ENGINE OIL ANALYSIS OF BIODIESEL–FUELED ENGINES

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ABSTRACT. *The University of Missouri−Columbia and the University of Idaho monitored 1991, 1992, 1994, 1995, 1996, 1998, and 1999 Dodge pickup trucks equipped with 5.9−L (360−in.^{3}) Cummins diesel engines from 1991 through 2001. These pickups have been fueled with 0, 1%, 3%, 20%, 50%, and 100% blends of methyl−esters and ethyl−esters of soybean, canola, and rapeseed oil (biodiesel). Analysis of engine lubricating oil, taken when the oil was changed on the vehicles, was compared to the analysis of oil samples taken from 100% petroleum−fueled diesel engines. The findings indicated that the biodiesel and biodiesel blend−fueled engines were wearing at a normal rate.*

Keywords. *Biofuels, Biodiesel, Methyl−Ester, Ethyl−Ester, Engine oil analysis, Transesterification.*

Over 100 years have passed since the invention of the compression ignition engine (Anonymous, 2001d). Rudolph Diesel saw his engine as a solution to the high polluting and inefficient steam engines of his time (Anonymous, 2001c). During the 1880s, a steam engine was, at best, 10% efficient and produced large amounts of smoke as it operated. By 1896, Diesel's engine had demonstrated a mechanical efficiency of 75.6% (Anonymous, 2001b).

Mr. Diesel's early designs used coal dust as a fuel. However, at the 1889 World's Fair in Paris, France (Rovito, 2001), Diesel saw his new engine in operation as it was fueled with peanut oil. Petroleum−based fuel (diesel), a by−product of the gasoline manufacturing process, exhibited characteristics that were quite similar to vegetable oils. This inexpensive by−product became the fuel of choice for Diesel's engine and nearly all research that followed for the next 70 years focused on how to make Diesel's engine operate more efficiently on petroleum−based diesel fuel.

Research conducted largely with 5.9−L (360−in.^{3}) Cummins diesel engines (Dodge pickup trucks) from the early 1990s to July of 2001 in Idaho and Missouri has proven that diesel engines can be fueled successfully with biodiesel and biodiesel blends. Diesel engines were fueled with B1, B2, B20, B50, and B100 or "neat" biodiesel fuel (B20 is a 20% replacement of the petroleum diesel fuel with biodiesel) (Schumacher et al., 1991, 1996; Peterson et al., 1995a 1195b, 1196, 1999; Peterson and Reece, 1996a, 1996b).

Engine oil analysis is a simple way to determine the physical condition of an engine. A small amount of oil is drawn from the engine after it has been warmed to ensure that the oil and any contaminants are thoroughly mixed. The sample is sent off for analysis by an independent laboratory (Peterson, 2001). The sample is then analyzed for the presence of metallic elements (wear metals). Spectrometric analysis is used to determine the amount of wear metals in parts per million (ppm) by weight.

In the spectrometer, the oil is electrically excited to the point where light is emitted. Each element present in the burning oil emits light of its own particular color and frequency. Spectrometers translate the intensity of these colors into a computerized readout. The computer compares the output with a fresh oil sample and samples previously taken from the same engine to establish wear trends.

University of Missouri and University of Idaho researchers have monitored the wear metals found in the lubricating oil of biodiesel−fueled diesel engines while fueling their engines (Schumacher and Van Gerpen, 1998). Both universities have documented the wear metals found in the engine lubricating oil after fueling diesel engines with biodiesel blends through tests conducted by independent oil analysis laboratories. This article reports the data obtained from research spanning 10 years of biodiesel fueling with 12 vehicles.

MATERIALS AND METHODS

All of the used oil samples were taken from biodiesel−fueled direct−injected diesel engines. Although the rated power of the engines was not identical, all but one was a 5.9−L engine manufactured by Cummins Engine Company (Columbus, Ind.). Table 1 outlines specific information for each engine.

