A 2,000,000 Mile Evaluation of the Performance and Operational Impacts of B20 Biodiesel Usage in a Long-Haul Trucking Company.

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National Biodiesel Board (NBB)

Renewable Energy Group, Inc. (REG)

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INTRODUCTION

Biodiesel is a renewable fuel made from the transesterification of plant and/or animal triglycerides with methanol or other short-chain alcohols to form methyl or alkyl esters. Biodiesel used as a neat fuel or blended with petroleum diesel is a renewable source of energy that helps to reduce foreign oil consumption, reduce greenhouse gas emissions, and can help fleet users comply with several mandates for the use of renewable fuels. Lifecycle analysis indicates that biodiesel use produces a real reduction in petroleum usage and carbon dioxide emissions (Sheehan 1998), albeit at a slightly reduced fuel economy due to the lower energy content of biodiesel (Graboski 1998). Legislative efforts have called for an increase in the use of renewable fuels both at the local and national level. Currently, three states (Minnesota, Washington and Oregon) require a 2% blend of biodiesel to be sold; and several other states including New Mexico, Pennsylvania, Massachusetts and Louisiana will have biodiesel mandates in place in the very near future (Illinois Soybean Association 2009). Additionally, guidelines set forth by the Energy Independence and Security Act of 2007 will require the use of 1 billion gallons of biomass-based diesel nation-wide by the year 2012 (Energy Act 2007). Although many in the transportation industry embrace the idea of renewable fuels in general and biodiesel in particular, more information is needed regarding the practical use of biodiesel in a commercial, over-the-road setting.

Several well-documented studies have reported on the use of biodiesel under a variety of settings. Chase (2000) described the commercial operation of a single heavy-duty truck running on a 50% blend of biodiesel with petroleum diesel for more than 200,000 miles. The source of fuel was used vegetable cooking oil transesterified with ethanol (hydrogenated soy ethyl ester, or HySEE biodiesel). The average fuel economy reported for this study was 5.27 mpg. No operational problems were described and an engine tear-down and analysis revealed no excessive wear; however, only one unit was used in this study. Bickel and Strebig (2000) describe the use of a 20% blend of biodiesel with petroleum diesel during a 2-year field study in Minnesota. The study compared two groups of road maintenance vehicles using either B20 or 100% petroleum diesel. Fuel economy was comparable and no unusual engine wear or deposits were noted. Fraer (2005) detailed a study with the United States Postal Service using B20 for a 4-year period. Four cargo vans and four tractor trailers were chosen for the study with two of each running on B20 and the other two running on petroleum diesel. Anecdotally, the authors did not feel that any discernible differences were noted for fuel economy; however, specific fuel usage data was not collected for each vehicle. Overall engine wear was normal for both vehicle types running on either fuel. Several differences were noted for the biodiesel tractor units including additional engine sludge on top of the cylinder heads, filter plugging, and injector nozzle replacements. Overall fuel-related maintenance costs were reported to be essentially the same for both vehicle types irrespective of the fuel used.

Several studies detail the use of biodiesel in public transit busses. The BIOBUS project in Montreal, Canada utilized 155 busses operating with biodiesel synthesized from either vegetable oil, animal fat, or used cooking oil at the 5% or 20% blend level (BIOBUS 2003). Maintenance profiles were similar for busses using biodiesel and no operability issues were recorded except for several episodes of fuel filter fouling. The use of 10 micron filters and possible contamination from fuel tank residues were noted as possible contributors to the filter plugging.

The Regional Transportation District in Boulder, Colorado conducted a two-year study with five busses operating on B20 matched with 4 busses running on petroleum diesel (Proc 2006). Fuel economy for both groups was identical. Overall maintenance costs were approximately 6% lower in the B20 group; however, maintenance costs related to the engine and fuel components specifically were approximately 39% higher in the B20 group, with much of this being attributed to a cylinder head and injector replacement in one of the B20 units. The B20 group also experienced an increase in fuel filter plugging and while not a major cost factor did result in disruptions in service. Analysis by GC/MS revealed plant sterols in the B20 blend as a possible contributing factor to filter plugging. Oil analysis revealed no significant differences in the presence of wear metals, and a significantly lower soot level in the B20 group.

The St. Louis Metro in St. Louis, Missouri conducted An 18-month evaluation with eight busses running on B20 matched with 7 busses running on petroleum diesel (NREL). Fuel economy for this study was reported to be 1.7% lower in the B20 group but was not considered to be statistically significant. Overall maintenance costs were similar for both groups. The fuel- and engine-specific costs were higher for the B20 group; however, the authors suggested that this may have been due to the overall higher engine mileage in the B20 group. Maintenance issues did not have an impact on customer service as the overall reliability for both groups was comparable. The B20 group experienced increased filter plugging and injector replacements, with the contributing factors to these incidences attributed to cold weather and higher overall engine mileage in the B20 group. Lube oil analysis revealed a decrease in soot loading and wear metals in the B20, while lead corrosion and viscosity decay were increased for this group.

Most recently, McKinley and Lumkes (2009) conducted a 12-month evaluation comparing 10 Class-8 on-highway trucks using B20 with 10 matched controls. Fuel economy was reported to be similar for both groups with 6.97 mpg for the B20 group and 6.91 mpg for the control group. Overall maintenance and repair cost data were not reported for this study; however, it was noted that both groups experienced an increase in the rate of filter plugging coincident with the introduction of #2 ULSD in September 2006. Engine oil analyses revealed a slight decrease in viscosity and base number with the B20 group and a slight increase in the acid number and oxidation value for the B20 group. Wear metals analysis revealed a 6-fold increase in the lead content in the B20 group; however, this may have been attributed to two B20 units that had accumulated over 500,000 miles each by the end of the study period. Because the control and B20 units had already been in service prior to the start of the study, it was not clear if the excessive lead contamination in these two units was due to normal engine wear or a pre-existing condition. Engine tear-downs were not performed for this study.

The work in this study provides quantitative information for the use of B20 in a commercial over-the-road trucking company. The study utilizes 10 Class-8 tractor trailers operating on a blend of 20% soy biodiesel with 80% #2 ultra-low sulfur diesel (ULSD) matched with a control group of 10 Class-8 tractor trailers running on 100% #2 ULSD, and was conducted for a 26 month period in which each group collectively logged over two million miles. Information was collected regarding fuel economy, fuel quality and physical properties, operability, maintenance costs and engine oil performance. In addition, several engines were torn down for analysis. This study is unique in that it utilized brand-new tractors that will eliminate any questions regarding pre-existing conditions. The study also consists of a relatively large sample size and duration (two years and two million miles) with control and test groups that have been specifically matched regarding chassis and trailer configuration, emissions configuration and route. Additionally, the study was conducted through two complete seasonal rotations including the harsh winters experienced in the upper Midwest.

APPROACH

Vehicle and Driver Selection

The study consisted of a control (ULSD) group with 10 units and a matching B20 test group, for a total of 20 units (Table 1). All units were factory delivered with less than 500 miles on the odometer and consisted of a Peterbilt chassis with C-13 Caterpillar engines rated at 430 horsepower matched with Eaton-Fuller convertible 9 to 13 speed transmissions left in the 9 speed mode. Nine units in each group contained 2004 EPA Certified engines and one unit in each group contained a 2007 EPA Certified engine. Fuel filters consisted of a 20 or 25 micron primary (tank-side) fuel filter and a 10 micron secondary fuel filter. Both groups used API CI-4 15W-40 engine oil for the units equipped with the 2004 EPA Certified engine and API CJ-4 15W-40 engine oil for the units equipped with the 2007 EPA Certified engine. All units ran with flatbed trailers on matched routes to either Minneapolis or Chicago. The ULSD group used 100% #2 ULSD petroleum diesel whereas the B20 test group used a blend of 20% soy biodiesel with 80% #2 ULSD petroleum diesel. Due to a severe cold snap in February 2007, #1 diesel was used at a rate of 40% #1 and 60% #2 for the ULSD group, and 40% #1 with 40% #2 and 20% biodiesel for the B20 group.

ULSD Unit	B20 Match	Model	EPA Cert.	Wheels	Sleeper	Destination
1320	1325	379	2004	Duals	Yes	Minneapolis
1321	1323	379	2004	Duals	Yes	Chicago
1322	1324	379	2004	Duals	Yes	Chicago
1334	1335	379	2004	Singles	Yes	Minneapolis
1340	1341	386	2004	Duals	Yes	Chicago
1347	1348	388	2007	Duals	Yes	Chicago
1349	1346	386	2004	Duals	No	Minneapolis
1376	1336	379	2004	Duals	Yes	Minneapolis
1377	1375	379	2004	Duals	Yes	Minneapolis
1379	1378	379	2004	Duals	Yes	Chicago

Table 1. Unit specifications.

The energy content of B100 is approximately 8% less per gallon than petroleum diesel (Knothe 2005), which translates to an approximate decrease in energy content of 1.5% for the B20 blend. Such a small difference in energy content will make it difficult to precisely gauge any real differences in fuel economy between the ULSD and B20 groups. In fact, our study shows a driver-to-driver variability in fuel economy of over 20%, which could easily mask any real differences in fuel economy. To address this, the two driver groups were matched for historical fuel economy performance where possible. Thirteen of the 20 drivers were current employees who previously ran either short- or long-haul routes, while the remaining drivers had no historical fuel economy data available. Using available data, the pre-study average for the ULSD group was 6.25 ± 0.36 mpg (n of 6) and for the B20 group was 6.40 ± 0.46 mpg (n of 7). The difference in these values was not statistically significant using a two-tailed, unpaired t test ($P = 0.51$). A normality plot suggested that the variation in average fuel efficiencies for both groups followed a Gaussian distribution ($P > 0.10$ for both groups). To further address any possible bias in the driver groups, the groups were switched at a little more than half-way through the study so that the ULSD drivers in the first column of Table I took possession of the corresponding B20 test unit in column two, and vice-versa. If an observed difference in fuel economy between the two groups was due to group variation alone and not fuel type, then one would expect the fuel economy averages to switch as well.

Vehicle Fueling

The decision to use a 20% biodiesel blend for the study was driven by several factors. Most original equipment manufacturers (OEMs) already accept the use of up to 5% biodiesel blends in their equipment, and many have stated that blends up to 20% (or more in some cases) are acceptable (NBB 2006). Recognizing the increased usage of B20, the National Biodiesel Board and other groups formed the B20 Fleet Evaluation Team (B20 FET) to develop fact-based technical guidelines for B20 use, published in their bulletin "Technical Recommendations for B20 Fleet Use Based on Existing Data" (NBB 2005). Most recently, ASTM has introduced the new D7467 standard for biodiesel blends from B6 to B20. In addition, a 20% blend level would allow for a more meaningful and quantitative comparison in fuel quality and performance without being too difficult to implement during the cold Midwestern winters.

