Engine testing both in and out of the laboratory were needed to substantiate these visual observations.

PURPOSE AND OBJECTIVES

The purpose of this investigation was to determine the effects of fueling a diesel engine with methyl-ester soybean oil as compared to fueling the engine with diesel fuel. Factors investigated were: (1) fuel efficiency, (2) engine wear. (3) horspower. and (4) exhaust emission levels.

METHODOLOGY

A 1991 and a 1992 Dodge pickup equipped with direct injection turbocharged 5.9 L diesel engines were the OTR vehicles used in these tests. The pickup engines were fueled with diesel fuel during the first months of operation. Fueling with soydiesel began after 4,827 km (3000 miles) of opeiation (1991 pickup) and after 2,413.5 km (1500 miles) of operation (1992 pickup).

Horsepower determinations were made using a chassis dynamometer with the engine operating at 1700, 1900, 2100, 2300, 2500, and 2700 RPM.

Engine exhaust emissions were recorded in an EPA certified laboratory at Cummins Engine Company.

Initially the 1991 pickup engine lubricating oil (Mopar 15w-40) and the engine lubricating oil filter (Mopar) 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 Company Laboratories. The engine lubricating oil sampling interval and the oil change interval were subsequently lengthened to 1.609 km (1,000 miles) and 4.827 km (3,000 miles) based on recommedations made by MFA Oil Company Laboratory analysists. The 1992 pickup engine lubricating oil sampling procedures and change intervals have remained at 1.609 km (1.000 miles) and 4,827 km (3,000 miles) intervals.

The engine was examined internally using a boroscope by a John Fahick Tractor Company technician to determine engine wear. Engine oil analysis, boroscoping, power measurement, and emissions measurements were conducted by industry specialists. MFA technicians used an atomic absorhtion spectrphotometer when analyzing the lubricating oil samples. The horoscope was a CAT 8T9290. The chassis dynamometer used by John Fahick tractor company was a Super Flow Corporation model SF-601 Vehicle Test System.

Vehicle Modifications:

The engines were not modified. The fuel storage and delivery systems of the trucks were modified. Nitrile rubber-based components in the OEM fuel lines deteriorated when exposed to soydiesel. These components were replaced with either aluminum or nylon reinforced tubing. Original equipment manufacturer (OEM) fuel lines were replaced and the new lines were insulated. -Fuel heaters were installed to warm the fuel when the engine was operating and when the vehicle was not in use. The engines were operated on diesel fuel five minutes before shut down and ten minutes after startup in extremely cold weather (-23" C. (-10" F.).

The soydiesel gelled at 3.30° C (38° F). Stainless steel heat exchangers were installed in the fuel tank and activated during operation in cold weather. These devices were an after-market product that is commonly installed on OTR trucks to prevent diesel fuel from gelling during engine operation. Fuel lines and soydiesel fuel tank were insulated, and two 1 10V thermostaticly controlled flat mat heating , pads were placed beneath the soydiesel tank. The flat mat heating pads were operated in during cold weather. The insulation and flat mat heating pads kept the fuel from gelling when the engine was not running.

RESULTS

The fuel economy while the vehicles were operating on diesel fuel was 9.7 km/L (22.8 mpg). Soydiesel fueling began August 13, 1991 and May 27, 1992. Fuel efficiency during soydiesel fueling fluctuated. depending on how the pickup was operated. The pickups averaged 7 .09 km/L (16.7 mpg - 1991) and 7.3 km/L (17.2 mpg -1992). Fuel efficiency was nearly identical to that obtained when the engine was fueled with diesel fuel under comparable conditions. These information are summarized in Table I.

Table 1. Fuel efficiency of a 1991 and 1992 Dodge pickup equipped with a 5.9 L direct injection Cummins engine when fueled with Soydiesel.

	1991 Pickup	1992 Pickup
Range km/L	5.1-9.7	5.5-9.8
(MPG Range)	(12-22.8)	(12.87-23)
Total Kilometers on Pickup	47,613.0	21,330.0
(Total Miles on Pickup)	(29,592.0)	(13,257.0)
Total Kilometers on Soydiesel	41,982.0	18,698.0
(Total Miles on SoyDiesel)	(26,092.0)	(11,621 .0)
Total Hours on Pickup	777.0	334.0
Total Liters	5,917.0	2,553.0
(Total Gallons)	(1,563.3)	(674.5)
Kilometers per liter	7.1	7.3
(Miles per gallon)	(16.7)	(17.2)
Liters per hour	7.6	7.6
(Gallons per hour)	(2.0)	(2.0)

The engine oil was initially sampled and analyzed every 805 km (500 miles) by MFA labs and the oil changed every 4.027 km (2.500 miles). The results of these analyses indicated that the engine wear was at a normal rate. The levels of chromium, copper, silicon, and iron were either below or the same as expected when fueled on diesel fuel. The engine oil sampling interval was increased to 1,609 km (1,000 miles) and the oil change interval lengthened to 4.830 km (7,000 miles) after 21,136 km (13,136 miles) of operation. A trained mechanic from John Fabick Tractor Company boroscoped the cylinder walls after 450 hours of operation. No abnormal coking was noted on the injectors, on top of the pistons, or on the valve stems. The engine did not appear to be wearing at an accelerated rate.