Each engine was broken−in according to engine manufacturer (OEM) recommendations. Some were fueled for a short time on diesel fuel [160−4,800 km (100−3,000 miles)] before they were fueled with biodiesel/biodiesel blends. Some were fueled with biodiesel blends from the first day of operation. The 1992 100% biodiesel−fueled, University of Missouri, Soybean Methyl Ester−fueled biodiesel engine (B100 MO − SME engine) was shipped to Columbus, Indiana, disassembled and inspected by Cummins engineers, and then rebuilt by University of Missouri technicians. At that time,

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Table 1. Vehicles that were monitored using engine oil analysis by researchers at the University of Idaho and the University of Missouri: 1991−2001.

Model Year[a]	Displacement (L)	Manufacturer	Fuel Source[b]	% Biodiesel	km (mile)
1991	5.9	Cummins	MO – SME	100	127,916 (79,451)
1992	5.9	Cummins	MO – SME	100	161,081 (100,050)
1992	5.9	Cummins	MO – SME	2	243,472 (151,225)
1996	5.9	Cummins	MO – SME	2	153,852 (95,560)
1998	5.9	Cummins	MO – SME	1	167,062 (103,765)
1992	5.9	Cummins	ID – RME	20	164,119 (101,937)
1994	5.9	Cummins	ID – REE	100	160,174 (99,487)
1995	5.9	Cummins	ID – REE	100	149,730 (93,000)
1997	14.6	Caterpillar, 3406E	Hysee (Soybean)	50	326,318 (202,682)
1995	5.9	Cummins	Baseline DF	0	60,749 (37,732)
1992	5.9	Cummins	Baseline DF	0	93,702 (58,200)
1992	5.9	Cummins	Baseline DF	0	177,857 (110,470)

[a] Each row represents a single engine and vehicle.
[b] MO − SME = fueled with methyl−esters of soybean oil and logged at University of Missouri.
ID − RME = fueled with methyl−esters of rapeseed or canola oil and logged at University of Idaho.
ID − REE = fueled with ethyl−esters of rapeseed or canola oil and logged at University of Idaho.
Hysee = fueled with ethyl−esters of hydrogenated soybean oil and logged at University of Idaho.
DF = pump run diesel fuel.

the engine had logged 243,472 km (151,225 miles) with a 2% blend of biodiesel and 98% petroleum diesel fuel (B2) (table 1). The 1992 100% biodiesel−fueled, University of Idaho, rapeseed methyl ester−fueled biodiesel engine (ID − RME engine) was also shipped to Columbus, Indiana (Cummins Engine Co.), disassembled and inspected by Cummins, and then rebuilt by University of Idaho technicians and put back into service. The 1994 ID rapeseed ethyl ester (REE) B100 and the 1995 ID − REE B100 were also, respectively, disassembled at the University of Idaho and a Cummins dealership. Both engines were inspected by Cummins personnel, rebuilt by University of Idaho technicians, and then put back into service. The disassembled evaluations in all engines were within specifications (Peterson et al., 1999; Taberski, et al., 1999; Peterson and Thompson, 1998). The 1997 Caterpillar engine (B50)(Kenworth truck) was disassembled and inspected by Caterpillar and "passed with flying colors" (Chase et al., 2000).

The diesel fuel that was blended with the biodiesel was purchased at local diesel filling stations in Idaho, Michigan, and Missouri (two of the Missouri Dodge pickup trucks were fueled and operated in Michigan). Mixing of the blend was conducted in the OEM fuel tank. A predetermined volume of biodiesel was first added to the fuel tank. The operator then topped off the tank with the amount necessary to prepare the respective blend (B1, B2, B20, etc.). Mixing occurred while filling the tank and while the operator drove the vehicle, a procedure that is commonly used in the industry to mix ethanol in gasoline before it is delivered to the local filling station. The 1997 Caterpillar engine (Kenworth truck) was fueled through a blending valve that drew fuel from a diesel nurse tank and a biodiesel nurse tank. The 1992 − ID B20 engine had an on−board mixing system (Peterson and Thompson, 1998).

