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Field Evaluation of Biodiesel (B20) Use by Transit Buses

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ABSTRACT

The objective of this research project was to compare B20 (20% biodiesel fuel) and ultra-low-sulfur (ULSD) diesel-fueled buses in terms of fuel economy, vehicle maintenance, engine performance, component wear, and lube oil performance. We examined 15 model year (MY) 2002 Gillig 40-foot transit buses equipped with MY 2002 Cummins ISM engines. The engines met 2004 U.S. emission standards and employed exhaust gas recirculation (EGR). For 18 months, eight of these buses operated exclusively on B20 and seven operated exclusively on ULSD. The B20 and ULSD study groups operated from different depots of the St. Louis (Missouri) Metro, with bus routes matched for duty cycle parity.

The B20- and ULSD-fueled buses exhibited comparable fuel economy, reliability (as measured by miles between road calls), and total maintenance costs. Engine and fuel system maintenance costs were also the same for the two groups after correcting for the higher average mileage of the B20 group. Fuel filter plugging during unseasonably cold temperatures was more prevalent for the B20 group. Lube oil samples were collected over a wide range of mileage within the drain interval, and analyses indicate reductions in soot loading and wear metals in the B20 buses. Viscosity loss and lead corrosion were greater in the B20 group, while the total base number (TBN) loss was not significantly changed.

INTRODUCTION

Biodiesel is an important petroleum displacement fuel that is produced from various fats, oils, and greases. It consists of fatty acid methyl esters produced from the various feedstocks by transesterification with methanol. Biodiesel used in the United States must meet the quality requirements of the ASTM D6751 specification. The National Biodiesel Board estimates that 700 million gallons of biodiesel were produced in the United States in 2008 [1]. Typically, biodiesel is used as a blend with petroleum diesel at levels ranging from 2% to 20% by volume. Energy content per gallon is slightly lower for B20, resulting in a small reduction in peak torque and fuel economy, but no change in thermal efficiency [2].

Because biodiesel is still a relatively new fuel, the impact of biodiesel blends on engine maintenance costs and durability is of great interest to engine manufacturers and diesel vehicle users. These potential impacts have been evaluated in several prior studies [3-7] that found no significant differences in fuel economy, maintenance costs, or engine wear. The higher incidence of fuel filter plugging for B20 reported in some studies can be traced to low-temperature operability issues or out-of-specification biodiesel. A recent study has shown that out-of-specification biodiesel is far less prevalent in the marketplace today than it was just a few years ago [8].

The objective of this project was to evaluate the extended in-use performance of transit buses employing engines equipped with EGR, a newer engine technology than those assessed in prior studies. Specific objectives were to compare fuel economy, vehicle maintenance costs, reliability, and lube oil performance in comparison to ULSD. The buses were operated by St. Louis Metro from October 2006 to April 2008. Thus, the initiation of this test coincided with the introduction of ULSD that occurred in most of the United States in October 2006.

BACKGROUND AND METHODS

St. Louis Metro owns and operates the St. Louis Metropolitan region's public transportation system. The system includes MetroLink, the region's light rail system;

MetroBus, the region's bus system; and Metro Call-A-Ride, a paratransit van system. In FY 2005, Metro transported more than 46.5 million passengers on the MetroLink, MetroBus, and Metro Call-A-Ride systems. Metro maintains a fleet of 433 buses, 77 light rail vehicles, and 125 paratransit vans.

Metro maintains four garage facilities, two of which are the focus of this evaluation. The Brentwood Garage dispatched and maintained the B20-fueled buses and the Debaliveire Garage handled the diesel bus control group. Buses at each garage are fueled every few days at two indoor fueling dispensers. As part of service and cleaning operations, the buses are washed and fueled in the evening hours as they return to the garage.

Service and cleaning personnel fuel the buses, while hubodometer readings and fuel volume dispensed are automatically logged electronically. Maintenance is also performed on the buses at each facility in several bays dedicated to maintenance operations. Maintenance work is recorded electronically by mechanics by capturing data on repair codes, parts, and labor hours.

VEHICLE SELECTION - Fifteen identical buses were included in this evaluation project. Basic vehicle attributes are presented in Table 1, and detailed vehicle specifications can be found in a preliminary report [9]. Eight of the buses operated on B20 fuel and seven operated on ULSD as a control group.

While all 15 buses were acquired in February 2004, the two study groups had not accumulated exactly the same mileage at the start of the evaluation, as shown in Table 2. On average, the B20 buses had driven about 20,000 additional miles per bus prior to the start of the evaluation.

Table 1. Metro B20 Transit Bus Basic Description

Vehicle Information	Evaluation Buses
Number of Buses	7 Diesel (Bus #s 3401-3407) 8 B20 (Bus #s 3408-3415)
Chassis Manufacturer	Gillig
Chassis Model Year	2002
Engine	Cummins ISM
Engine Model Year	2002 (2004 emissions certification)
Max. Horsepower Max. Torque	280 hp @ 2100 rpm 900 lb-ft @ 1200 rpm
Fuel Capacity	125 gallons
Transmission	Voith DIWA 863
Curb Weight	29,000 lb.
Gross Vehicle Weight	40,600 lb.

Table 2. Study Bus Information

Bus Unit Number	Date of Acquisition	Fuel	Evaluation Start Mileage
3401	2/3/2004	ULSD	110,990
3402	2/4/2004	ULSD	98,042
3403	2/5/2004	ULSD	113,496
3404	2/9/2004	ULSD	87,056
3405	2/3/2004	ULSD	110,583
3406	2/3/2004	ULSD	103,929
3407	2/3/2004	ULSD	129,510
	ULSD Vehicle Average		*107,658*
3408	2/3/2004	B20	127,467
3409	2/3/2004	B20	125,630
3410	2/3/2004	B20	127,825
3411	2/3/2004	B20	123,374
3412	2/16/2004	B20	133,231
3413	2/23/2004	B20	129,086
3414	2/18/2004	B20	125,081
3415	2/3/2004	B20	129,530
	B20 Vehicle Average		*127,653*

ROUTE/DUTY-CYCLE SELECTION - The B20-fueled study buses are driven on the 11 Chippewa route out of the Brentwood garage, while the ULSD-fueled study buses are operated on the 32 Wellston route from the Debaliveire garage. Route duty-cycle characteristics are summarized in Table 3. Average speed is a more accurate representation of real-world driving and was therefore the defining metric in selecting these two routes for comparison.

Table 3. Evaluation Duty-Cycle Descriptions

Route	11 Chippewa	32 Wellston
Garage (Fuel)	Brentwood (B20)	Debaliveire (ULSD)
Average Speed (mph)	13.75	14.57
Revenue Speed (mph)	12.32	14.18
Passengers/Mile	3.03	2.9
Passengers/Trip	47	56
Total Boardings/Day	5100	4932

VEHICLE FUELING AND DATA COLLECTION - Rack-blended (in-line proportional blending) B20 was delivered to Brentwood by Hartford Wood River Terminal. ULSD was delivered to Debaliveire by Energy Petroleum. Brentwood has four 20,000-gallon underground storage tanks (USTs), which have been converted to B20 storage. Debaliveire has tanks in equal number and relative location. All USTs are connected to three interior fuel dispensers by about 1,000 feet of underground supply line. There is a 30-μm filter downstream of the supply pump, and a 10-μm filter at the fuel dispenser. Two dispensers are actively used and one is kept as a spare.

Each bus is scheduled to fuel every other day. As the bus enters the fueling island area, a radio frequency connection is established between the bus, the fueling dispenser, and Metro's M5 electronic database. The bus is recognized, and the odometer reading, fueling volume, and lube oil requirements are uploaded to M5. These fueling records were transferred to NREL for evaluation and analysis.