Table 2 reppresents the findings of the engine oil analysis. The data. was compared with engine lubricating oil samples taken from diesel powered farm tractor engines (Schumacher et. al., 199 I). Data was first analyzed to determine if differences existed between the 1991 and IY92 pickups using a t-test. No significant differences were noted at the .05 alpha level. Data from the pickups was subsequently combined and analyzed to detemine if differences existed between the pickup engines and the farm tractor engines. The tractor engine oil samples that had greater than 90 hours of use were excluded from this analysis. Note that the number of hours on the lubricating oil is not statistically different between groups. Note also that chromium and copper engine deposiw were not statistically significantly different.

Table 2. T-test analysis between engines grouped by tractor and pickup.

Wear metal		N	Mean (ppm)	StDev (ppm)	t-value	t-prob.
Iron	(T)	46	38.39	28.88	6.56	.000
	(P)	40	8.40	10.55		
	(M)		1 0-40			
Lead		46	9.09	8.12	6.04	.000
		40	1.37	2.78		
			1-12			
Copper		46	10.22	34.42	1.62	.113
		40	2.00	2.14		
			3-l 5			
Chromium		46	3.28	4.20	.43	.666
		40	2.80	5.86		
			.5-8			
Silicon		46	4.91	2.81	6.40	.000
		40	1.75	1.70		
			o-12			
Hours on oil		46	40.22	24.56	-1.27	.207
		40	46.48	21.04		

T = Oil samples from farm tractors, operated on 100% diesel fuel
P = Oil samples from Dodge pickups, operated on 100% methyl-ester soybean oil
M = Expected wear metal values for engines fueled with diesel as reported by Minnesota Valley Testing Laboratories

The pickup engines were tested for power at Fabick Power Systems. John Fahick Tractor Company, St. Louis. MO using a digital dynamometer. The 1991 pickup had 501 hours on the engine at the time of the test. The 1992 pickup had 22 hours on the engine at the time of the test. Power (kW) comparison tests were measured at 1.700, 1,900, 2,100, 2.300, 2,500. & 2,700 rpm. The 1991 pickup engine produced approximately three percent more power during these tests when fueled on soydiesel. The 1992 pickup tested approximately seven percent less power when fueled with soydiesel. This information is found in Tables 3 and 4.

Table 3. Power produced by a 5.9 L turbocharged direct injection Cummins diesel engine.

Engine rpm	kW (hp) Power #2 Diesel	kW (hp) Power Soydiesel
1700	88 (118)	93 (125)
1900	96 (130)	102 (137)
2100	106 (143)	110 (148)
2300	114 (153)	116 (156)
2500	114 (154)	120 (161)
2700'	56 (76)	55 (74)

Note: The engine was not fully loaded at this rpm.

Table 4. Power produced by a 1992, 5.9 L turbocharged direct injection Cummins diesel engine (22 hours on engine)

Engine rpm	hp Power #2 Diesel	hp Power Soydiesel
1700	85 (115)	79 (107)
1900	96 (130)	89 (120)
2100	105 (142)	101 (136)
2300	106 (143)	102 (138)
2500	104 (140)	96 (130)
2700'	60 (81)	57 (77)

Note: The engine was not fully loaded at this rpm.

Emissions tests were performed using a Missouri-certified engine exhaust emissions analyzer at Ackerman Buick Company in St. Louis, Mo. A series of diesel/soydiesel blends were prepared. randomly selected and analyzed (100 percent to 0 percent soydiesel/diesel fuel blends in 10 percent increments) for exhaust emissions. The engine exhaust emissions analysis machine was capable of testing CO (carbon monoxide), CO, (carbon dioxide), and hydro-carbons. These readings, which were taken while the engine was idling, were not observed to be statistically different when the engine was fueled with soydiesel blends.

Transient emissions tests were conducted by Cummins Engine company at Columbus, Indiana. The tests were run on a 1991 6BTAA diesel engine, 119.7 kW (160 hp) automotive rating, in an EPA certified laboratory. Carbon monoxide **emissions** were reduced hy one percent. hydrocarbon emissions **were reduced by 48 percent, and particulate matter emissions were reduced by 20 percent with soydiesel fueling of the engine. Oxides of nitrogen emissions were increased by 13 percent when the engine was fueled with soydiesel (Table 5).**

Table 5. Exhaust emissions produced by a 5.9 L turbocharged, intercooled, direct injection Cummins diesel engine.