Two companies assisted with fuel analysis. NOPEC Corporation (Lakeland, Fla.) provided the analysis of the 100% neat biodiesel, and Cleveland Technical Center (Kansas City, Kans.) analyzed the B2 (biodiesel/diesel fuel blend) (table 2). The Idaho fuel samples were analyzed by the University of Idaho Analytical Laboratory and by Phoenix Chemical (Chicago, Ill.). Additional information concerning fuel analysis can be found in articles previously published by the authors.

The engines were not modified in any way to facilitate biodiesel or biodiesel blend fueling. The manufacturer recommended lubricant was used in each engine. The Missouri engines used 15W−40 Cummins Blue E (Valvoline Premium Blue E, Valvoline Europe, Zwijndrecht, The Netherlands) lubricating oil. Idaho, for the most part, used 15W−40 Chevron Delo 400 (ChevronTexaco Corporation, San Francisco, Calif.) engine oil in its engines. The exception was the 1997 Caterpillar engine (Kenworth truck), which used 15W−40 Pennzoil (SOPUS Products, Houston, Tex.). Some of the engines were modified so that a "hot" oil sample could be taken from the engine while the engine was running. A device that looks much like the "needle" used when filling air into a basketball or a football was secured to a short length

Table 2. Typical fuel analysis of biodiesel and B2 used when fueling 5.9−L Cummins engines.[a]

Fuel Property	ASTM Test Procedure[b]	Fuel[c]	
		Biodiesel	B2 Blend
Gross heat value	D2382	N/T	38,546 kJ/L
Color	D1500	N/T	N/T
Corrosion	D130	1A	1A
Cloud point	D2500	0°C	0°C
Pour point	D97	−3.1°C	−36.6°C
Flash point	D92	140.5°C	62.7°C
Viscosity	D445	4.8 cS@100°C	N/T
Sulfur	D129	0.01%	N/T
Carbon residue	D4530	0.03%	N/T
Cetane index	D976	N/T	47.8
Ash	D482	0.001%	N/T
Free glycerin	G.C.	0.033%	N/Ap.
Total glycerin	G.C.	0.295%	N/Ap.
Acid number	D664	0.25 mg KOH/g	N/T
Water and sediment	1796/4807	0.0%	N/T
Distillation			
IBP		N/T	174.5°C
10		N/T	213.3°C
50		N/T	263.3°C
90		N/T	314.4°C
End		N/T	334.4°C

[a] Additional fuel analysis information can be found in Peterson and Thompson (1998), Chase et al. (2000), Taberski et al. (1999), and Peterson and Reece (1996a, 1996b).
[b] G.C. = Gas Chromatograph.
[c] N/T = Not tested.
N/Ap. = Not applicable.

of polyvinyl tubing. An oil−fitting plug on the oil filter housing was removed, and a fitting designed to receive the “needle” was tightened into place. The engine was started, and after it was warmed, the needle was inserted. Engine oil pressure then pumped the oil through the needle and tubing into a clean steel can for later analysis.

Lubricant oil samples were analyzed by MFA Labs in Columbia, Missouri; Cleveland Technical Center in Kansas City, Missouri; Cleveland Technical Center in Spokane, Washington; and Western States Caterpillar in Boise, Idaho. A computer−generated report provided a breakdown of wear metals, contaminants, water and sediment, glycols, and oil additives.

The descriptive statistics were conducted using SAS (SAS Institute Inc., Cary, N.C., and SPSS Inc., Chicago, Ill.) to determine the levels of iron, copper, chromium, silicon, lead, and aluminum wear metals in each sample (table 3).

Analysis of variance (PROC GLM, SAS Institute, Inc., Cary, N.C.) was conducted to determine if differences existed among the wear metal means. When differences were noted among these means, the multiple range test LSMEANS and an α level of 0.05 was used to determine the statistical differences (table 4).