Renewable Energy Group supplied 100% soy biodiesel meeting BQ-9000 quality specifications from their Wall Lake, Iowa facility and #2 ULSD petroleum diesel was procured from Des Moines at either the Magellan or British Petroleum (BP) terminals. For cold weather operation, commercial additive was used in both groups per the manufacturer's recommendation at a treatment rate of 1:1000 (1000 ppm) for the ULSD group and 1:500 (2000 ppm) for the B20 group. The B20 blend was obtained by procuring 800 gallons of ULSD from the Magellan or BP pipeline and then bottom-loading 200 gallons of biodiesel from an on-site biodiesel storage facility in Fort Dodge. The blend was then pumped off into a tank wagon located on-site at Decker Truck Lines and re-circulated to ensure proper blending. Analysis of the blended fuel on several occasions revealed an average biodiesel content of 18.9 ± 0.4 percent (n = 4). For winter driving, cold-flow additive was introduced into the tank wagon during re-circulation. The blended fuel was then dispensed into each B20 unit from this tank wagon. ULSD units received fuel from the same shipment of ULSD used to make the B20 blend. Due to availability, the biodiesel used in the study was switched to biodiesel meeting BQ-9000 quality specifications made with 80% soy oil and 20% animal tallow from June 2008 to the end of the study.

Data Collection and Analysis

The study began the first week of October 2006 with a total of 6 tractor trailers; three for the ULSD group and three for the B20 group. New units were added into the study as they were purchased. A total of 12 units were in the study by February 2007 and all 20 units were in the study by April 2007. Data collection for the road portion of the study commenced in October 2006 and continued through the end of November 2008, for a total period of 26 months. Real-time data was collected for each unit using a Qualcomm SensorTRACS performance monitoring system and downloaded once weekly. Channels collected for this study included average speed, total distance, engine idle time, total engine fuel economy (which includes idle time), and moving engine fuel economy (which excludes idle time). Mileage and fuel economy data for this study relied upon the Sensor TRACS data and not individual driver records. Both ULSD and B20 fuel samples were collected at least once a month for fuel analysis including distillation profiles, cetane values, and BTU content. During the months when winter additives were used, fuel samples were also analyzed for cloud and plug points. Used engine oil samples were collected for analysis including wear metals, soot, fuel dilution, moisture, viscosity, total acid number, total base number and ethylene glycol content. Maintenance records were analyzed for overall maintenance and operational costs including fuel-specific items. Because each ULSD unit was specifically paired with a B20 test unit, all statistical data were obtained using pair-wise comparisons assuming a Gaussian distribution of driver performance.

RESULTS

Fuel Economy

The ULSD group logged 2,003,333 miles and the B20 group logged 2,035,968 miles for the entire study. Seasonal variations in fuel economy were noted for both groups, with peak fuel efficiencies for both groups observed in the warmer months from approximately May through October (Figure 1). Along with the reduced fuel economy in the colder months, an increase in fuel filter replacements occurred as might be expected. Also worth mentioning was the general trend for an increase in fuel economy for both groups throughout the study seen in Figure 1. Since all units in the study were new, this may reflect a “breaking in” period for the new engines and other drive-train components, or possibly reduced road friction due to the gradual wearing down of tire tread (Bridgestone Tires). Further continuation of the study would have been required to see any plateau phase to this breaking-in period.

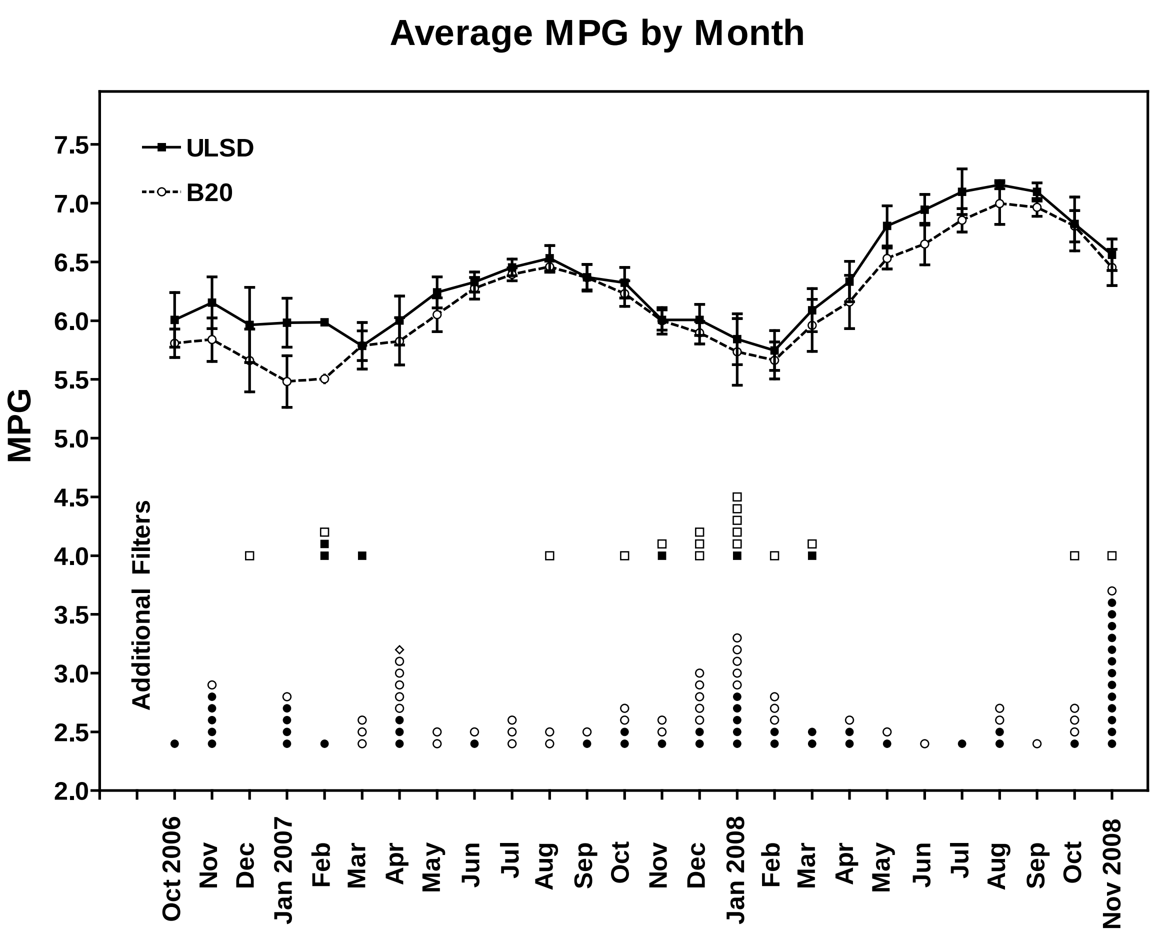


Figure 1. Average fuel economy by month. For presentation purposes, monthly averages were determined for each unit by dividing the total number of miles driven by the total number of gallons consumed by that unit. Each data point represents the monthly average of 10 units for the ULSD group (solid symbols and solid line) and 10 units for the B20 group (open symbols and dashed line). The number of unscheduled fuel filter replacements is also shown for each group by month with the ULSD group represented by squares and the B20 group represented by diamonds. The solid symbols represent filters that were replaced due to actual fouling whereas the open symbols represent filters that were replaced in anticipation of fouling. These data do not include filters replaced during the regular PM-B service intervals.

A comparison of fuel economy (both including and excluding idle time) was made for both groups (Tables 2 and 3). Fuel economy for the entire study was determined by taking the total number of miles traveled by each unit divided by the total number of gallons consumed by that unit (Table 2). The values from the 10 individual units in each group from Table 2 were then averaged to give the overall fuel economy for each group for the entire study with or without idle time (Table 3). Average fuel economy for the ULSD group was 6.34 ± 0.41 mpg while the average economy for the B20 group was slightly reduced at 6.25 ± 0.37 mpg. When comparing unit averages for the entire study using a paired, two-tailed Student's t-test, this reduction in fuel economy was not statistically significant (Table 3). When excluding idle time, fuel economy went up slightly in both groups as would be expected, but again, there was no significant difference in fuel economy between the two groups. These data do not include three weeks during February 2007 when #1 diesel was used in both groups due to a severe cold snap. When using #1 diesel, the average fuel economy for both groups dropped substantially when compared with data from the preceding or following weeks. Average economy for the ULSD group during this time was 5.31 ± 0.78 mpg, and for the B20 group the average fuel economy was 4.99 ± 0.30 mpg. We were not able to tell if this drop in fuel economy was due to the extreme cold or to the different fuel being used, or some combination of the two.

Entire Study Including Idle Time								**Entire Study Excluding Idle Time**							
ULSD				**B20**				**ULSD**				**B20**			
Unit	**Gal.**	**Mi.**	**MPG**	**Unit**	**Gal.**	**Mi.**	**MPG**	**Unit**	**Gal.**	**Mi.**	**MPG**	**Unit**	**Gal.**	**Mi.**	**MPG**
1320	37,800	226	5.98	1325	40,100	241	6.01	1320	37,600	226	6.00	1325	39,700	241	6.08
1321	36,200	231	6.37	1323	35,300	221	6.24	1321	35,900	231	6.42	1323	34,900	221	6.32
1322	35,900	237	6.61	1324	36,300	224	6.18	1322	35,500	237	6.68	1324	35,700	224	6.29
1334	36,300	224	6.16	1335	37,700	229	6.09	1334	36,100	224	6.19	1335	37,300	229	6.14
1340	24,800	180	7.23	1341	21,900	159	7.26	1340	24,600	180	7.32	1341	21,800	159	7.32
1347	22,400	128	5.70	1348	22,500	133	5.92	1347	21,800	128	5.86	1348	22,200	133	6.01
1349	32,500	211	6.50	1346	31,800	202	6.34	1349	32,300	211	6.54	1346	31,800	202	6.37
1376	24,400	150	6.17	1336	32,900	203	6.15	1376	24,300	150	6.18	1336	32,600	203	6.22
1377	32,400	202	6.23	1375	34,700	213	6.16	1377	32,300	202	6.26	1375	34,400	213	6.20
1379	25,700	166	6.47	1378	25,900	159	6.16	1379	25,500	166	6.53	1378	25,500	159	6.25

Table 2. Fuel economy for individual units for the entire study. Fuel economy was determined for each unit by taking the total number of miles traveled divided by the total number of gallons consumed by that unit during the entire study. The number of gallons is rounded to the nearest hundred and the number of miles is reported in thousands and is rounded to the nearest thousand. These data were used with a paired, two-tailed student's t-test with results presented in Table 3.

	Fuel Economy By Unit Including Idle Time				Fuel Economy By Unit Excluding Idle Time				
	ULSD (mpg)	**B20 (mpg)**	**Diff. (%)**	**p Value**	**ULSD (mpg)**	**B20 (mpg)**	**Diff. (%)**	**p Value**	***n***
Entire Study	6.34 ± 0.41	6.25 ± 0.37	-1.37	0.1647	6.40 ± 0.41	6.32 ± 0.37	-1.25	0.1619	10

Table 3. Fuel economy by group when averaged by unit for the entire study. Fuel economy was determined by averaging the fuel economy obtained by each unit for the specified period as shown in Table 2. The stated percent differences are relative to the ULSD values. No significant difference in fuel economy was found between the ULSD and B20 groups when comparing the values using paired, two-tailed student's t-tests.