VEHICLE RELIABILITY - A road call (RC) is defined as a call-in to a dispatcher to report a mechanical problem. Depending on the nature of the problem, the dispatcher may instruct operators to continue driving their routes. Alternatively, a RC may stem from an issue that requires the bus to stop driving and allow for roadside mechanical repair or a tow back to the maintenance facility. These RCs and average miles (driven) between road calls (MBRC) are important reliability indicators for the transit industry. For the purposes of this analysis, data received from Metro indicating that an RC occurred was recorded as such, regardless of its relative severity.

VEHICLE MAINTENANCE AND DATA COLLECTION - Scheduled maintenance is performed as required, and preventive maintenance (PM) events are conducted every 6,000 miles of driving. Maintenance events in the form of labor hours and parts costs are captured electronically by M5. These events are separated by work order and further by job line. Each job line is specific to the vehicle subsystem under repair. Metro submitted maintenance records electronically to NREL, where they were reviewed for accuracy and analyzed for a maintenance cost per mile comparison of the B20 and diesel groups. Maintenance cost per mile figures were calculated for specific vehicle subsystems that could be impacted by B20 fuel use.

For the B20-fueled buses in this evaluation, routine maintenance was identical to the diesel buses, with one exception. During the first two months of the study, fuel filters on the B20 buses were replaced every 2,000 miles rather than at the 6,000-mile PM interval. This is a common practice for fleets starting to use B20 because biodiesel, which is thought to be a stronger solvent than petroleum diesel, can loosen deposits in the storage system or vehicle, and this can result in fuel filter plugging. We are not aware of quantitative data to support this practice, but many biodiesel producers and fleet operators believe it to be a conservative approach.

The buses evaluated in this study had a 2-year/100,000-mile general warranty, with emissions control systems warranted to 200,000 miles. Thus, all buses operated in this study were outside their warranty or went out of warranty shortly after the start of the evaluation. Data on warranty repairs were collected in a manner similar to that for data on normal maintenance actions. However, the cost data are not included in the operating cost calculation. Labor costs may be included, depending on whether or not those hours were reimbursed under the warranty agreement. Warranty maintenance information is collected primarily as an indication of reliability and durability.

FUEL AND LUBRICANT ANALYSIS – B20 samples were obtained from the fuel supplier delivery trucks approximately weekly from February 2007 through July 2007. The samples were tested for biodiesel content by FTIR method EN14078 and for cloud point by ASTM D2500. Results of this fuel analysis can be found in a previous NREL technical report [9].

LUBE OIL ANALYSIS - Metro uses Chevron RPM 15W-40 lube oil in the evaluation buses. Oil is changed every 6,000 miles as part of Metro's PM schedule. Metro maintenance staff sampled lube oil from the Cummins ISM sampling port every 2,000 miles, and sometimes more frequently. Lube oil samples were collected in sampling containers and mailed in prelabeled packing provided by Cummins. Cummins conducted analyses to compare the performance of lube oil samples of vehicles fueled with B20 and ULSD. Analyses included these:

- TBN decay
- Soot content
- Wear metals (Fe, Cu, Cr)
- Evaporative metals (Ca, Zn, P)
- Other (Ba, Mg, Mo, Sn, Pb, Al, Si, Na)

RESULTS

BUS USE - Table 4 presents information on bus utilization during the study period for the two groups. The overall 18-month average monthly miles per bus for the B20 buses was about 3.7% higher than for the ULSD buses at Debaliveire. Based on a two-tailed, paired t-test, the difference between the two groups is not statistically significant with a high degree of confidence (P = 0.13). The average mileage accumulated per bus during the study is also very similar for the two groups. The approximately 20,000-mile difference in average total miles per bus noted at the start of the study is also seen at the end of the study. Figure 1 shows cumulative average monthly miles per bus for each study group. The average usage of the buses declined slightly during the evaluation period, in which the B20 and ULSD study bus groups accumulated 590,042 and 497,654 miles, respectively.

Table 4. Average Miles Driven per Month per Bus by Study Group

Bus Group	Average Miles per Month	Average Study Miles	Average Total Miles
B20	4,097	73,755	201,420
ULSD	3,950	71,093	178,251

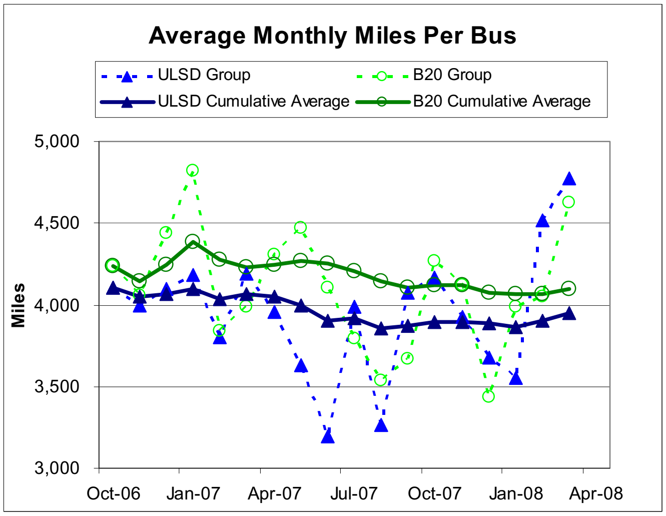

Figure 1. Cumulative Average Monthly Mileage per Bus

FUEL ECONOMY - Fuel consumption and economy data are presented in Table 5. The calculated 18-month average fuel economy for the B20 buses is 1.5% lower than that of the ULSD buses. This difference is expected because of the approximately 2% lower energy content in a gallon of B20; however, based on a two-tailed, paired t-test, the difference between the two groups is not statistically significant with a high degree of confidence (P = 0.2).

Figure 2 shows the average monthly fuel economy for the two study groups for the 18-month evaluation period.

Table 5. Bus Fuel Use and Economy

Fuel Economy Comparison October 2006 - March 2008)				
Bus	**Fuel**	**Mileage Total**	**Fuel Used (gallons)**	**Fuel Economy (mpg)**
3401	ULSD	75,795	21,519	3.52
3402	ULSD	65,026	18,044	3.60
3403	ULSD	71,679	19,664	3.65
3404	ULSD	74,478	20,941	3.56
3405	ULSD	67,241	18,289	3.68
3406	ULSD	70,401	19,463	3.62
3407	ULSD	73,034	19,080	3.83
Total	**ULSD**	**497,654**	**137,000**	**3.63**
3408	B20	80,241	22,250	3.61
3409	B20	78,561	21,384	3.67
3410	B20	71,113	20,429	3.48
3411	B20	77,461	22,191	3.49
3412	B20	72,667	19,957	3.64
3413	B20	68,320	19,734	3.46
3414	B20	73,202	19,695	3.72
3415	B20	68,477	19,327	3.54
Total	**B20**	**590,042**	**164,967**	**3.58**

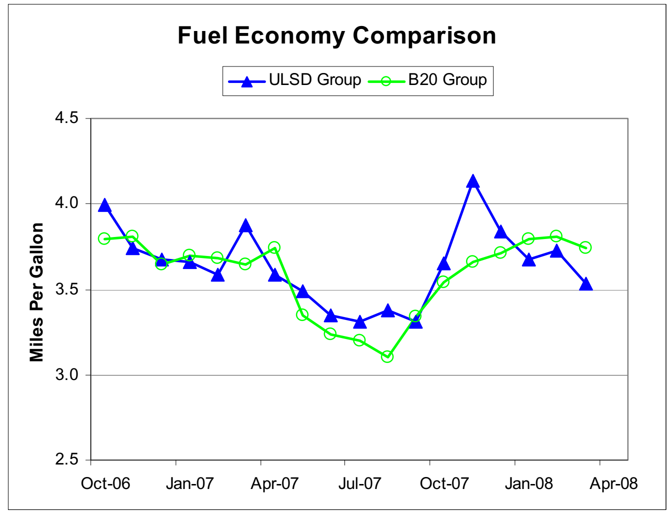

Figure 2. Average Fuel Economy

VEHICLE RELIABILITY ANALYSIS - Figure 3 shows the cumulative MBRC for all RCs for the ULSD and B20 groups. Average MBRC values over the evaluation period were 2,690 and 2,694 for ULSD and B20 groups, respectively, a difference that is not statistically significant based a two-tailed, paired t-test (P = 0.95).