With the exception of the 1997 Caterpillar engine (Kenworth truck), the samples that were included in this analysis were taken when the engine oil was changed. The 1997 Caterpillar was sampled at 9700 km (6000 miles) intervals and oil was changed at approximately 40,000 km (25,000 miles) or about 574.5 h. Nine of the Cummins engines’ oil change intervals varied from 6651 to 7026 km (3141 to 4364 miles) or about 72.2 to 100.3 h of operation. Two of the Cummins engines had the oil changed between 9554 and 10,640 km (5934 and 6609 miles), which was about 136.4 to 151.9 h of operation.

Table 3. Number of oil samples (N), Mean, and standard deviation levels of wear metals found in oil samples taken from Cummins 5.9−L engines (Dodge pickups), a 1997 Caterpillar engine (1997 Kenworth truck), and Missouri farm tractors.

Wear Metal	Concentration of Biodiesel	N	Mean (ppm)	StDev (ppm)	Wear Metal	Concentration of Biodiesel	N	Mean (ppm)	StDev (ppm)
Iron	’92 MO − Dodge @ 100%	24	6.79	4.03	Chromium	’92 MO − Dodge @ 100%	24	1.42	4.23
	’92 MO − Dodge @ 2%	14	7.85	3.88		’92 MO − Dodge @ 2%	14	0.79	0.43
	’91 MO − Dodge @ 100%	13	9.00	12.59		’91 MO − Dodge @ 100%	13	1.85	2.91
	’96 MO − Dodge @ 2%	14	11.28	1.72		’96 MO − Dodge @ 2%	14	0.78	0.43
	’98 MO − Dodge @ 1%	14	20.14	7.68		’98 MO − Dodge @ 1%	14	0.86	1.03
	’92 ID − Dodge @ 20%	30	6.23	2.26		’92 ID − Dodge @ 20%	30	0.73	0.45
	’94 ID − Dodge @ 100%	18	15.5	3.88		’94 ID − Dodge @ 100%	18	0.67	0.59
	’95 ID − Dodge @ 0%	5	21.2	4.54		’95 ID − Dodge @ 0%	5	2.40	1.34
	’95 ID − Dodge @ 100%	25	12.4	6.32		’95 ID − Dodge @ 100%	25	0.24	0.44
	ID Pepsi Trk − Dodge @ 0%	17	8.94	4.14		ID Pepsi Trk − Dodge @ 0%	17	1.00	0.00
	ID McGregor Trk − Dodge @ 0%	7	20.28	8.01		ID McGregor Trk − Dodge @ 0%	7	2.00	1.53
	’97 ID − Kenworth @ 50%	17	12.47	6.06		’97 ID − Kenworth @ 50%	17	0.18	0.39
	MO − Tractors	50	49.46	37.23		MO − Tractors	50	3.00	2.89
	Minnesota Valley Testing[a]		10−40			Minnesota Valley Testing[a]		0.5−8	
	Trigard Oil Analysis Lab[b]		20−60			Trigard Oil Analysis Lab[b]		1−10	
Lead	’92 MO − Dodge @ 100%		1.46		Silicon	’92 MO − Dodge @ 100%	24	2.58	2.08
	’92 MO − Dodge @ 2%		2.71			’92 MO − Dodge @ 2%	14	5.29	1.77
	’91 MO − Dodge @ 100%	24	2.00	1.84		’91 MO − Dodge @ 100%	13	2.15	1.86
	’96 MO − Dodge @ 2%	14	2.36	1.26		’96 MO − Dodge @ 2%	14	4.36	4.80
	’98 MO − Dodge @ 1%	13	3.86	3.16		’98 MO − Dodge @ 1%	14	11.00	22.86
	’92 ID − Dodge @ 20%	14	1.53	1.28		’92 ID − Dodge @ 20%	30	2.43	1.14