Driver selection for the study was done carefully to minimize variability due to driver performance. However, the possibility exists that each population of 10 drivers picked for the study may exhibit a different group average fuel economy by chance. If this were the case, it would be difficult to ascertain whether any differences in fuel economy were due to the fuel type or due to a difference in group driver performance. To account for this possibility, the drivers from the ULSD group switched units with the corresponding drivers from the B20 group during the month of January 2008. Fuel economy for each group was calculated for the original assignment of drivers from October 2006 through December 2007 (Original Assignment) and then again for each group after driver reassignment from February 2008 to November 2008 (Reassignment; Tables 4 and 5). The values from the 10 individual units in each group from Table 4 and 5 were then averaged to give the overall fuel economy for each group for the entire study with or without idle time (Table 6). Fuel economy for both groups increased from the first year to the second year of the study; however, the B20 group again experienced a slight, albeit insignificant, reduction in fuel economy regardless of the population of drivers assigned to this group.

Original Assignment Including Idle Time								Original Assignment Excluding Idle Time							
ULSD				**B20**				**ULSD**				**B20**			
Unit	**Gal.**	**Mi.**	**MPG**	**Unit**	**Gal.**	**Mi.**	**MPG**	**Unit**	**Gal.**	**Mi.**	**MPG**	**Unit**	**Gal.**	**Mi.**	**MPG**
1320	23,100	132	5.71	1325	26,200	149	5.70	1320	23,100	132	5.72	1325	25,900	149	5.77
1321	21,900	135	6.17	1323	18,700	116	6.22	1321	21,800	135	6.20	1323	18,500	116	6.29
1322	22,700	149	6.55	1324	19,700	115	5.84	1322	22,400	149	6.62	1324	19,400	115	5.92
1334	19,400	118	6.10	1335	20,300	118	5.82	1334	19,300	118	6.14	1335	20,200	118	5.85
1340	10,500	77	7.31	1341	11,800	82	6.96	1340	10,500	77	7.36	1341	11,700	82	7.02
1347	14,200	80	5.59	1348	11,800	70	5.91	1347	13,700	80	5.81	1348	11,800	70	5.94
1349	15,300	95	6.22	1346	18,000	111	6.20	1349	15,300	95	6.25	1346	17,900	111	6.22
1376	12,300	76	6.22	1336	16,400	101	6.15	1376	12,200	76	6.27	1336	16,300	101	6.18
1377	16,300	98	6.01	1375	19,000	116	6.09	1377	16,200	98	6.05	1375	18,900	116	6.12
1379	13,800	88	6.33	1378	13,900	86	6.19	1379	13,600	88	6.42	1378	13,800	86	6.20

Table 4. Fuel economy for individual units with the original driver assignment. Fuel economy was determined for each unit by taking the total number of miles traveled divided by the total number of gallons consumed by that unit during the portion of the study utilizing the original driver assignment. The number of gallons is rounded to the nearest hundred and the number of miles is reported in thousands and is rounded to the nearest thousand. These data were used with a paired, two-tailed student's t-test with results presented in Table 6.

Reassignment Including Idle Time								Reassignment Excluding Idle Time							
ULSD				B20				ULSD				B20			
Unit	Gal.	Mi.	MPG	Unit	Gal.	Mi.	MPG	Unit	Gal.	Mi.	MPG	Unit	Gal.	Mi.	MPG
1320	14,600	94	6.41	1325	13,900	92	6.58	1320	14,600	94	6.44	1325	13,800	92	6.65
1321	14,300	95	6.69	1323	16,700	104	6.26	1321	14,100	95	6.76	1323	16,400	104	6.35
1322	13,200	89	6.71	1324	16,600	109	6.59	1322	13,000	89	6.79	1324	16,300	109	6.73
1334	16,900	105	6.23	1335	17,400	111	6.40	1334	16,800	105	6.26	1335	17,100	111	6.49
1340	14,300	103	7.18	1341	10,100	77	7.61	1340	14,100	103	7.29	1341	10,100	77	7.66
1347	8,100	48	5.88	1348	10,700	64	5.93	1347	8,100	48	5.94	1348	10,500	64	6.06
1349	17,200	116	6.75	1346	13,800	90	6.52	1349	17,000	116	6.80	1346	13,700	90	6.57
1376	12,100	74	6.08	1336	16,500	102	6.16	1376	12,100	74	6.10	1336	16,300	102	6.26
1377	16,100	104	6.44	1375	15,600	97	6.23	1377	16,100	104	6.47	1375	15,500	97	6.30
1379	11,900	79	6.62	1378	12,000	74	6.13	1379	11,800	79	6.66	1378	11,700	74	6.31

Table 5. Fuel economy for individual units after driver reassignment. Fuel economy was determined for each unit by taking the total number of miles traveled divided by the total number of gallons consumed by that unit during the latter portion of the study after driver reassignment. The number of gallons is rounded to the nearest hundred and the number of miles is reported in thousands and is rounded to the nearest thousand. These data were used with a paired, two-tailed student's t-test with results presented in Table 6.

	Fuel Economy By Unit Including Idle Time				Fuel Economy By Unit Excluding Idle Time				
	ULSD (mpg)	B20 (mpg)	Diff. (%)	p Value	ULSD (mpg)	B20 (mpg)	Diff. (%)	p Value	*n*
Original Assign.	6.22 ± 0.48	6.11 ± 0.35	-1.78	0.2398	6.28 ± 0.46	6.15 ± 0.35	-2.10	0.1421	10
New Assignment	6.50 ± 0.38	6.44 ± 0.46	-0.86	0.5548	6.55 ± 0.39	6.54 ± 0.44	-0.20	0.8864	10

Table 6. Fuel economy by group when averaged by unit for the original driver assignment and after driver reassignment. Fuel economy was determined by averaging the fuel economy obtained by each unit for the specified period as shown in Tables 4 and 5. The stated percent differences are relative to the ULSD values. No significant differences in fuel economy were found between the ULSD and B20 groups in all cases when comparing the values using paired, two-tailed student's t-tests.

Driver-to-driver variability in fuel consumption within each group was several-fold greater than the overall difference in fuel consumption between the two groups (Figure 2). From the initial assignment, driver economy in the ULSD group ranged from a high of 7.30 mpg to a low of 5.65 mpg, which represents a 22.6% difference in driver performance. In the B20 group, driver economy ranged from 6.96 mpg to 5.72 mpg which represents a difference of 16.3%. After driver reassignment, driver variability for the ULSD group was at 17.7% which was similar to the 16.3% variability when these drivers were initially assigned to the B20 group. Variability in the B20 group after reassignment was 22.8% which was similar to the 22.6% variability when these drivers were originally assigned to the ULSD group. These data suggest that driver performance is not related to fuel type.

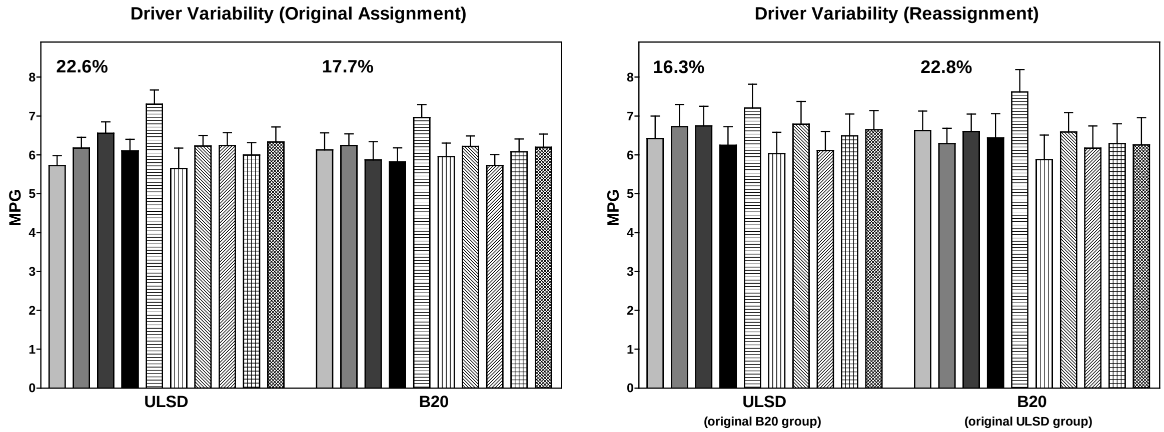


Figure 2. Driver variability. Bars represent the average weekly fuel economy for each unit ± SD.

Given The significant driver-to-driver variation, it is possible that any real, albeit slight, differences in fuel economy will be masked by the relatively small sample size of only 10 drivers per group. As such, an additional approach was taken for comparing fuel economy between the two groups where weekly averages were calculated for each group and used for a pair-wise comparison over the entire 112 weeks of the study. This approach of using weekly group averages instead of individual unit averages will minimize the driver-to-driver variation observed when calculating the unit averages. When using this approach, the difference in fuel economy was statistically significant in all cases when using paired, two-tailed Student's t-tests (Table 7). Given the relatively large driver-to-driver variations in fuel economy, a paired group-wise comparison such as this may be more appropriate than comparing individual matched units when attempting to detect small differences in fuel economy with studies utilizing a relatively small sample size. It should be pointed out that regardless of the statistical method used to analyze the data, addressing the much larger driver-to-driver variability in a fleet will be more meaningful for the management of overall fuel economy given the small differences in fuel economy attributed to fuel type.