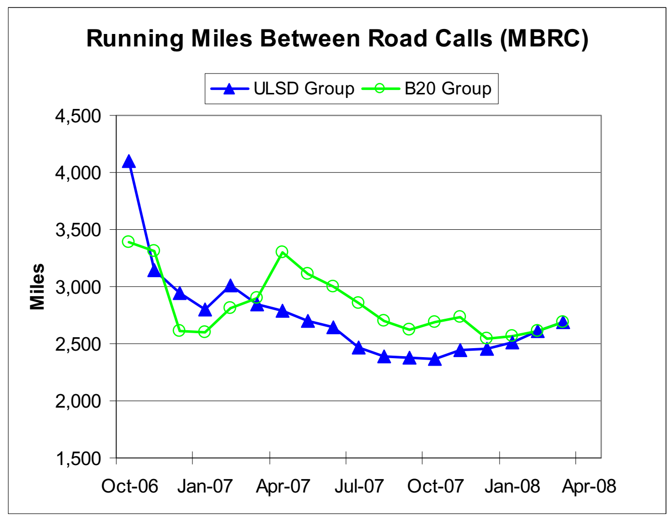

Figure 3. Cumulative MBRCs

In addition, reliability as measured in MBRCs is assessed for the engine and fuel systems. Figure 4 shows the cumulative MBRC for all engine and fuel system RCs for the ULSD and B20 groups. The ULSD group had a three-month run of exceptionally high MBRC numbers, creating a spike, but that was followed by a few months of a high number of road calls that dragged the cumulative average below that of the B20 group for seven months. For the last four months of the 18-month evaluation, the B20 buses and ULSD buses were comparable, with cumulative engine and fuel system MBRC values of 8,435 and 8,310 for the ULSD and B20 groups, respectively, at the end of the evaluation period. Based on a two-tailed, paired t-test, this difference is not significant (P = 0.8).

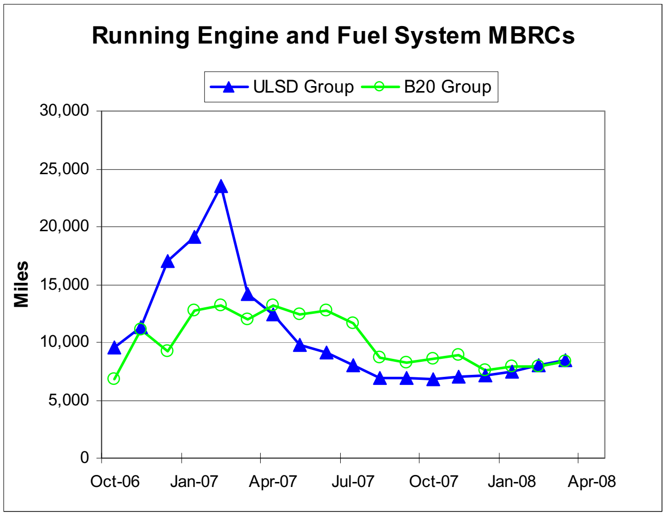

Figure 4: Cumulative MBRCs, Engine and Fuel System

MAINTENANCE COST ANALYSIS The total maintenance cost includes the cost of parts and assumes an hourly labor cost of $50 per hour, but it does not include warranty costs. The cost per mile is calculated as follows:

Cost per mile = ((labor hours * 50) + parts cost)/mileage.

The labor rate has been arbitrarily set at a constant rate of $50 per hour. This rate does not directly reflect Metro's current hourly mechanic rate.

Table 6 shows total maintenance costs for the study buses during the evaluation period. The total maintenance cost per mile was 4.4% higher for the B20 buses than for the ULSD buses ($0.027/mile higher), a difference that is not significant based on a two-tailed, paired t-test (P = 0.48).

Table 6. Total Maintenance Costs

Total Maintenance Cost Comparison					
Bus	**Fuel**	**Mileage Total**	**Labor Hours**	**Parts Cost**	**Cost ($/mile)***
3401	ULSD	75,795	609	$ 18,770	$ 0.649
3402	ULSD	65,026	633	$ 11,875	$ 0.670
3403	ULSD	71,679	556	$ 13,286	$ 0.573
3404	ULSD	74,478	462	$ 9,761	$ 0.441
3405	ULSD	67,241	548	$ 7,395	$ 0.517
3406	ULSD	70,401	614	$ 14,526	$ 0.642
3407	ULSD	73,034	571	$ 19,080	$ 0.652
Total	**ULSD**	**497,654**	**3,992**	**$ 94,693**	**$ 0.591**
3408	B20	80,241	793	$ 19,857	$ 0.741
3409	B20	78,561	943	$ 16,974	$ 0.816
3410	B20	71,113	653	$ 14,954	$ 0.670
3411	B20	77,461	578	$ 9,259	$ 0.493
3412	B20	72,667	645	$ 14,005	$ 0.637
3413	B20	68,320	598	$ 8,707	$ 0.565
3414	B20	73,202	477	$ 10,115	$ 0.464
3415	B20	68,477	517	$ 10,289	$ 0.528
Total	**B20**	**590,042**	**5,205**	**$ 104,159**	**$ 0.618**

The monthly and running average of maintenance costs for the diesel and B20 groups are compared in Figure 5. The running average or cumulative presentation of maintenance costs shows the average of the costs up to a given month and smoothes occasional spikes in monthly maintenance costs. Maintenance costs are initially higher for the B20 group, but ultimately they gain parity with the diesel group by the ninth month of the evaluation. Parity is maintained for the remaining nine months despite increased volatility in the monthly data.

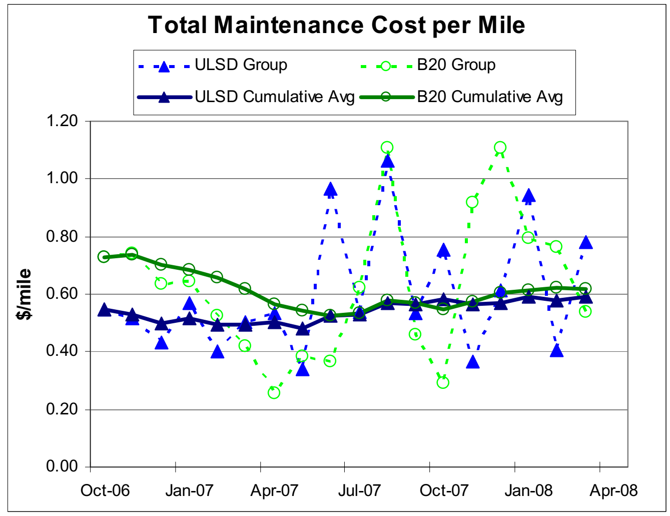

Figure 5. Total Maintenance Costs

Engine and Fuel System Maintenance Costs - Bus maintenance costs related to the engine and fuel system during the evaluation period are presented in Table 7. Note that maintenance costs for these subsystems make up only 4% to 5% of the total maintenance. The engine and fuel system maintenance cost per mile was $0.03/mile higher, or about 50%, for the B20 (P = 0.03 based on a paired t-test). Engine- and fuel system-related maintenance was not a significant driver of the total maintenance cost, but it does appear to be the primary difference between the groups.