Exhaust Emissions Variables	Emissions #2 Diesel		Soydiesel	
NOx - g/kW-hr (g/bhp-hr)	6.65	(4.810)	7.38	(5.500)
HC - g/kw-hr (g/bhp-hr)	0.51	(0.380)	0.27	(0.200)
CO - g/kW-hr (g/bhp-hr)	2.01	(1.500)	1.99	(1.490)
PM - g/kW-hr (g/bhp-hr)	0.33	(0.245)	0.26	(0.195)
@2500 rpm - Peak Power				
Power - kW (bhp)	125.35	(168.10)	1 18.72	(159.20)
Fuel Flow g/hr (#/hr)	29,110.40	(64.12)	30,894.70	(68.05)
Smoke - bsu	0.88		0.15	
@1700 rpm - Peak Torque				
Peak Torque N.m (ft-lbs)	**44.49**	**(393.80)**	42.46	(374.80)
Fuel Flow g/hr (#/hr)	19,966.62	**(43.98)**	21,596.78	(47.57)
Smoke - bsu	0.72		0.10	

CONCLUSIONS

The following conclusions were made based on the findings of the investigation:

1. **The fueling of a compression ignition engine on soydiesel does** not **significantly reduce the torque** of the engine when fueled with 100% soydiesel as compared to the torque developed when fueled with diesel fuel.

2. **The power developed by a compression ignition engine fueled on soydiesel will vary depending on engine design and fuel delivery. The 1991 developed three percent more horsepower while the 1992** developed six percent less horsepower. Cummins engine company changed the design and **fuel delivery of the 1992 engine.**

3. **Rubber OEM fuel lines and other fuel line components that are made out of** nitrile rubber **deteriorate rapidly** when **fueling** an **engine with soydiesel.**

4. **Soydiesel gels when temperatures drop below 3.3" C.** (38° **F).**

5. **CO. HC, Particulate matter. and smoke** exhaust **emissions tend to be lower when fueled on** soydiesel than when fueled on diesel fuel. NO, exhaust emissions tend to he higher when fueled on soydiesel.

6. Materials from engine wear are found to be significantly lower as measured by analysis of the engine lubricating oil (Fe, Ph. Si) when the engine is fueled on 100 percent soydiesel as compared to #2 diesel fuel. Fueling of the engines on 100 percent soydiesel did not increase the amount of engine wear materials normally found in the engine lubricating oil.

RECOMMENDATIONS

1. Rubber OEM fuel lines and other rubber fuel line components should be replaced before fueling an engine with soydiesel. Research should he conducted that examines fuel line component compatiblity with soydiesel.

2. Heating devices must he used to prevent gelling of soudiesel fuel when ambient temperatures drop below 3.31" C. (38° F). Research must be conducted to analyze the effectiveness of existing pour point enhancers on soydiesel.

3. Research must be conducted to determine the most efficient means of reducing NO, exhaust emissions. Concurrent research must be conducted to determine how HC, CO, and PM emissions will change when the engine has been optimized for NO, emissions.

4. Engine lubricating oil analysis data collection should he replicated. Preliminary findings suggest that the engine is not out wearing more rapidly than if it were fueled with #2 diesel fuel.

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HAZARDOUS EMISSIONS, OPERATING PRACTICES, AND AIR REGULATIONS AT INDUSTRIAL WOOD-FIRED FACILITIES IN WISCONSIN

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Abstract

Since October of 1988 the State of Wisconsin Department of Natural Resources has regulated over four hundred substances as hazardous air pollutants The rule regulates new as well as existing sources of air pollution in Wisconsin. Consequently, all permits to operate an air pollution source in Wisconsin must address the hazardous air emissions potential of the source.

While widely perceived, a clean-burning fuel, wood is often burned in a manner which clearly results in significant emissions of very hazardous air pollutants. Research conducted on a 20 million BTU per hour wood-fired spreader stoker boiler in northern Wisconsin showed that this boiler has the potential to emit 0.022 pound of benzene and 0.012 pound of formaldehyde per ton (lb/ton) of wood fired. Recent stack tests at more than a dozen other small industrial wood-fired facilities in Wisconsin show a range of formaldehyde emissions of 0.0007 - 0.1950 lb/ton.

Work at Birchwood Lumber & Veneer showed that the benzene and formaldehyde emission rates under good firing conditions are an order of magnitude lower than the benzene and formaldehyde emission rates under poor firing conditions. This finding has supported Wisconsin's regulatory approach of encouraging wood-fired facilities to enhance the quality of the combustion process as a technique to minimize the hazardous air pollution potential of industrial wood combustion. The Wisconsin strategy is to define "good combustion technology" through easily measurable combustion parameters rather than emission standards.

This paper presents several techniques in use in Wisconsin to comply with "good combustion technology" for industrial wood-fired furnaces. These techniques include fuel blending, over-fire air, furnace insulation, and proper grate design.