	Fuel Economy By Group Including Idle Time				**Fuel Economy By Group Excluding Idle Time**				
	ULSD (mpg)	**B20 (mpg)**	**Diff. (%)**	**p Value**	**ULSD (mpg)**	**B20 (mpg)**	**Diff. (%)**	**p Value**	***n***
Entire Study	6.35 ± 0.45	6.19 ± 0.46	-2.49	<0.0001	6.40 ± 0.44	6.25 ± 0.44	-2.25	<0.0001	109
Original Assign.	6.15 ± 0.26	5.99 ± 0.33	-2.55	<0.0001	6.21 ± 0.27	6.04 ± 0.31	-2.64	<0.0001	63
New Assignment	6.62 ± 0.51	6.46 ± 0.49	-2.45	<0.0001	6.66 ± 0.49	6.54 ± 0.43	-1.80	<0.0001	46

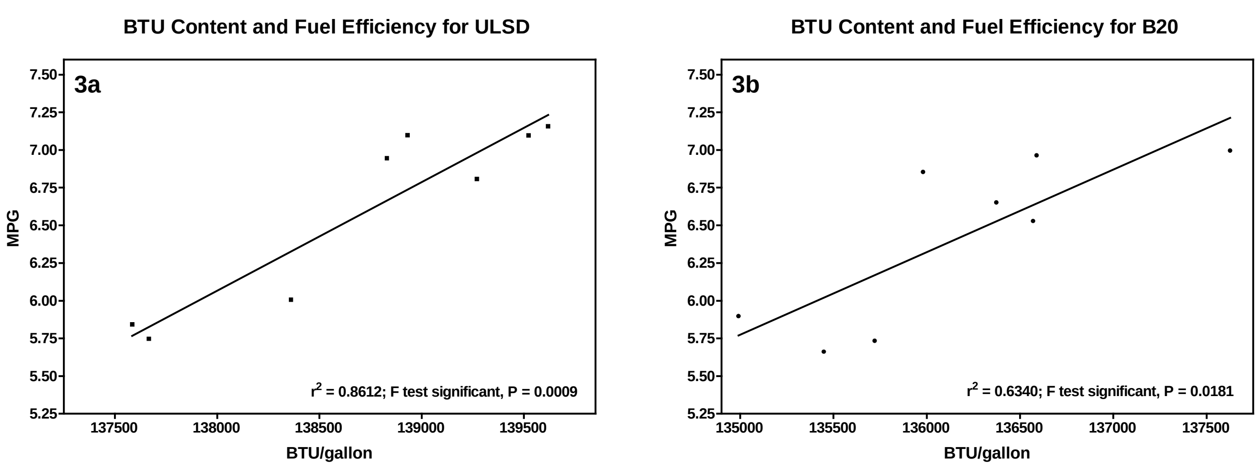
Table 7. Fuel economy by group when averaged by week. Fuel economy was determined by averaging the fuel economy obtained by each group on a weekly basis for the specified period. The stated percent differences are relative to the ULSD values. The differences in fuel economies were significant in all cases when comparing the values using paired, two-tailed student's t-tests.

Fuel Properties

Fuel samples were routinely analyzed for cetane value, distillation profile and energy content using ASTM procedures. During the winter driving months, the fuels were also analyzed for cloud and plug point values (Table 8 and Figures 3 and 4). As expected, the average BTU content of the blended fuel is slightly less than ULSD alone (compare 141,385 BTU/gallon for ULSD with 138,551 BTU/gallon for B20) and the cetane value of the blended fuel is slightly higher than that for ULSD (compare a value of 45.19 for B20 with 43.40 for ULSD; Table 8). For the months where BTU content was analyzed, we found a positive correlation between BTU content and fuel economy for both groups (Figure 3a and 3b). We found no correlation between cetane values and fuel economy for either group (Figure 3c and 3d). The distillation profiles of both fuels were similar as expected, with the B20 blend showing slightly higher distillation temperatures (Figure 4). Both fuels were additized with a commercial additive for winter driving. The cloud points of the additized fuels averaged 3.9 °F for ULSD and 5.6 °F for B20 and the cold filter plugging point of the fuels averaged -25.6 °F for ULSD and -19.4 °F for B20 (Table 8).

	ULSD	***n***	**B20**	***n***	**Difference**
BTU/gallon	141,385	10	138,551	10	-2.00%
Cetane Value	43.40	10	45.19	10	4.12%
Cloud Point	3.9 ± 2.8	22	5.6 ± 3.4	27	1.7
Cold Filter Plug Point	-25.6 ± 10.4	21	-19.4 ± 8.0	26	6.2

Table 8. Fuel properties. Temperatures are in degrees Fahrenheit. The stated percent differences are relative to the ULSD values. The BTU content was determined according to ASTM D240 and the cetane value was determined by ASTM D 613. Cold-flow properties were determined according to ASTM D 2500 (cloud point) and ASTM D 6371 (cold filter plugging point).



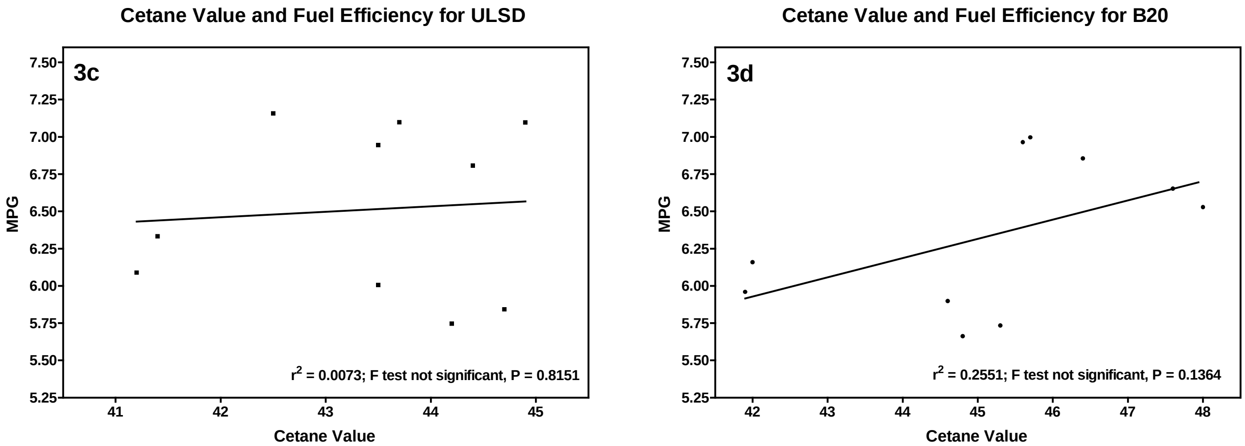


Figure 3. Correlation plots for BTU content and fuel economy, and cetane values and fuel economy. Monthly BTU content and cetane values were obtained from December 2007 to the end of the study and plotted with the monthly average fuel economy for each group. Linear regression was performed and a correlation was established by performing an F test to determine whether the slope of the linear regression was significantly different than zero.

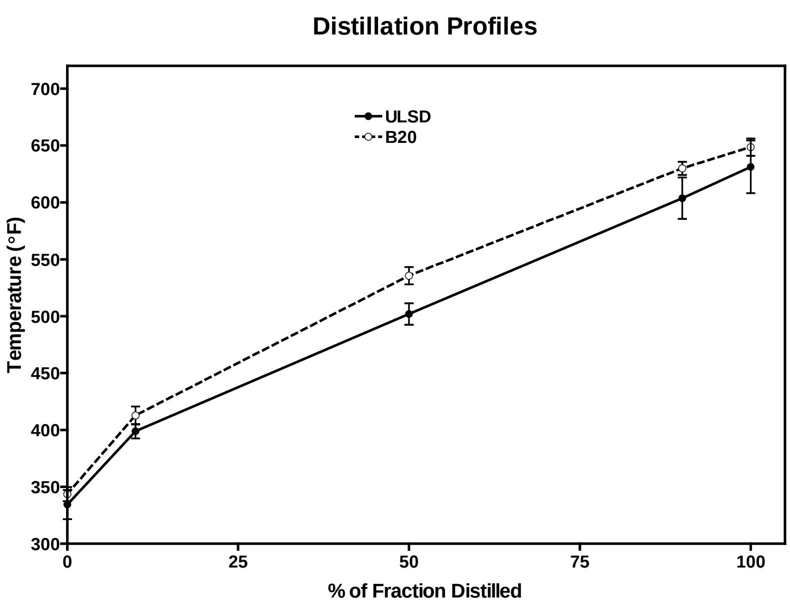


Figure 4. Distillation profiles. Distillations were performed according to ASTM D 1160. The initial and final distillation temperatures were recorded in addition to the temperatures corresponding to 10%, 50% and 90% distillation. Error bars represent the average of 10 determinations ± SD.

Winter Driving

Winter driving produced relatively few problems regarding cold-flow issues. Fuel for both groups was treated with a commercial fuel additive, and #1 diesel was used for a brief time during a severe cold snap in February 2007. No drivers experienced fuel gelling problems; however, several episodes of fuel filter fouling and/or unscheduled fuel filter replacements did occur. The majority of these incidents occurred during the colder months (Figure 1), and the B20 group experienced a major filter plugging episode during the last month of the study (November 2008). This single episode accounted for one fourth of all the plugged filters for the B20 group. The cloud point and plug point data suggest several instances where one or both fuels were not treated with cold flow improver during the cold weather which may have been the case in November 2008 when an unexpected cold snap occurred (data not shown). The combination of improperly treated fuel and unexpected cold snaps may have contributed to as many as 20 or more plugged filters in the B20 group during the study.

Approximately two-thirds of the unscheduled fuel filter replacements for the B20 group occurred on the Minneapolis route (Table 9); however, this was due to a substantially greater number of filters being replaced as a preventive measure. The actual number of plugged filters was similar for B20 units on either route with the Chicago units experiencing a plugged filter every 37,400 miles and the Minneapolis units experiencing one every 41,800 miles.

9a. Minneapolis route.

ULSD					B20			
Unit #	**Fouled**	**Preventive**	**Total**		**Unit #**	**Fouled**	**Preventive**	**Total**
1320	0	4	4		1325	9	7	16
1334	0	3	3		1335	4	10	14
1349	2	1	3		1346	5	6	11
1376	1	1	2		1336	2	7	9
1377	1	1	2		1375	6	7	13
TOTALS	**4**	**10**	**14**		**TOTALS**	**26**	**37**	**63**

9b. Chicago route.

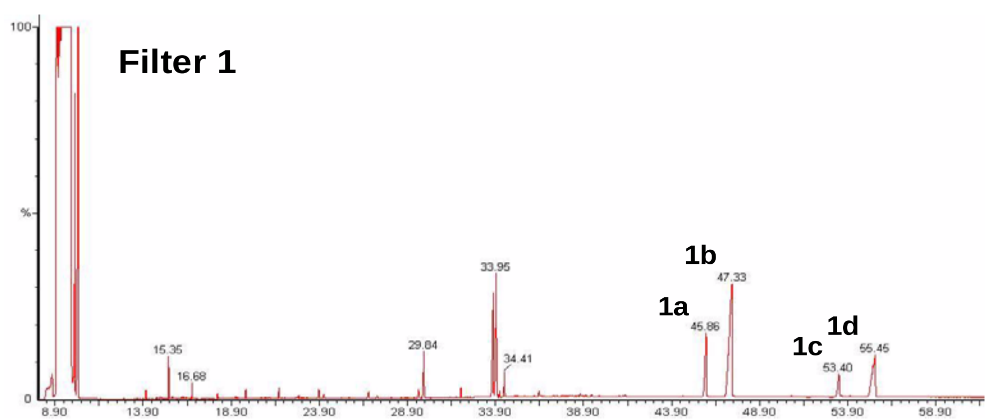
ULSD					B20			
Unit #	**Fouled**	**Preventive**	**Total**		**Unit #**	**Fouled**	**Preventive**	**Total**
1321	0	1	1		1323	8	7	15
1322	0	2	2		1324	9	1	10
1340	0	1	1		1341	2	1	3
1347	2	0	2		1348	2	0	2
1379	0	3	3		1378	3	1	4
TOTALS	**2**	**7**	**9**		**TOTALS**	**24**	**10**	**34**

Table 9. Unscheduled fuel filter replacements. The number of unscheduled fuel filter replacements was given for each matched pair of units traveling to either Minneapolis (9a) or Chicago (9b). An unscheduled fuel filter replacement refers to fuel filters that were replaced due to actual fouling (Fouled) as well as replacement of fuel

filters during PM-A service in anticipation of cold weather and/or possible fouling (Preventive). These do not include fuel filter replacements that are a normal part of the PM-B service procedure.