Table 7. Engine and Fuel System Maintenance Costs

Engine and Fuel Systems Maintenance Cost Comparison					
Bus	**Fuel**	**Mileage Total**	**Labor Hours**	**Parts Cost**	**Cost ($/mile)***
3401	ULSD	75,795	46	$ 696	$ 0.040
3402	ULSD	65,026	83	$ 953	$ 0.079
3403	ULSD	71,679	83	$ 993	$ 0.072
3404	ULSD	74,478	68	$ 356	$ 0.050
3405	ULSD	67,241	49	$ 636	$ 0.046
3406	ULSD	70,401	44	$ 2,585	$ 0.068
3407	ULSD	73,034	87	$ 235	$ 0.063
Total	**ULSD**	**497,654**	**460**	**$ 6,454**	**$ 0.059**
3408	B20	80,241	150	$ 962	$ 0.106
3409	B20	78,561	158	$ 1,031	$ 0.114
3410	B20	71,113	108	$ 2,512	$ 0.111
3411	B20	77,461	66	$ 650	$ 0.051
3412	B20	72,667	118	$ 1,780	$ 0.106
3413	B20	68,320	73	$ 1,017	$ 0.068
3414	B20	73,202	74	$ 1,260	$ 0.068
3415	B20	68,477	81	$ 1,589	$ 0.082
Total	**B20**	**590,042**	**828**	**$ 10,801**	**$ 0.089**

Looking specifically at fuel system parts that may be considered potentially susceptible to B20 use, we examined the following maintenance items in detail:

- Fuel filter
- Fuel injector
- Fuel pump
- Fuel system flush

The fuel filter and fuel system flush are grouped with a suite of preventive maintenance repair checks and part replacements. A fuel system flush is performed every 50,000 miles. A fuel system flush occurring outside this interval could indicate that fuel system diagnostic activities should be further investigated. Fuel filters are replaced at 6,000-mile intervals, but Metro changed B20 bus fuel filters every 2,000 miles for the first two months to avoid RCs caused by fuel filter plugging. This is a common practice for fleets beginning to use B20. The B20 group also used more filters during unusual winter cold snaps when the outside temperature dropped below the cloud point of the fuel. The diesel group did not experience this issue. Neither group experienced fuel pump failures. The B20 group experienced more fuel injector failures, but they relate to bus mileage rather than to the fuel used (this is explained in detail in the discussion section). Table 8 shows monthly replacements of fuel system components for each group.

Table 8. Monthly Fuel System Replacements

Part Replaced	ULSD Fuel Sys Maintenance				B20 Fuel Sys Maintenance			
	Filter	Injector	Pump	Sys Flush	Filter	Injector	Pump	Sys Flush
Oct-06					10			
Nov-06	2				8	1		
Dec-06	1				4	1		1
Jan-07	1			2	1	2		2
Feb-07		2			10	3		
Mar-07	1				1			1
Apr-07	1				3			
May-07	2					1		
Jun-07	3					1		
Jul-07	1					2		
Aug-07						2		
Sep-07	1	1				2		
Oct-07	1	7			1	1		
Nov-07	2	1		1	6			1
Dec-07	2	2		1	10			1
Jan-08		1			14			1
Feb-08	1				22	4		1
Mar-08	1			1	3	2		1
Total	**20**	**14**	**0**	**5**	**93**	**22**	**0**	**9**

Table 9 breaks down the costs associated with the elevated number of fuel filter and fuel injector failures experienced by the B20 group. The high number of fuel filters caused the related hours and parts costs of the B20 group to be six times higher than those of the ULSD group; however, they are still not a substantial percentage of the engine and fuel system cost per mile. The additional fuel injector failures in the B20 group resulted in an increase of $0.007 per mile of operating costs.

Table 9. Total Maintenance Costs

Fuel Injector & Fuel Filter Maintenance Cost Comparison					
Component	**Labor Hours**	**Parts Cost**	**Cost ($/mile)***	**% of E&FS Maint.**	**% of Total Maint.**
ULSD Fuel Filter	10.5	$49	$0.0012	1.9%	0.2%
ULSD Fuel Injector	40.7	$2,608	$0.0093	15.8%	1.6%
ULSD Total	**51.2**	**$2,657**	**$0.0105**	**17.7%**	**1.8%**
B20 Fuel Filter	65.8	$317	$0.0061	6.9%	1.0%
B20 Fuel Injector	83.2	$5,433	$0.0163	18.4%	2.6%
B20 Total	**149**	**$5,750**	**$0.0224**	**25.3%**	**3.6%**

FUEL AND LUBRICANT ANALYSIS AND RESULTS - B20 samples represent fuel consumed by Metro from February through July 2007 and results are summarized in Table 10. Samples were taken from the fuel dispensers used to fuel the buses and thus are indicative of the properties of the fuel in the tank on the date the sample was taken. Biodiesel blend content results indicate many samples with significantly less than 20 volume percent biodiesel, which suggests that loads containing less than the specified level of biodiesel were delivered on a regular basis. A few samples contain more than 20% biodiesel, which may be an indication of the accuracy of the blending process; however, the sample taken on May 9, containing nearly 25% biodiesel, is difficult to explain on this basis. Nevertheless, it appears that the B20-fueled buses did operate on fuel containing approximately the intended level of biodiesel during the fuel sampling period.

The B20 samples had almost the same cloud point over the study period, in spite of the fact that the 10th percentile minimum ambient air temperature is -13ºC in February, -8ºC in March, and higher in April through July [10]. The St. Louis area experienced unseasonably cold temperatures during February 2007 and January 2008; temperatures at the St. Louis airport dropped to -15ºC on February 4-5 and 15-16, 2007, and again on January 20 and 25, 2009. Just 25 km west of St. Louis in Chesterfield, a low temperature of -18ºC was recorded on February 4 [11]. These temperatures are below the cloud point of the B20, indicating that low-temperature operability problems could be expected for fuels without additives, like the ones used here. This could indicate that cold flow issues contributed to the increase in fuel filter changes during those months.

Table 10. Summary of B20 Fuel Analytical Results (NA=not analyzed)

Sample Date	Biodiesel Content, vol%	Cloud Point, °C
02/07/2007	20.09	-14
02/08/2007	17.17	-15
02/21/2007	18.23	-13
02/22/2007	20.97	-12
02/23/2007	17.18	-13
03/09/2007	18.35	-14
03/15/2007	20.08	-14
05/09/2007	24.50	-12
05/17/2007	15.64	-12
06/05/2007	17.08	-10
06/13/2007	17.34	-11
06/19/2007	17.50	-14
06/20/2007	16.41	-14
06/22/2007	NA	-12
07/03/2007	21.48	-11
07/06/2007	22.89	-11
07/13/2007	21.96	-11
07/18/2007	17.82	-11
07/20/2007	16.40	-13

Sixty-four lube oil samples from ULSD and B20 buses were analyzed by Cummins. Samples had a range of

833 to 6,477 oil miles. The figures below present results graphically. See Appendix for additional data.