	’94 ID − Dodge @ 100%	14	2.17	2.34		’94 ID − Dodge @ 100%	18	3.05	1.80
	’95 ID − Dodge @ 0%	30	3.40	0.63		’95 ID − Dodge @ 0%	5	4.40	0.55
	’95 ID − Dodge @ 100%	18	2.88	1.15		’95 ID − Dodge @ 100%	25	4.12	4.81
	ID Pepsi Trk − Dodge @ 0%	5	1.29	1.67		ID Pepsi Trk − Dodge @ 0%	17	2.06	0.97
	ID McGregor Trk − Dodge @ 0%	25	6.42	1.30		ID McGregor Trk − Dodge @ 0%	7	3.71	1.11
	’97 ID − Kenworth @ 50%	17	7.18	0.58		’97 ID − Kenworth @ 50%	17	5.23	1.52
	MO − Tractors	7	14.24	5.09		MO − Tractors	50	5.16	2.75
	Minnesota Valley Testing[a]	17	1−12	4.51		Minnesota Valley Testing[a]		0−12	
	Trigard Oil Analysis Lab[b]	50	5−25	17.06		Trigard Oil Analysis Lab[b]		1−15	
Copper	’92 MO − Dodge @ 100%	24	3.25	3.70	Aluminum	’92 MO − Dodge @ 100%	24	0.46	0.64
	’92 MO − Dodge @ 2%	14	6.43	22.04		’92 MO − Dodge @ 2%	14	1.93	0.92
	’91 MO − Dodge @ 100%	13	3.23	3.32		’91 MO − Dodge @ 100%	13	0.23	0.44
	’96 MO − Dodge @ 2%	14	5.86	5.44		’96 MO − Dodge @ 2%	14	1.64	0.50
	’98 MO − Dodge @ 1%	14	4.28	6.91		’98 MO − Dodge @ 1%	14	2.21	0.58
	’92 ID − Dodge @ 20%	30	4.07	6.16		’92 ID − Dodge @ 20%	30	2.00	1.17
	’94 ID − Dodge @ 100%	18	2.39	2.38		’94 ID − Dodge @ 100%	18	1.67	0.84
	’95 ID − Dodge @ 0%	5	2.20	1.64		’95 ID − Dodge @ 0%	5	3.20	0.84
	’95 ID − Dodge @ 100%	25	3.88	6.45		’95 ID − Dodge @ 100%	25	2.16	1.07
	ID Pepsi Trk − Dodge @ 0%	17	1.47	0.80		ID Pepsi Trk − Dodge @ 0%	17	2.65	1.22
	ID McGregor Trk − Dodge @ 0%	7	2.57	1.13		ID McGregor Trk − Dodge @ 0%	7	5.71	2.13
	’97 ID − Kenworth @ 50%	17	33.00	21.44		’97 ID − Kenworth @ 50%	17	2.53	0.87
	MO − Tractors	50	10.94	32.98		MO − Tractors	50	N/A	
	Minnesota Valley Testing[a]		3−15			Minnesota Valley Testing[a]		1−8	
	Trigard Oil Analysis Lab[b]		5−40			Trigard Oil Analysis Lab[b]		1−15	

[a] These concentrations are considered to be “rule of thumb” normal values by Minnesota Valley Testing Laboratory.
[b] These concentrations are considered normal by the Trigard Oil Analysis Laboratory (www.hampeloil.com/trigardlab/metals.asp).

In 1988, oil samples were collected from 98 diesel−fueled tractors at seven locations in Missouri (Schumacher et al., 1991). A very small number of these tractors were equipped with 5.9−L Cummins off−highway engines. The tractor engine oil samples that had less than 50 or greater than 150 h of use were excluded from these analyses since there were no oil samples from the Cummins engines that had logged fewer than 50 or greater than 150 h of operation.