It is interesting to note that the rate of filter plugging was not consistent across the B20 group. In fact, only three units were responsible for half of the plugged filters (units 1323, 1324 and 1325), while four units experienced 3 or fewer plugged filters for the entire study (units 1336, 1341, 1348 and 1378). Even when correcting for the fact that the lowest-plugging units entered the study at later dates, the highest-plugging units experienced a plugged filter on average every 26,380 miles whereas the lowest-plugging units experienced one every 72,770 miles. While no specific cause has been linked to an increase in filter plugging in some units compared to others, contributing factors may include the route driven and driver habits such as the extent of engine idling and if the unit was left outside overnight.

Several filters from the B20 group were removed for analysis by GC/MS (Figure 5). Visual inspection revealed an off-white substance with the consistency of petroleum jelly present on filters 1, 2 and 4, with filter 1 containing large amounts of the substance. Filter 3 was permeated throughout with fuel, as expected, but did not have any unusual presentation otherwise. The filter residues were analyzed using a modified version of ASTM D 6584 (Table 10) followed by mass spectrometry. The analysis revealed a mixture consisting of the B20 blend and several higher molecular mass compounds for filters 1, 2 and 4, with filter 3 revealing the B20 mixture only. In all chromatograms, the multiple peaks having retention times between 13 and 30 minutes represent diesel hydrocarbons whereas the peaks at approximately 34 minutes represent biodiesel methyl esters. The prominent peaks between 44 and 56 minutes on filters 1, 2 and 4 represent silylated monoglyceride species derived from palmitic acid, stearic acid and eicosanoic acid; all fully saturated fatty acids (Table 5). Filter 3 contained a very small amount of high molecular mass compounds that were evident when using the ASTM D 6584 method, but we were not able to resolve these peaks using the column and reduced temperature method available to us at the time (data not shown).



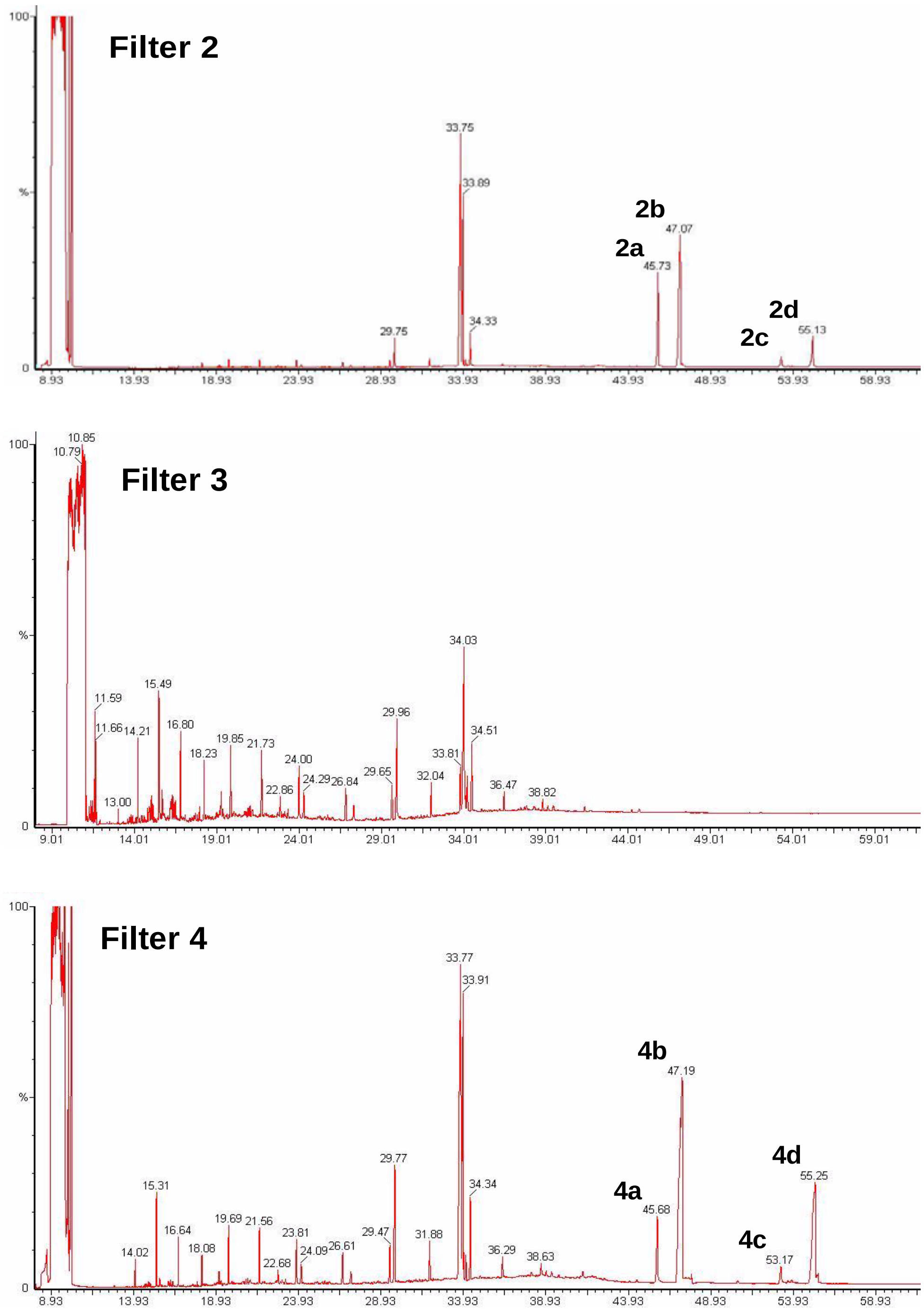


Figure 5. Analysis of filter residues by GC/MS. Data for individual peaks is given in Table 5.

Ramp Rate (°C/min)	Ramp Temperature (°C)	Hold (min)
15	180	0
7	230	10
10	290	38

Table 10. Oven program for filter analysis by GC/MS. Samples were derivatized using N-methyl-N-(trimethylsilyl)trifluoroacetamide (MSTFA) and run according to ASTM D 6584 with the oven program modified for the lower temperature limits of the column and mass spectrometer. The column used was an Elite-Petro 100 m column with a 0.25 mm diameter (Perkin Elmer, Waltham, Massachusetts).

Filter and Peak #	Peak Retention Time (min)	Molecular Mass (g/mol)	Peak Identification
1a	45.86	474	Silylated 2-monopalmitate
1b	47.33	474	Silylated 1-monopalmitate
1c	53.40	502	Silylated 2-monostearate
1d	55.45	530	Silylated 1-monoeicosanoate
2a	45.73	474	Silylated 2-monopalmitate
2b	47.07	474	Silylated 1-monopalmitate
2c	~53.0	502	Silylated 2-monostearate
2d	55.13	530	Silylated 1-monoeicosanoate
4a	45.68	474	Silylated 2-monopalmitate
4b	47.19	474	Silylated 1-monopalmitate
4c	53.17	502	Silylated 2-monostearate
4d	55.25	530	Silylated 1-monoeicosanoate

Table 11. Components of fuel filter residue identified by mass spectrometry. The sample from filter 3 did not resolve any materials other than the B20 blended fuel.

After an initial bout of cold weather and subsequent fuel filter fouling episodes early in the study, fuel filter heaters were purchased and installed on the B20 units with the intention of purchasing and installing them on the ULSD units as well. However, the cost of such prevented the placement of any fuel filter heaters in the ULSD group and the units in the B20 group were subsequently removed as a matter of consistency. No discernible differences in the rate of fuel filter fouling in the B20 group were noted when comparing the time period during which the filter heaters were used with the rest of the study when the filter heaters were not in use (data not shown).

Maintenance Records

Maintenance records were analyzed for the total cost of maintenance and repairs for each unit in the ULSD and B20 groups (Tables 12 and 13). The maintenance data were categorized into several groups. Preventive maintenance (PM) items included the PM-A and PM-B services in addition to the costs associated with additional fuel filter replacements, either as a result of actual filter plugging or in anticipation of filter plugging. Fuel-related engine costs included items that potentially could be fuel-related such as injector replacements, exhaust issues, replacement of crankcase filters, or issues with regeneration of the diesel particulate filter on the 2007 EPA Certified engines. It should be noted that repairs in this category were not actually attributed to fuel usage but rather would have the potential to be. In fact, no units in either group experienced any engine malfunctions that were felt to be directly attributable to fuel usage. Unit #1348 in the B20 group (which was equipped with the 2007 EPA Certified engine) had to be removed two weeks after entering the study for an engine replacement due to malfunctions in the electronics and sensors relating to the emissions control systems. The replacement costs were covered under warranty and were not disclosed in the maintenance records. Non-fuel related engine costs included items related to the starter, power steering, air conditioning, and block heater; in addition to belt replacements and transmission and clutch adjustments. Another category included costs associated with tires, axles, brakes and suspension components; and the category of miscellaneous expenses included costs associated with inspections, structural components not related to accidents, lights and other electrical issues, and any miscellaneous work requested by the drivers. Two major accidents were recorded during the study: one unit in the ULSD group (# 1376) experienced a major rollover accident towards the end of the study with repairs exceeding $25,000, and one unit in the B20 group (# 1378) experienced a significant accident with repairs approaching $9,000. Because any one such incident can significantly affect the maintenance and repairs cost totals, we felt it necessary to disclose these items in a separate category of accident costs.

The overall maintenance and repairs costs for the two groups, including accident costs, were comparable (Tables 12 and 13). On a cost-per-mile basis, total maintenance and repairs costs were 4.08 cents/mile for the ULSD group and 3.30 cents/mile for the B20 group (Table 14). Because of the unpredictable nature of maintenance and repairs costs (i.e. accidents), a more meaningful analysis might be to look at the costs associated with the preventive maintenance and possible fuel-related engine repairs. Total preventive maintenance costs were $17,880 for the ULSD group and $21,882 for the B20 group (Tables 12 and 13). On a cost-per-mile basis, this represents a preventive maintenance cost of 0.893 cents/mile for the ULSD group and a cost of 1.075 cents/mile for the B20 group, or an increase of 20.4% for the B20 group (Table 14). To determine what was responsible for this cost difference, the preventive maintenance data was broken down and analyzed further.