Figure 6 presents weight percent soot in oil. Ideally, soot should be below 5.0% by weight [12]. Both ULSD and B20 groups exhibit very low soot; however, the B20 group oil samples have lower soot and soot level is increasing with mileage at a lower rate. Figure 7 presents the kinematic viscosity of oil at 100°C. Viscosity can be used as an indication of fuel dilution. The 15W-40 oils have a minimum viscosity specification of 12.5 cSt. As shown in Figure 7, viscosity remains above this value throughout the oil drain period for both groups; however, oil from the B20-fueled vehicles is showing a significantly higher rate of viscosity loss, which suggests a higher level of fuel dilution. Figure 8 presents total base number (TBN) of the oil. Ideally, TBN should be above 2.5 mg KOH/g [12]. Here, TBN appears slightly lower with B20, but both oils show sufficient TBN retention at the end of the drain. Figure 9 shows the iron content of the oil, an indication of engine wear. Wear appears slightly lower with B20, based on this analysis. Figure 10 shows the lead content of the oil; an indication of engine corrosion. Corrosion appears slightly higher with B20, especially at high mileage. Increased lead corrosion for B20 has been reported in the Mack T-12 lube oil performance test [13, 14], and it is believed to be caused by oxidation of biodiesel in the lube oil to form corrosive acids. It is not yet clear if this level of corrosion can have a significant impact on engine life.

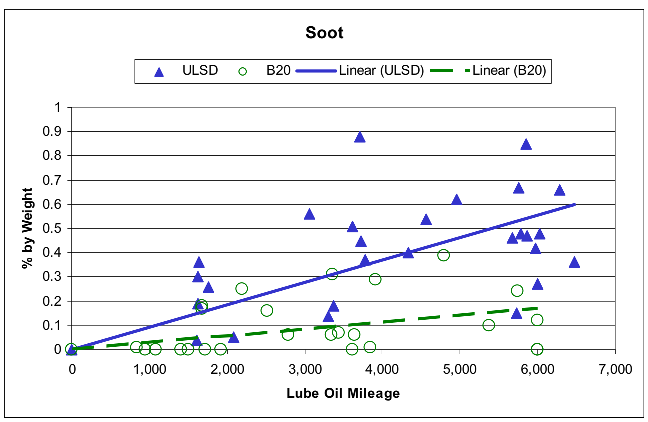

Figure 6. Soot in Lube Oil

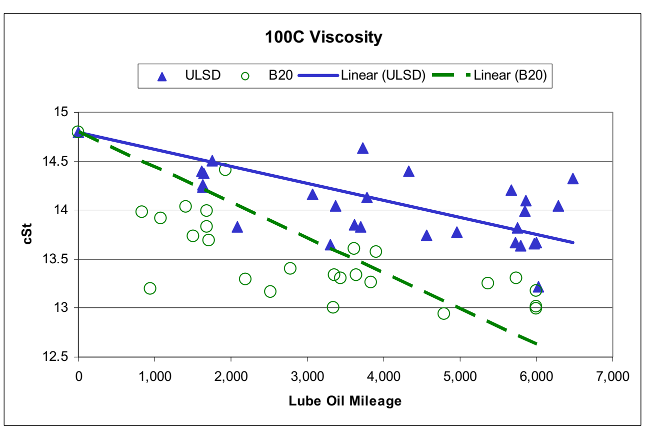

Figure 7. 100°C Viscosity of Lube Oil

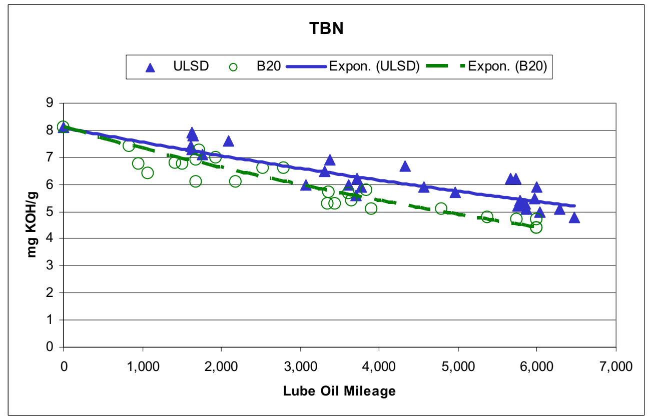

Figure 8. TBN of Lube Oil

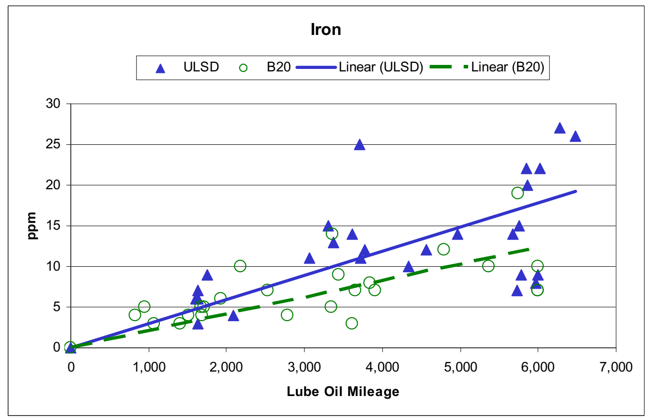

Figure 9. Iron in Lube Oil

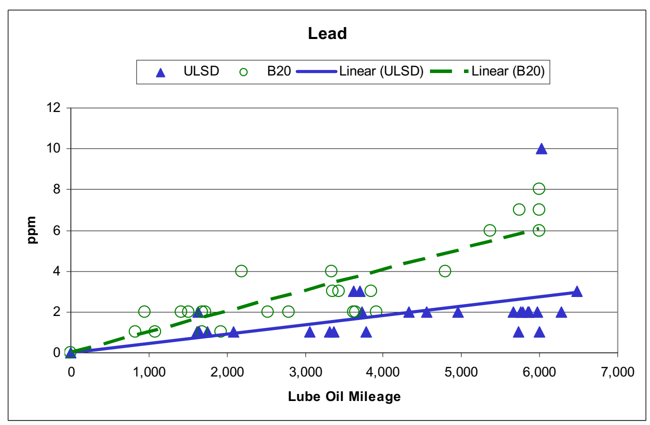

Figure 10. Lead in Lube Oil

DISCUSSION

According to Metro, injectors on this group of buses have been observed to fail as early as 100,000 miles, and indeed, the control group had a failure at 106,000 miles during the study period. Table 11 presents the miles accrued on the buses and injector replacements for each bus during this evaluation. Some of the buses had an injector replacement prior to the start of the study, as shown in the table. Of note is the wide range of miles driven on B20 prior to injector failure (standard deviation greater than half the average miles on B20), suggesting that total bus/injector mileage may be a more important factor than exposure to a specific fuel. Note also the higher average starting and ending mileage of the B20 evaluation group— 22,669 miles by the end of the study.