The time it takes to obtain a representative number of samples for statistical analysis from the same engine that has performed the same type of work makes data collection from the "same engine" impractical. Thus, the researchers used different engines in an effort to establish a diesel−fueled baseline. Hence, the oil analysis data from three diesel−fueled Cummins engines and the diesel−fueled farm tractors listed in table 1. Data were compared to data published by the Minnesota Valley Testing Laboratory (Schumacher et al., 1991) and Trigard Oil Analysis Laboratory (Anonymous, 2001a).

RESULTS

The wear metals that reflect the condition of the engine were examined to determine if the engines were wearing at a normal rate. The wear element aluminum reflects piston wear; iron reflects cylinder wall/liner, valve shafts, and/or gear wear; copper reflects bearing and bushing wear and may be high if the engine has a copper oil cooler; lead reflects bearing wear; and chromium reflects piston ring wear. Silicon was also examined, as this reflects the wear material that moves through the air filter and into the engine. Silicon can also reflect additives in the lubricating oil but may give a false reading if silicon gasket sealers have been used in the engine.

The SAS PROC GLM procedure was used to analyze the differences among the mean wear metal values for chromium, copper, lead, aluminum, silicon, and iron. The F−values ranged from 4.62 (silicon) to 16.27 (iron). The P−value for each respective F−value was less than the 0.05−α level indicating that significant differences existed among the means when grouped by wear metal category (table 4).

Table 4. Anova, df, F−values and P−values for wear metals found in used engine lubricating oil.

Wear Metal	df Between Groups	df Within Groups	F−Value	P−Value
Aluminum	11	186	4.71	0.0001
Feedstock			3.03	0.083
Fuel			9.99	0.002
Chromium	12	235	4.71	0.0001
Feedstock			3.03	0.083
Fuel			9.99	0.002
Iron	12	235	16.27	0.0001
Feedstock			0.01	0.903
Fuel			17.76	0.0001
Lead	12	235	7.54	0.0001
Feedstock			0.05	0.832
Fuel			7.28	0.0075
Silicon	12	235	4.62	0.0052
Feedstock			11.45	0.0008
Fuel			0.01	0.904
Copper	12	235	5.22	0.0001
Feedstock			0.15	0.702
Fuel			0.00	0.971

The data were then grouped two different ways to determine if the differences were due to the "feedstock" (origin of the biodiesel – soybean vs. rapeseed) or due to the type of fuel that was used to fuel the diesel engine (biodiesel/biodiesel blend vs. diesel).

The data in table 3 reflect the results of a SAS PROC GLM Least Square Means test. The results of these tests are categorized by either "feedstock" or "fuel." The P−values ranged from 0.002 to 0.903. An α of 0.05 was used to determine if statistical differences existed between means. For the feedstock effect, all but one case was not statistically different. The outlier in this case was the wear compound silicon. However, one of the biodiesel vehicles, the 1998 Dodge from Michigan, had silicon levels that were excessive in the first and only the first oil change. According to the OEM, this outlier was to be expected as silicon is used as a gasket sealer in new engines. The OEM reported that some of the gasket sealer had made its way into the lubricating oil. Based on this information from the OEM and the statistical analysis, the researchers concluded that no statistical differences existed due to a feedstock effect.

The SAS PROC GLM Least Square Means test was then used to determine if the variance among the means could be attributed to a "fuel" effect (biodiesel/biodiesel blend vs. petroleum diesel). No statistical differences were noted at the 0.05−α level for silicon and copper (table 3). However, the P−values ranged from 0.0001 to 0.0075 for lead, iron, chromium, and aluminum. This data indicated that statistical differences existed when the means were grouped in such a way as to isolate a fuel effect. Further review of these data and the results of the statistical analysis indicated that biodiesel/biodiesel blend−fueled diesel engines had statistically lower levels of the wear metals lead, iron, chromium, and aluminum.