ULSD Unit	Miles	Total PM Cost ($)	Total Engine Costs; Fuel Related ($)	Total Engine Costs; Non-fuel Related ($)	Costs: Tires, Axles, etc ($)	Total Miscell. Costs ($)	Accident costs ($)	Total Maintenance & Repair Costs ($)
1320	233,547	1,504	0	28	2,113	984	4,125	8,755
1321	239,192	2,247	0	62	459	1,206	0	3,974
1322	243,990	1,912	52	17	967	466	0	3,415
1334	232,131	2,353	48	348	2,512	1,234	0	6,495
1340	179,733	941	67	0	838	359	0	2,204
1347	129,071	966	581	290	3,357	480	3,196	8,870
1349	218,494	2,063	65	20	3,505	785	0	6,438
1376	150,190	1,606	0	355	1,077	2,000	24,025	29,064
1377	210,699	2,214	0	56	4,703	1,673	0	8,646
1379	166,286	1,434	201	35	801	805	0	3,276
Totals:	**2,003,330**	**17,880**	**1,014**	**1,211**	**20,332**	**9,992**	**31,346**	**81,777**

Table 12. Overall maintenance and repair costs for ULSD units

B20 Unit	Miles	Total PM Cost ($)	Total Engine Costs; Fuel Related ($)	Total Engine Costs; Non-fuel Related ($)	Costs: Tires, Axles, etc ($)	Total Miscell. Costs ($)	Accident costs ($)	Total Maintenance & Repair Costs ($)
1323	226,965	2,508	176	55	625	2,180	0	5,543
1324	230,222	2,515	272	407	853	931	0	4,976
1325	249,465	2,689	0	82	3,252	2,103	0	8,126
1335	237,239	3,313	0	37	5,105	1,212	0	9,666
1336	208,188	1,643	0	75	4,040	993	0	6,752
1341	159,439	1,134	11	15	462	1,532	0	3,155
1346	210,344	2,451	0	16	1,131	259	0	3,857
1348	133,492	1,589	1,408	193	894	1,238	0	5,322
1375	221,198	2,485	0	30	1,485	2,389	0	6,389
1378	159,416	1,555	0	13	2,073	1,058	8,788	13,486
Totals:	**2,035,970**	**21,882**	**1,867**	**923**	**19,920**	**13,895**	**8,788**	**67,272**

Table 13. Overall maintenance and repair costs for B20 units.

Group	Miles	Total PM Cost (¢ per mi.)	Total Engine Costs; Fuel Related (¢ per mi.)	Total Engine Costs; Non-fuel Related (¢ per mi.)	Costs: Tires, Axles, etc (¢ per mi.)	Total Miscell. Costs (¢ per mi.)	Accident costs (¢ per mi.)	Total Maintenance & Repair Costs (¢ per mi.)
ULSD	2,003,330	0.893	0.051	0.060	1.015	0.499	1.565	4.082
B20	2,035,970	1.075	0.092	0.045	0.978	0.682	0.432	3.304

Table 14. Total maintenance and repairs costs expressed in cents per mile.

The preventive maintenance “A” level service (PM-A) includes a chassis lubrication only; however, on several occasions, the fuel filters were replaced in anticipation of filter fouling during the PM-A service. When comparing the cost of the PM-A service alone, the average cost for each service is nearly identical for each group with $22.28 for the ULSD group and $21.92 for the B20 group (Tables 15 and 16). However, the service interval for the B20 group was shorter at 23,136 miles compared with 24,431 miles for the ULSD group, which means that more PM-A services were performed with the B20 group during the study (88 with the B20 group compared with 82 for the ULSD group; Tables 18 and 19). In addition, the cost of replacing fuel filters as a precautionary measure was approximately $400 more in the B20 group.

The preventive maintenance “B” level service (PM-B) costs were higher for the B20 group as well (Tables 15 and 16). This service includes an oil change, replacement of the oil and fuel filters, and chassis lubrication. During the PM-B service, additional items may be replaced including coolant filters and air filters. When looking at the cost of the basic PM-B level service, the average cost is again nearly identical with $145.11 for the ULSD group and $144.66 for the B20 group for each service. However, the service interval for the B20 group was 18,852 miles compared with 19,835 miles for the ULSD group, translating to several more PM-B level services performed on the B20 group during the study (107 with the B20 group compared with 101 for the ULSD group; Tables 18 and 19). In addition, the B20 group recorded more coolant filter replacements (11 compared with 6 for the ULSD group) and more air filter replacements (23 compared with 13 for the ULSD group), adding an additional $638 dollars to the cost of PM-B service for the B20 group for these items.

ULSD Unit	Miles	PM-A Cost ($)	Cost of Additional Filters ($)	Total PM-A Cost ($)	Total PM-B Cost ($)	Cost of Plugged Filters ($)	Total PM Costs ($)	Total Cost per Mile (¢)
1320	233,547	198	27	226	1,278	0	1,504	0.644
1321	239,192	323	6	329	1,918	0	2,247	0.939
1322	243,990	154	24	178	1,735	0	1,912	0.784
1334	232,131	341	36	377	1,976	0	2,353	1.014
1340	179,733	82	12	94	847	0	941	0.523
1347	129,071	0	0	0	966	144	1,110	0.860
1349	218,494	184	12	196	1,868	432	2,495	1.142
1376	150,190	141	16	157	1,449	37	1,643	1.094
1377	210,699	192	12	204	2,011	28	2,242	1.064
1379	166,286	212	24	236	1,198	0	1,434	0.862
Total Cost ($):		**1,827**	**169**	**1,997**	**15,246**	**641**	**17,879**	--

Table 15. Total preventive maintenance costs for ULSD units.

B20 Unit	Miles	PM-A Cost ($)	Cost of Additional Filters ($)	Total PM-A Cost ($)	Total PM-B Cost ($)	Cost of Plugged Filters ($)	Total PM Costs ($)	Total Cost per Mile (¢)
1323	226,965	267	83	350	2,003	155	2,508	1.105
1324	230,222	269	10	279	2,018	217	2,515	1.092
1325	249,465	262	135	397	2,131	161	2,689	1.078
1335	237,239	332	113	445	2,243	626	3,313	1.397
1336	208,188	220	77	297	1,292	54	1,643	0.789
1341	159,439	119	6	125	777	232	1,134	0.712
1346	210,344	167	70	238	2,091	122	2,451	1.165
1348	133,492	44	0	44	1,496	50	1,589	1.191
1375	221,198	232	70	302	1,947	235	2,485	1.123
1378	159,416	15	10	25	1,433	96	1,555	0.975
Total Cost:		**1,927**	**574**	**2,504**	**17,431**	**1,948**	**21,882**	--

Table 16. Total preventive maintenance costs for B20 units.

Group	Miles	PM-A Cost (¢ per mi.)	Cost of Additional Filters (¢ per mi.)	Total PM-A Cost (¢ per mi.)	Total PM-B Cost (¢ per mi.)	Cost of Plugged Filters (¢ per mi.)	Total PM Costs (¢ per mi.)
ULSD	2,003,330	0.091	0.008	0.100	0.761	0.032	0.893
B20	2,035,970	0.095	0.028	0.123	0.856	0.096	1.075

Table 17. Total preventive maintenance costs expressed in cents per mile.

ULSD Unit	Miles	A-service	A-service Interval (mi.)	B-service	B-service Interval (mi.)
1320	233,547	7	33,364	9	25,950
1321	239,192	9	26,577	12	19,933
1322	243,990	9	27,110	12	20,333
1334	232,131	17	13,655	13	17,856
1340	179,733	3	59,911	6	29,956
1347	129,071	0	--	7	18,439
1349	218,494	10	21,849	12	18,208
1376	150,190	9	16,688	9	16,688
1377	210,699	11	19,154	13	16,208
1379	166,286	7	23,755	8	20,786
AVERAGE	**200,333**	**8.2**	**24,431**	**10.1**	**19,835**

Table 18. Preventive maintenance intervals for ULSD units.

B20 Unit	Miles	A-service	A-service Interval (mi.)	B-service	B-service Interval (mi.)
1323	226,965	10	22,697	13	17,459
1324	230,222	8	28,778	12	19,185
1325	249,465	12	20,789	13	19,190
1335	237,239	18	13,180	13	18,249
1336	208,188	9	23,132	8	26,024
1341	159,439	3	53,146	6	26,573
1346	210,344	11	19,122	12	17,529
1348	133,492	3	44,497	9	14,832
1375	221,198	13	17,015	12	18,433
1378	159,416	1	--	9	17,713
AVERAGE	**203,597**	**8.8**	**23,136**	**10.7**	**18,852**

Table 19. Preventive maintenance intervals for B20 units.

To summarize, several factors contributed to the higher preventive maintenance costs for the B20 group. While the cost of each individual PM-A and PM-B level service was nearly identical for each group, the B20 group exhibited a shorter mileage interval for each of these services which translated to more of these services being performed for the B20 group during the study. In addition, the B20 group had more fuel filters replaced in anticipation of filter fouling and also had more coolant and air filter replacements compared to the ULSD group. Furthermore, the costs associated with fouled filters were three times higher in the B20 group ($1,948 with the B20 group compared with $640 for the ULSD group; Tables 15 and 16). Taken together, all of these factors contributed significantly to the 20% increase in preventive maintenance costs for the B20 group.

Engine repairs that could possibly be related to fuel usage were relatively minor for both groups (Tables 15 and 16). In the ULSD group, unit #1347 (equipped with the 2007 EPA Certified engine) had several problems with the regeneration unit including replacement of the after-treatment regeneration device (ARD) assembly ($365) and replacement of some of the exhaust components ($120). In addition, this unit had to have the crankcase seals replaced ($95). Aside from some exhaust work on the other units, the only other repair worth noting in the ULSD group was a broken valve spring in unit # 1379 ($201). In the B20 group, the 2007 EPA Certified unit #1348 also had several problems with the regeneration unit including one episode where the unit failed to regenerate, costing approximately $1000 to repair. In addition, this unit required several crankcase filter replacements ($400). Other notable expenses for the B20 group include a new fuel sending unit for unit # 1323 ($125) and replaced injectors in unit #1324 ($242; this was not felt to be fuel-related at the time). Collectively, the engine repair costs that could be associated with fuel usage were less than 3% of the total maintenance and repair costs for both groups; and most of the expense in this category was associated with problems arising from the 2007 EPA Certified regeneration system on each of the ULSD and B20 units that were so equipped.

Engine Oil Analysis

Engine oil samples were taken periodically at the 18,000 mile oil drain interval to analyze wear, additive and contaminant metals by Shell Lube Analyst (Stafford, Texas). Several readings were below the limit of quantification; the values reported in Table 20 represent the averages for quantifiable data. Iron, chromium, copper, and lead are indicators of engine wear (Bently Tribology Services) and show no differences in concentration betweeen the ULSD and B20 units (Figure 6 and Table 20). These metals all showed a decreasing trend throughout the study with the exception of lead which showed an increasing trend which was more pronounced in the ULSD group. Several metals are associated with the oil additive package and include calcium and magnesium from detergents and phosphorus and zinc from zinc dialkyldithiophosphate (zddp), a polar substance added to engine oils to help protect metal surfaces against wear. Both groups exhibit similar levels of these elements and the concentrations remained relatively constant throughout the two-year period with the exception of magnesium which showed a decreasing trend (Figure 7 and Table 20). It should be noted that several metals show a trend in decreasing concentration throughout the study. In some cases these trends achieved statistical significance when testing for non-zero slope; however, one needs to consider the relevance of the statistical test when considerinig the degree of scatter in the data. No other significant differences were found for the remaining metals tested (Table 20).