Table 11. Injector Failures

Unit No	Fuel	Evaluation Start Mileage	Evaluation End Mileage	Evaluated Miles	Injector Failure Mileage	B20 Miles Before Failure	Injectors Replaced
3408	B20	127,467	207,708	80,241	182,822	55,355	2
3409	B20	125,630	204,191	78,561	172,900	47,270	1
3410	B20	127,825	198,938	71,113	131,690	3,865	1
3410	B20	127,825			146,460	18,635	2
3410	B20	127,825			194,772	66,947	1
3410	B20	127,825			194,881	67,056	1
3411	B20	123,374	200,835	77,461	133,738	10,364	1
3411	B20	123,374			135,706	12,332	1
3412	B20	133,231	205,898	72,667	144,762	11,531	1
3412	B20	133,231			164,985	31,754	1
3412	B20	133,231			171,988	38,757	1
3413	B20	129,086	197,406	68,320	164,347	35,261	1
3413	B20	129,086			169,249	40,163	1
3413	B20	129,086			179,598	50,512	1
3414	B20	125,081	198,283	73,202	145,873	20,792	1
3415	B20	129,624	198,101	68,477	167,734	38,110	1
3415	B20	129,624			191,162	61,538	2
3415	B20	129,624			194,457	64,833	2
Average Miles		**127,665**	**201,420**	**73,755**	**168,274**	**39,793**	**22**
Standard Deviation		3,074	3,977	4,548	21,867	21,147	
Unit No	**Fuel**	**Evaluation Start Mileage**	**Evaluation End Mileage**	**Evaluated Miles**	**Injector Failure Mileage**	**ULSD Miles Before Failure**	**Injectors Replaced**
3401	ULSD	110,990	186,785	75,795	161,146	50,156	1
3402	ULSD	98,042	163,068	65,026	143,828	45,786	1
3402	ULSD	98,042			148,100	50,058	1
3402	ULSD	98,042			148,692	50,650	1
3403	ULSD	113,496	185,175	71,679	170,361	56,865	1
3403	ULSD	113,496			173,743	60,247	1
3404	ULSD	87,056	161,534	74,478	106,157	19,101	1
3404	ULSD	87,056			133,587	46,531	1
3405	ULSD	110,583	177,824	67,241	124,711	14,128	1
3405	ULSD	110,583			155,491	44,908	1
3405	ULSD	110,583			158,496	47,913	1
3405	ULSD	110,583			162,553	51,970	1
3406	ULSD	103,929	174,330	70,401	153,403	49,474	1
3407	ULSD	129,510	202,544	73,034	178,428	48,918	1
Average Miles		**107,658**	**178,751**	**71,093**	**151,335**	**45,479**	**14**
Standard Deviation		13,305	14,345	3,869	19,674	12,930	

We can adjust the group failure rates to try to compensate for the differences in the populations – the different number of buses of the two groups and different average total mileage. First the B20 group can be corrected for the higher number of buses by multiplying by 7/8. This reduces the 22 injector failures to an adjusted level of 19.6 failures. The ULSD group can be corrected for the lower average miles on the ULSD buses by calculating a per mile injector failure rate an then using this to project additional injector failures that would occur if these buses had the same miles as the B20 buses. The fuel injector replacement rate for the ULSD buses during the study period is 14 in 497654 cumulative miles or 2.81x 10^{-5} injectors per mile. The average ULSD bus had 22,669 fewer total miles at the end of the study than the average B20 bus, and at our observed injector failure rate this leads to a projected additional 0.64 injector replacements per bus. For 7 buses this would be 4.5 additional injector replacements for a total of 18.5. This leads to comparing 19.6 versus 18.5, or about one injector difference. Our estimate indicates that fuel injector replacements for the two groups at equivalent bus mileage would be approximately equal.

Another way to compare the populations is to consider the lifetime fuel injector failures rather than just the 18-month study period on B20 and see if the populations are different. Figure 11 shows a comparison of cumulative injector failures for each bus group at given mileages from new through March 2009. The groups had a comparable rate of failures through 200,000 miles which confirms that the fuel injector failures correlate to bus miles rather than exposure to a specific fuel. The injector failure events below 200,000 miles were compared and found to be not significant, based on a two-tailed, paired t-test (P = 0.3). The ULSD group only has two buses past 225,000 miles, while the B20 group buses are all past that mark and six have passed 250,000 miles. The corrected B20 series has been multiplied by 7/8 to better compare with the seven buses of the ULSD group. Even uncorrected, the B20 group had fewer injector failures at 200,000 miles than the ULSD group did.

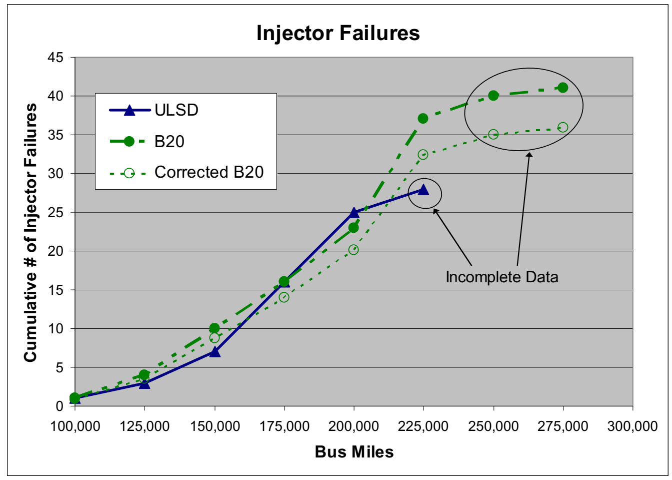

Figure 11. Fuel Injector Failure Mileages

Based on these considerations that fuel injector failures relate to higher bus miles rather than to B20 fuel, there is not a significant difference between the two bus groups in maintenance costs for the engine and fuel system.

CONCLUSIONS

In comparison to buses running on ULSD, the following observations can be made for buses running on B20:

- No statistical difference in fuel economy. With similar usage and duty cycle, the B20 study group exhibited a 1.7% lower fuel economy than the ULSD study group did. This difference is expected because of the lower energy content of B20 fuel. However, the difference is considered to be not statistically significant (P = 0.19).
- No statistical difference in MBRC or engine & fuel system MBRC. The reliability of the B20 study group was similar (as measured in MBRC) to that of the ULSD study group.
- No statistical difference in total maintenance cost per mile between the two study groups.
- Engine- and fuel-system-related maintenance was the same for the two groups after we corrected the ULSD group data to equivalent mileage.

- The B20 study group had a higher number of fuel filter replacements because of low-temperature operability problems caused by unseasonably low temperatures. Operators of fleets fueled with B20 need to be aware of the potential for low-temperature operability problems to be more severe for B20 during unseasonable weather.
- Lube oil analysis indicates reduced soot loading and wear metals for B20. Viscosity decay and lead corrosion was increased for B20, and there was no difference in TBN deterioration.

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

APTA: American Public Transit Association

ASTM: American Society of Testing and Materials

AVTA: Advanced Vehicle Testing Activity

bhp: brake horsepower

DOE: U.S. Department of Energy

DPF: diesel particulate filter

EGR: exhaust gas recirculation

g/bhp-hr: grams per brake horsepower-hour

GVWR: gross vehicle weight rating

MBRC: miles between road calls

NREL: National Renewable Energy Laboratory

PM: preventive maintenance

RC: road call

TBN: total base number

ULSD: ultra-low-sulfur diesel

UST: underground storage tank

μm: micrometer

APPENDIX

Additional lube oil data and charts.