DISCUSSION

As noted by Schumacher et al. (1998), the mean values of the measured wear elements did not vary much regardless of the biodiesel blend. The only exception to this trend was for the wear element copper. The copper level for the 1997 Caterpillar engine (Kenworth truck) was significantly greater when compared to any of the other samples. The manufacturer of the 1997 Caterpillar engine (Kenworth truck) indicated that the high levels of copper in the lubricating oil during the first 80,000 km (50,000 miles) of operation was probably due to a copper oil cooler. The 1997 Caterpillar engine had a copper oil cooler and the samples that were taken during the first 80,000 km (50,000 miles) of operation (two to three samples) were two to three times higher in copper than any sample taken after that point. The OEM verified this was normal and to be expected.

All the wear elements, except silicon and copper, were statistically different when compared to the samples taken from the diesel−fueled engines. An examination of these mean wear metal values suggests that biodiesel, even when substituted in small amounts, can retard the wear rate of iron, chromium, aluminum, and lead in a diesel engine.

An important observation to note was that the samples that were taken from engines fueled with soybean−derived biodiesel were not statistically different from those taken from engines fueled with rapeseed−derived biodiesel. This documents the lack of a "feedstock" effect and supports the premise that quality biodiesel can be produced from different feedstocks.

It was interesting to note that there was not a difference for the wear element silicon when the biodiesel−derived oil samples were compared with the diesel fuel−derived fuel samples. This result was reassuring, as it suggests that even though the tractors and the pickup trucks were operated under different operating conditions (on−road vs. field operation), the amount of wear material that entered the lubricating oil, and normally increases the wear of the engine, was essentially the same. However, when grouped by feedstock (soybean vs. rapeseed), this was not the case. A closer examination of the data revealed that one sample from the 1998 Dodge truck from Missouri was of a magnitude that was nine times higher than any other sample taken from this engine. This was the first oil sample taken from this engine. Due to the fact that engine manufacturers have started using silicon to form gaskets in recent years, it was hypothesized that this sample may have been higher for this reason. When this sample was removed from the statistical analysis and the SAS PROC GLM statistical analysis was run again, the feedstock effect did not significantly affect silicon.

Conclusions

Although the findings from this analysis were not conclusive, the results are positive concerning the use of biodiesel and biodiesel blended fuels for diesel engines. The following conclusions were drawn from the investigation:

- Replacing the diesel fuel with biodiesel reduced the wear of aluminum, iron, chromium, and lead components in a diesel engine.
- The amount of wear metals found in the lubricating oil of rapeseed/canola−derived biodiesel−fueled engines was not statistically different from the amount found in soybean−derived biodiesel−fueled engine lubricating oil samples.
- Biodiesel did not result in wear rates that were worse than diesel fuel.

Recommendations

The findings from this investigation cannot be considered conclusive, as some of the data points were not under the complete control of the researchers. For example, the researchers relied upon laypersons that were not trained in research to collect the oil samples at specific intervals. Also, the researchers do not know for certain that the layperson collected every sample according to the instructions that were provided. Ideally, the researchers want data from the exact same engine so that valid comparisons can be made between biodiesel−fueled engines and diesel−fueled engines. Ideally, the engine would be operated under identical conditions (weather, load, driving habits, the same driver) to facilitate this comparison. The time necessary to log kilometers on an engine is a significant issue that limits the ability of a researcher to obtain identical data from the same over−the−road engine. Based on these assumptions, the researchers felt that it was impossible to duplicate the exact conditions over−the−road so that direct comparisons could be made between biodiesel and diesel fueling on the same engine. Therefore, any interpretations made from these data must be done with caution.

Based on these observations and the previously drawn conclusions, the recommendations are:

- An experimental research design should be determined which would quantify the amount of wear metals found in used lubricating engine oil samples as compared to engines that have been fueled with petroleum diesel fuel.
- Additional monitoring of diesel engines that are fueled with biodiesel, blends of biodiesel, and petroleum diesel fuel is needed to develop a biodiesel knowledge base. Specifically, a greater number of biodiesel−fueled vehicles must be monitored in conjunction with an equal number of control vehicles, i.e. petroleum diesel−fueled vehicles.

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