Kinematic viscosity was similar for both groups, with 14.9 centistokes for the ULSD group and 14.7 centistokes for the B20 group. The reported value for unused oil was 15.5 centistokes (Shell 2007). Residual water content was below 0.1%, for both ULSD and B20 units and no glycol was detected in engine oil from either group. Total acid number (TAN) and total base number (TBN) values were determined for the B20 group only (Table 20) and were found to be in-line with reported values from other studies. The reported TBN value for unused oil was 10.1 mg KOH/g (Shell 2007).

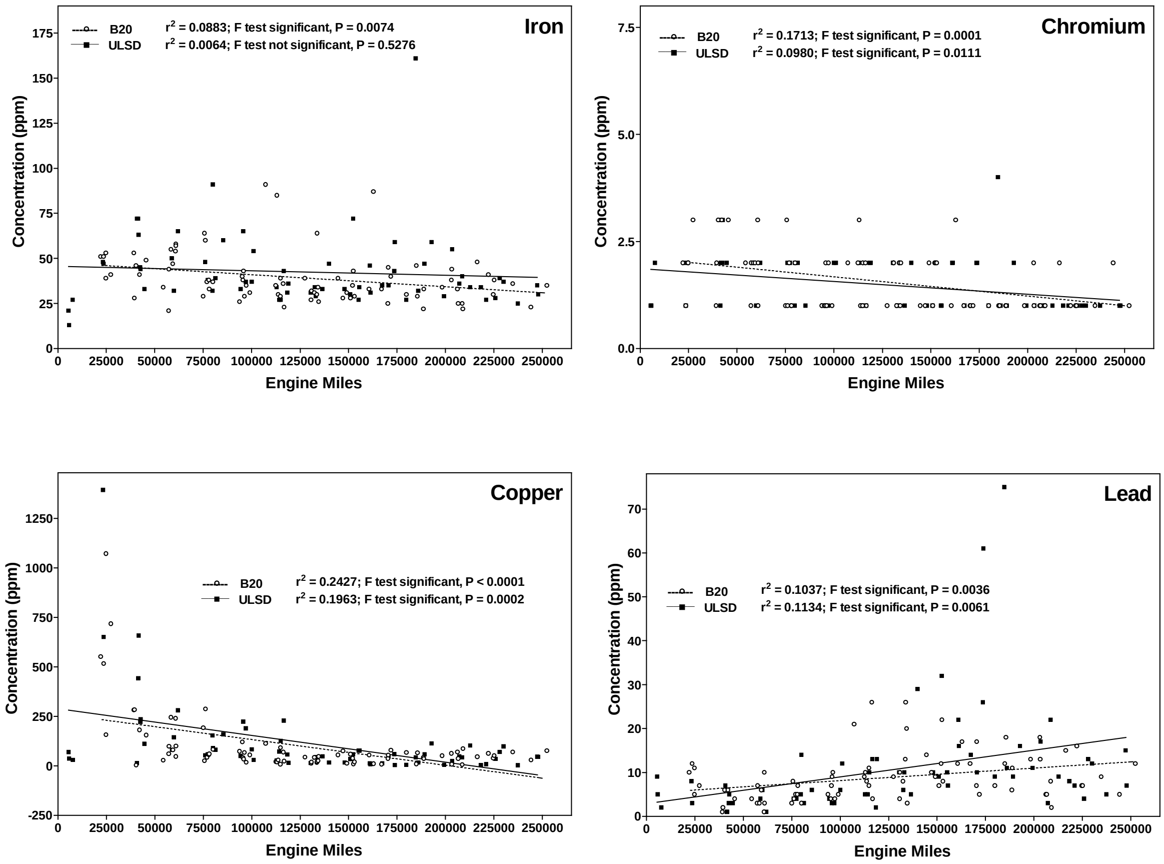


Figure 6. Metals analysis for iron, chromium, copper and lead. Concentration of metals in used engine oil was determined by ASTM D 5185. The average oil drain interval was 18,653 ± 896 miles for the ULSD group and 18,319 ± 1081 miles for the B20 group. Linear regression was performed and a correlation was established by performing an F test to determine whether the slope of the linear regression was significantly different than zero.

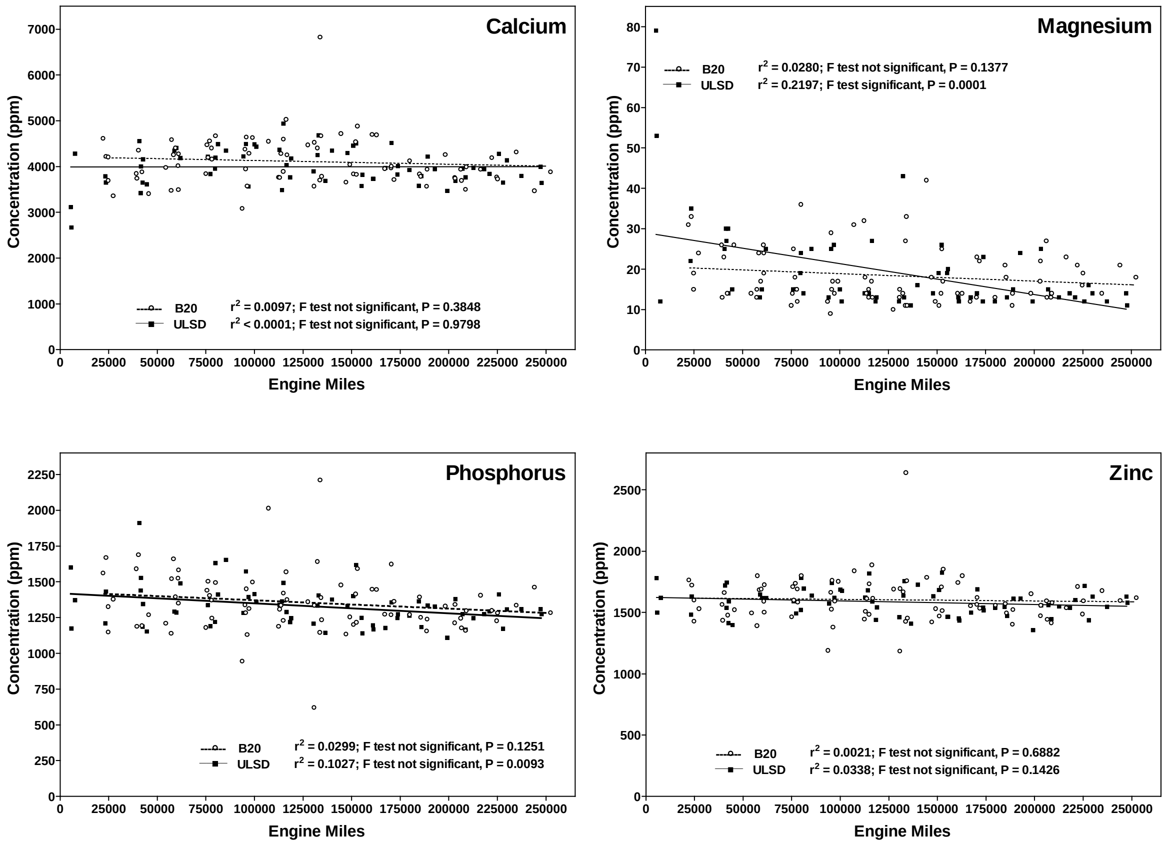


Figure 7. Metals analysis calcium, magnesium, phosphorus and zinc. Concentration of metals in used engine oil was determined by ASTM D 5185. The average oil drain interval was 18,653 ± 896 miles for the ULSD group and 18,319 ± 1081 miles for the B20 group. Linear regression was performed and a correlation was established by performing an F test to determine whether the slope of the linear regression was significantly different than zero.

Metal	ULSD (values in ppm)	B20 (values in ppm)	# 1348 (values in ppm)
Iron	42.4 ± 20.8	39.3 ± 14.0	78.5 ± 33.8
Chromium	1.48 ± 0.64	1.56 ± 0.67	7.50 ± 3.70
Copper	114 ± 206	100 ± 164	456 ± 235
Lead	10.8 ± 12.2	8.88 ± 5.38	3.25 ± 2.87
Calcium	3990 ± 390	4110 ± 510	2360 ± 30
Magnesium	19.2 ± 18.9	18.4 ± 6.9	49.5 ± 42.3
Phosphorus	1330 ± 150	1360 ± 210	1100 ± 30
Zinc	1590 ± 110	1600 ± 180	1300 ± 40
Aluminum	2.00 ± 1.03	2.06 ± 1.18	89.3 ± 44.8
Boron	4.82 ± 5.48	4.21 ± 4.52	14.3 ± 1.5
Silicon	11.4 ± 15.9	11.0 ± 11.4	21.5 ± 7.8
Silver	0.55 ± 1.03	0.34 ± 0.57	0.63 ± 1.05
Sodium	5.55 ± 3.04	5.14 ± 2.41	7.25 ± 3.95
TAN (mg KOH/g)	ND	4.78 ± 1.14 (*n* = 54)	5.05 ± 0.46 (*n* = 2)
TBN (mg KOH/g)	ND	6.99 ± 1.17 (*n* = 54)	4.87 ± 0.53 (*n* = 2)

Table 20. Wear metals analysis. Values represent the average ± SD for the number of measurements taken for the ULSD group (*n* = 65) and B20 group (*n* = 80). The total number of measurements taken for unit # 1348 was 4. For potassium, all but 8 readings were below the limit of quantitation (1 ppm) for the ULSD group and all but 13 readings were below the limit of quantitation for the B20 group. For tin, all but 13 readings were below the limit of quantitation (1 ppm) for the ULSD group and all but 12 readings were below the limit of quantitation for the B20 group. For barium and molybdenum, all but one reading were below the limit of quantification (10 ppm and 5 ppm, respectively). For antimony, nickel, vanadium and titanium, all readings were below the limit of quantification (30 ppm, 1 ppm, 1ppm and 1 ppm, respectively).

Fuel soot levels were measured by two different methods. Soot levels in lube oil from the ULSD group were measured using infra-red absorption (IR) whereas soot levels in lube oil from the B20 group were measured using the light extinction method (LEM), which is thought to minimize some of the interference observed with the IR method caused by the oxygenated biodiesel molecule. Soot levels in the ULSD group averaged 0.12 ± 0.06 absorbance units and soot levels in the B20 group averaged 0.25 ± 0.15, measured as percent volume. These values can not be directly compared because of the two different methods used; however, multiplying the absorbance value from the IR method by two will give a close approximation to the equivalent value using the LEM method (Hodges, 2009). With this approximation, the level of fuel soot found in both groups was similar, and it should also be noted that these levels are significantly lower than that found with other engine designs.