Bus Number	Fuel	Engine Miles	Oil Miles	TBN mg KOH/g	IrSoot % weight	Fe ppm	Sn ppm	Pb ppm	Cu ppm	Cr ppm	Al ppm	Mo ppm	Si ppm	Na ppm	Ca ppm	Ba ppm	Mg ppm	Zn ppm	P ppm	B ppm	40cVis cSt	100cVis cSt
3401	ULSD	141621	5753	5.2	0.67	15	0	2	4	1	3	106	13	5	3234	1	5	1416	1230	90	101.9	13.8
3401	ULSD	147903	6282	5.1	0.66	27	0	2	2	2	11	99	7	0	3094	0	2	951	1177	73	104.3	14.1
3401	ULSD	149658	1755	7.1	0.26	9	0	1	1	1	6	104	6	7	3375	1	4	1435	1284	122	109.1	14.5
3401	ULSD	153752	5849	5.3	0.85	22	0	2	4	2	10	108	8	10	3289	1	5	1539	1314	88	103.7	14.0
3402	ULSD	130673	5972	5.5	0.42	8	0	2	3	1	3	102	4	5	3138	1	4	1377	1202	91	100.3	13.7
3402	ULSD	141653	4959	5.7	0.62	14	0	2	3	1	4	106	4	4	3344	1	8	1464	1286	92	101.5	13.8
3403	ULSD	147110	6477	4.8	0.36	26	0	3	4	2	6	96	9	0	3005	0	2	956	1147	67	107.1	14.3
3404	ULSD	117892	4561	5.9	0.54	12	0	2	1	1	3	104	4	4	3256	0	5	1410	1251	97	101.2	13.8
3404	ULSD	122208	3064	6.0	0.56	11	0	1	0	1	3	100	3	0	3319	0	3	1321	1232	93	105.5	14.2
3404	ULSD	126725	1638	7.8	0.36	7	0	1	0	0	3	105	4	3	3356	1	5	1435	1322	124	107.7	14.4
3404	ULSD	128792	3705	5.6	0.88	25	0	3	4	2	7	103	6	8	3200	1	5	1382	1190	82	102.0	13.8
3405	ULSD	128757	5998	5.9	0.27	9	1	1	1	1	3	106	5	6	3251	1	6	1402	1238	104	100.4	13.7
3405	ULSD	137816	3368	6.9	0.18	13	0	1	2	1	3	106	4	7	3339	1	6	1422	1291	118	104.2	14.0
3405	ULSD	140476	6028	5.0	0.48	22	0	10	48	2	4	92	4	3	3137	1	3	1222	1162	78	95.7	13.2
3405	ULSD	144095	3619	6.0	0.51	14	0	3	8	1	3	104	5	8	3259	1	5	1421	1250	101	102.2	13.9
3405	ULSD	147983	1627	7.3	0.3	6	0	2	2	0	2	110	4	4	3532	0	7	1486	1352	120	106.5	14.3
3405	ULSD	150689	4333	6.7	0.4	10	0	2	2	1	3	109	5	4	3466	1	8	1469	1310	114	108.0	14.4
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3407	ULSD	176854	5788	5.4	0.48	9	0	2	1	1	3	111	5	5	3482	0	8	1477	1278	84	100.0	13.6
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3409	B20	147834	6000	4.4	0	7	0	8	2	1	4	161	3	3	2985	1	4	1233	1088	100	93.3	13.0
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3413	B20	153589	2523	6.6	0.16	7	0	2	2	0	4	122	3	6	3032	1	4	1295	1157	106	95.1	13.2
3413	B20	155862	4796	5.1	0.39	12	0	4	3	1	4	127	4	5	3007	0	5	1288	1122	84	92.8	12.9
3414	B20	136376	1077	6.4	0	3	0	1	1	0	3	147	2	10	2862	1	3	1206	1069	112	103.0	13.9
3414	B20	142670	1679	6.1	0.17	5	0	2	5	0	3	150	4	24	2837	1	4	1216	1063	109	102.0	13.8
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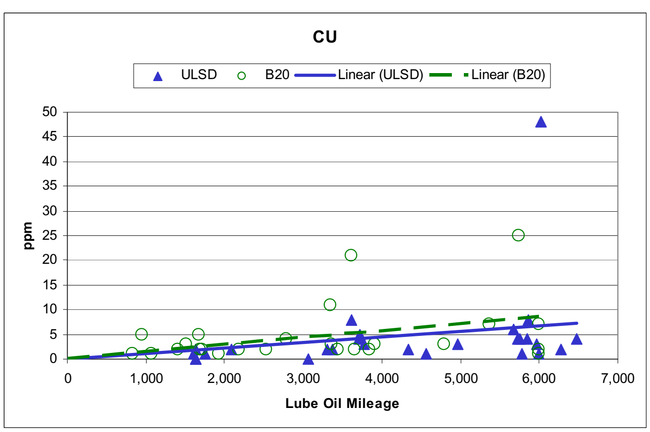

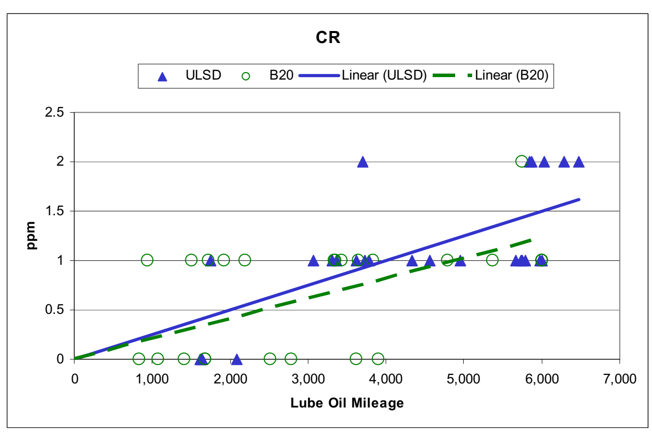

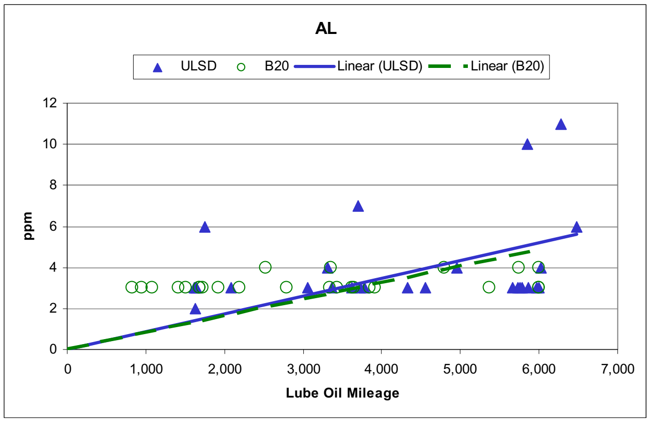
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Linear (B20)
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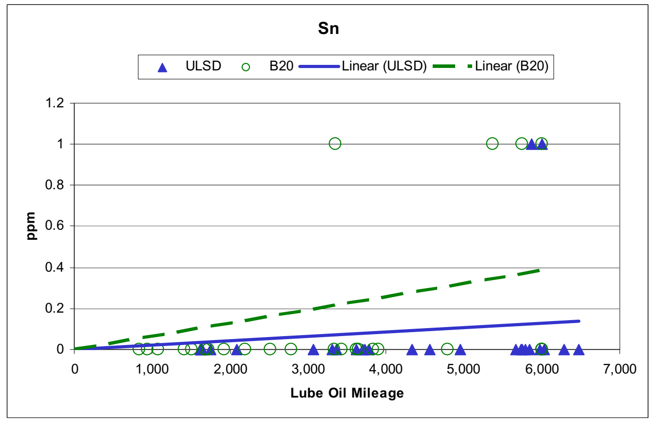
Lube Oil Mileage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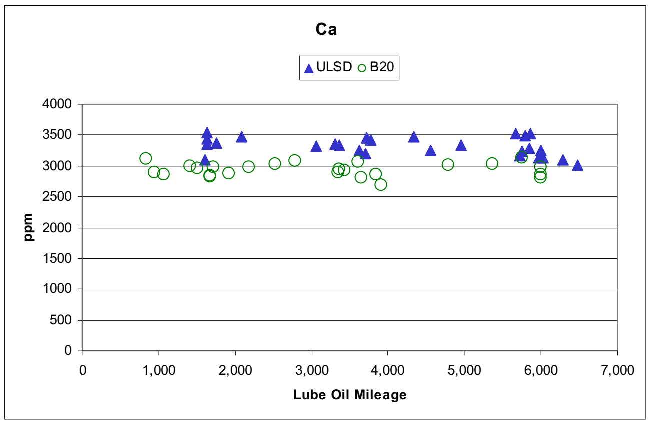
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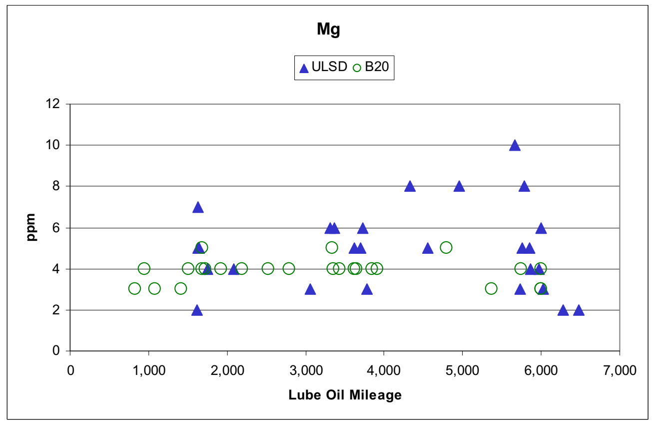
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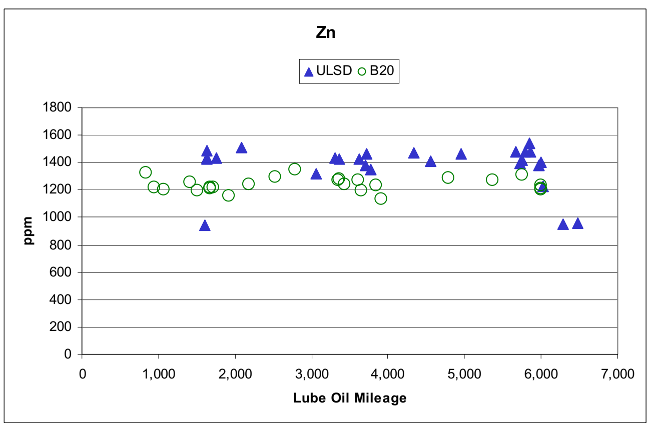
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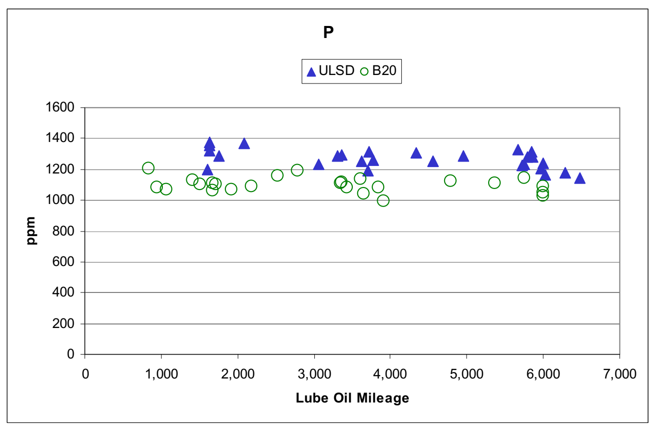
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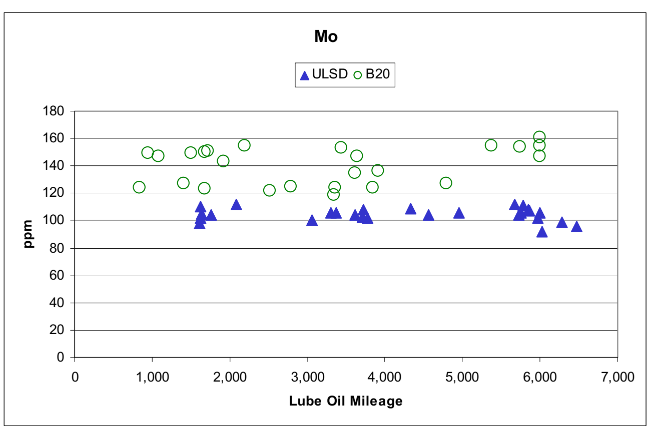
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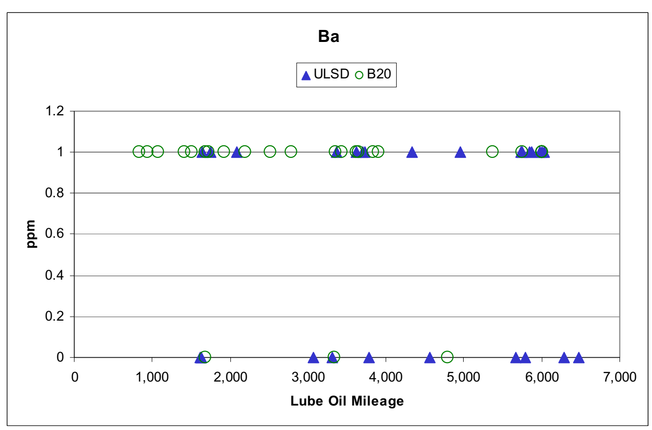
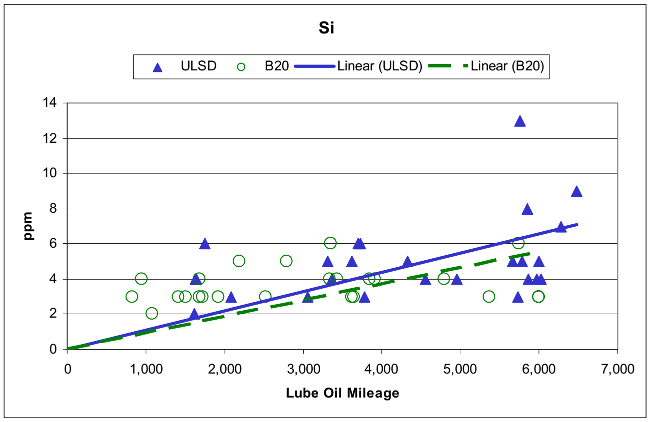
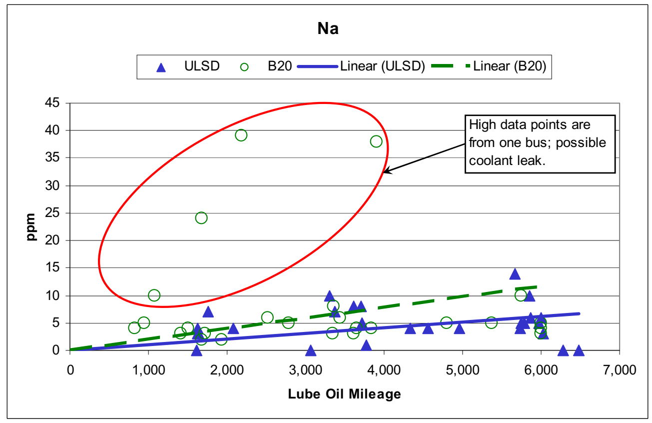
B20
ppm
Lube Oil Mileage


Ba
ULSD
B20
ppm
Lube Oil Mileage



Si
ULSD
B20
Linear (ULSD)
Linear (B20)
ppm
Lube Oil Mileage



Na
ULSD
B20
Linear (ULSD)
Linear (B20)
ppm
High data points are from one bus; possible coolant leak.
Lube Oil Mileage