When looking at the 2007 EPA Certified B20 unit alone, several differences are evident (Table 20). The 2007 engines used a different oil containing lower additive amounts which is reflected in the lower values for zinc, calcium and phosphorus. Several of the wear metals were significantly higher, including iron, chromium, aluminum and copper; however, the lead concentration was only half that of the other B20 units. Soot levels in the 2007 EPA Certified B20 unit averaged 0.52% (n = 4) which was twice the soot levels in the other B20 units. Only one set of measurements were taken for the 2007 EPA Certified

ULSD unit for the study. The values measured for the 2007 ULSD unit followed the same general trends as the 2007 B20 unit with a substantial increase in the wear metals and a decrease in the additive metals. Soot was higher and viscostiy was lower as well when compared with the EPA 2004 Certified ULSD units. With such a small replicate number with the 2007 EPA Certified units, it is difficult to ascertain whether these differences are fuel-specific, specific to the engine model, or the result of engine-to-engine variability.

Engine Teardown Analysis

The engine teardown and analyses performed by Caterpillar Inc. did not reveal any major concerns for the use of B20 in on-highway trucks in comparison to the ULSD group, with the only notable difference being an increase in the amount of ash accumulation in the diesel particulate filter for the B20 unit. Three units were presented for teardowns; units 1348 and 1377 from the B20 group and unit 1375 from the ULSD group (Table 21). Unit 1348 contained the 2007 EPA Certified engine. Components analyzed incuded fuel hoses, intake and exhaust valves, pistons, rings and liners (PRL), fuel injectors and diesel particulate filters (DPF).

Serial No. and Unit No.	**KCB89646, #1375**	**KCB89927, #1377**	**LEE04770, #1348**
Engine	2004 EPA Cert.	2004 EPA Cert.	2007 EPA Cert.
Group	B20	ULSD	B20
Hours	4559	4512	2630
Mileage	221,800	225,400	131,200
Average Load (%)	50	51	35
Destination	Minneapolis	Minneapolis	Chicago

Table 21. Engines returned for teardown and analysis.

Several fuel hose assemblies ranging in diameter from 7.9 mm ID to 12.7 mm ID were analyzed. All assemblies appeared to be of a similar hose style, although the manufacturer’s identification was not legible. Seventeen hose assemblies were cut for a visual inspection of the hose liner. None of the inspected hose assemblies exhibited adverse effects from B20 usage; the liner remained in good condition with minimal swell for all of them (Figure 8). A few hoses exhibited heat-hardening but not to a degree that would raise concern. It is important to note that these findings are related to the fuel hose styles used in the engines analyzed; other fuel hose styles may not show the same features or performance.

Figure 8. Cross-section of 12.7 mm ID fuel hose from a B20 unit.

Exhaust and intake valves were analyzed from unit 1377 in the B20 group. This engine had accumulated 221,000 miles at the time the parts were removed for inspection. The exhaust and intake valves on this unit exhibited some soot accumulation that did not appear to have an impact on the wear of the valves. Wear modes and wear measured on both exhaust and intake valves appear to be very similar to those observed on similar engines running ULSD for an equivalent run time. Overall, valve wear was acceptable and no features were specifically attributed to the use of B20 (Figure 9).

Figure 9. Cleaned intake valve from a B20 unit showing minimal wear.

Pistons, rings and liners (PRL) were evaluated from two 2004 EPA certified engines; one from unit 1377 of the B20 group and one from unit 1375 of the ULSD group. Both engines had similar hours, comparable mileage, and a similar load factor (the average percentage of full load the engine experienced over the testing period). Piston rings of the B20 engine and the ULSD engine showed similar wear patterns. Piston deposits of the B20 engine were approximately 20% higher in the top groove and top land area but approximately 40% lower in the intermediate groove in comparison to the ULSD pistons. Deposits appeared to be slightly worse overall in the B20 engine, but the difference is small enough to be attributed to engine-to-engine variation. Liners also showed similar features. Overall, the PRL of the

2004 B20 engine was comparable to the PRL of the 2004 ULSD engine, and both were within expected limits at this mileage.

PRL analysis was performed on unit 1348 from the B20 group containing a model year 2007 EPA certified engine and compared with a Caterpillar test truck engine of similar design, load factor and mileage ran on ULSD. It should be noted that the software and PRL hardware of the model 2004 and 2007 engines are of different designs, and the 2007 ULSD test engine used for this comparison did not come from this study. The examination indicated that the deposits were comparable between the B20 from the study and the Caterpillar ULSD test engine. The liners were also similar to other engines evaluated by Caterpillar and were as expected for model year 2007 on-highway truck engines. The top rings of both the B20 and ULSD engine were analyzed for wear and found to have very low levels of wear and, in fact, the differences noted were within the measurement error. Carbon deposits of the B20 pistons in the top groove, top land and second land area were similar to deposits found in the Caterpillar ULSD test engine, and both engines exhibited low carbon deposits overall. Overall, the PRL of the 2007 B20 engine was comparable to the PRL of the 2007 ULSD test engine, and both were within expected limits at this mileage.

Two sets of six EI500 injectors were analyzed from B20 unit 1377 and ULSD unit 1375. Injector performance was checked and a variety of the injector components were analyzed for signs of wear, scuffing and debris. Comparison of the various components of the injectors including O-ring, plunger and barrel, seating band and breakaway torque showed similar features and performance between the B20 and ULSD injectors. Both exhibited low or no wear and features expected at the engine mileage. No signs of varnishing or deposits were found on the seating band and clearances were within specification for all injectors (Figure 10).

No debris was found in any of the injectors. Analysis of the tips showed that the B20 injectors had a continuous layer of combustion product build-up throughout the sac up to the edge of the orifice holes not present on the ULSD injectors (Figure 11). The combustion product build-up on the B20 injectors did not impact the performance of the injector, and surface features of tips from both B20 and ULSD injectors were within acceptable limits for this mileage. No signs of excessive heat were noted.

Bench performance tests with some of the B20 and ULSD injectors were performed and compared with new injectors. Parameters measured included injector discharge, injector timing and peak injection pressure. Measurements for all components were similar between the B20 and ULSD injectors and were within the normal limits for used injectors. Overall, injector wear and performance was similar between the B20 and ULSD injectors and the combustion layer build-up in the B20 injectors did not affect performance at this mileage.

Figure 10. Biodiesel (left) and ULSD (right) injectors showing no discernable differences.

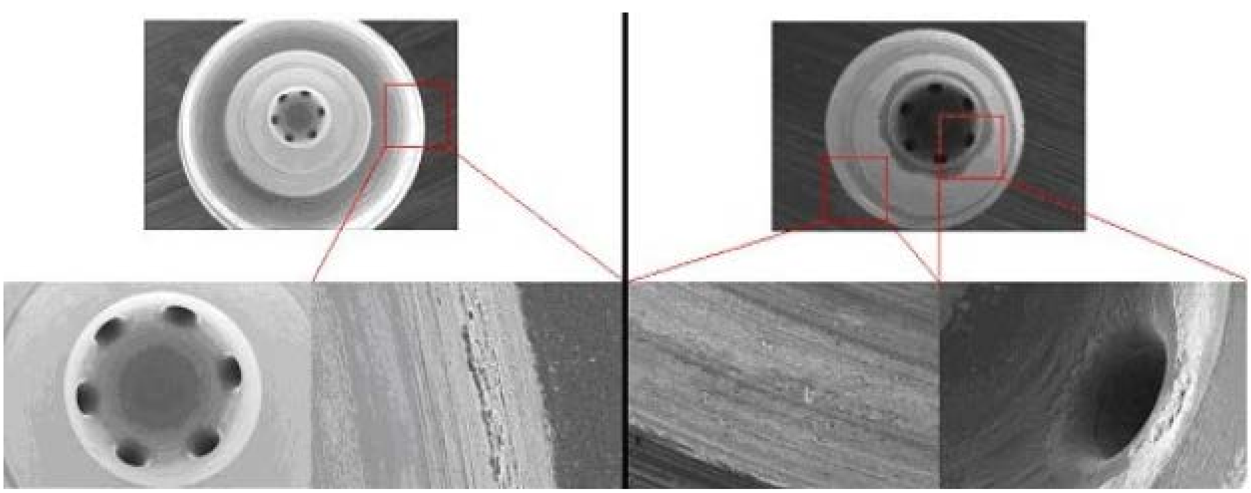


Figure 11. Seating band features for ULSD (left) and B20 (right) injector tips showing combustion product build up on B20 tip.

A single diesel particulate filter (DPF) was removed for analysis from the model year 2007 B20 truck (unit 1348). Ash accumulation was measured for the B20 DPF and compared to an average model year 2007 ULSD field aged DPF with equivalent hours and miles. The results showed an increase in ash accumulation of approximately 19% for the B20 DPF. Ash density was 238 g/L. Cleanability of the B20 ash was similar to that of the ULSD ash. It should be noted that only a single DPF was analyzed from the B20 unit and that the results were compared with the average test results for DPFs that were run on ULSD but did not originate from this study.

CONCLUSIONS

A comparison of ULSD with B20 revealed few significant differences regarding performance and operation. #2 ULSD and the B20 blend had similar physical properties with small, but expected, differences in the cetane value, energy content, cold flow properties and distillation profiles. No fuel-related mechanical breakdowns occurred in either group, no significant difference regarding engine oil performance was noted. The 2007 EPA Certified units from both groups exhibited several differences regarding wear and additive metals; however, it cannot be concluded from this study if these differences can be attributed to fuel type, engine to engine variation, or engine model.

One might expect a slight decrease in fuel economy with the B20 group due to the lower energy content of biodiesel. Given the significant driver-to-driver variability in fuel economy, this slight difference may be difficult to detect, and in fact we show no significant difference in fuel economy when comparing the fuel economy of the 10 individual ULSD units with their B20 counterparts. However, a statistically significant difference in fuel economy is realized when when making a weekly comparison using group averages. In light of the significant variance in driver performance, we feel that this may be a more appropriate method when utilizing a relatively small sample number. Regardless of statistical significance, one should recognize the much greater significance in the variation of driver performance over fuel performance.

Overall maintenance costs were comparable for the two groups; however, the B20 group exhibited a 20% increase in fuel- and engine-related expenses. Much of this additional expense was the result of increased fuel filter replacements and slightly shorter preventive maintenance intervals for the B20 group. These issues can easily be addressed by careful management of maintenance routines and by assuring proper fuel treatment, handling and storage. In addition, a simple way to reduce some of these expenses would be to run a lower blend of biodiesel during the winter months. While a 20% increase in maintenance costs may seem substantial, one should keep in mind that this represents less than 6% of the total maintenance costs.

A longer study would need to be conducted to explore the long-term effects of biodiesel on engine wear and whether this would negate any increased maintenance or fuel expenses. The engine tear-down analyses did not reveal any notable differences between the two groups, but two years may prove to be too short of a timeframe to detect any meaningful differences. Overall, we have demonstrated that B20 can be used successfully in an over-the-road setting, and with proper handling and management, is a viable alternative to ULSD alone.

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