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St. Louis Metro Biodiesel (B20) Transit Bus Evaluation

12-Month Final Report

R. Barnitt, R.L. McCormick, and M. Lammert

Technical Report
NREL/TP-540-43486
July 2008

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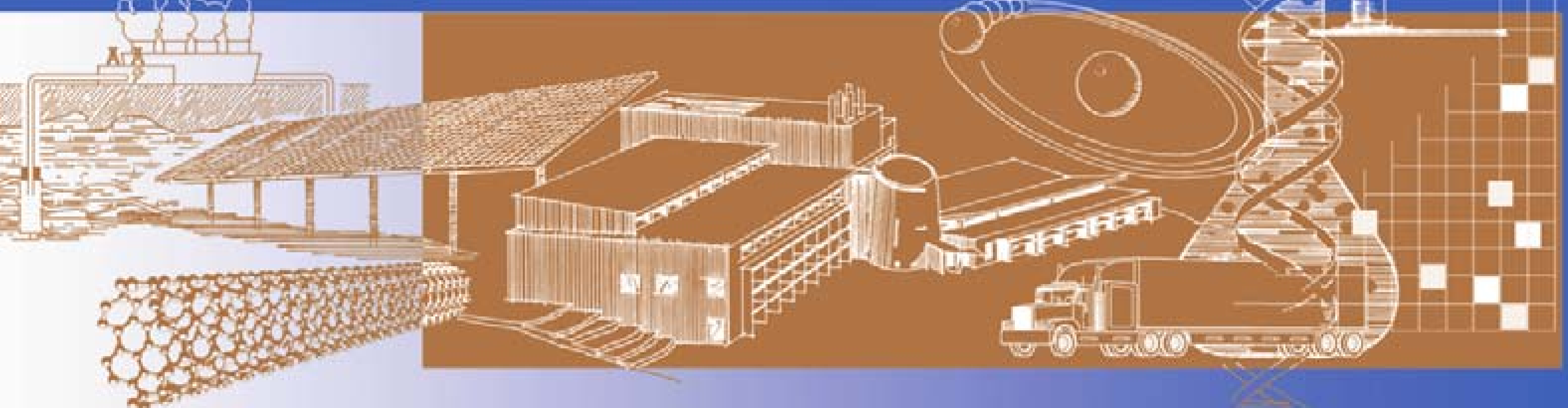

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List of Acronyms

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	preventative maintenance
RC	road call
TBN	total base number
ULSD	ultra-low sulfur diesel
UST	underground storage tank
um	micrometer

Executive Summary

The St. Louis Metro Biodiesel Transit Bus Evaluation project is being conducted under a Cooperative Research and Development Agreement (CRADA) between the National Renewable Energy Laboratory (NREL) and the National Biodiesel Board (NBB). NBB's funds were provided, in part, by the Federal Transit Administration (FTA). The project evaluated the extended in-use performance of buses operating on B20 (20% biodiesel; 80% conventional diesel) fuel. It is one component of a larger effort with respect to biodiesel testing and evaluation.

The objective of this research project is to compare B20 and ultra-low sulfur diesel (ULSD) buses in terms of fuel economy, vehicle maintenance, engine performance, component wear, and lube oil performance.

The evaluations we present in this report examine fifteen 40-foot model year (MY) 2002 transit buses manufactured by Gillig equipped with MY 2002 (2004 emissions certification) Cummins ISM engines. For a period of 12 months, eight of these buses operated exclusively on B20 and the other seven operated exclusively on petroleum ULSD. The B20 and ULSD study groups operated from different depots at St. Louis Metro, but bus routes were matched for duty cycle parity.

Based on the in-use evaluation results:

- The B20 buses exhibited 1.7% lower fuel economy than the ULSD study group.
- Reliability, as measured by miles between road calls (MBRC), was comparable between the two study groups.
- There was no significant difference in total maintenance costs between the two groups.
- Engine and fuel system maintenance costs were 35% higher for the B20 study group, but because of bus-to-bus variability in maintenance costs, a statistical analysis shows that this difference is not significant with a high level of confidence (P=0.21).
- The B20 study group had a higher incidence of fuel filter and fuel injector replacements. Analysis of B100 and B20 samples did not indicate poor fuel quality. No fuel injectors were retained for tear-down analysis to determine failure mode and cause.
- Lube oil samples were collected over a wide range of mileage within the drain interval, and analysis indicates no harm and some potential benefits with B20 use; notably, soot and wear metals were lower. Viscosity, total base number, and corrosive metals were generally less degraded by ULSD use, but these qualities were still "in-grade" for the B20 buses throughout the oil drain interval.

This evaluation is being continued for a second year in order to provide more definitive answers to questions about how B20 impacts engine and fuel system maintenance, as well as other factors.

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Background

This project is being conducted under a Cooperative Research and Development Agreement (CRADA) between the National Renewable Energy Laboratory (NREL) and the National Biodiesel Board (NBB). NBB's funds were provided, in part, by the Federal Transit Administration (FTA). This project is one component of a larger effort with respect to biodiesel testing and evaluation. Under the CRADA, NREL accomplished a detailed data collection and analysis on the St. Louis Metro (Metro) transit fleet's experience operating on B20 (20% biodiesel; 80% conventional diesel) for a period of 12 months. This study is the first B20 in-use fleet study using exhaust gas recirculation (EGR) equipped buses. This study is also the first study to compare the use of B20 to ultra-low sulfur diesel (ULSD).

The work is being performed by the Fleet Test and Evaluation (FT&E) team at NREL, which provides unbiased evaluations on alternative fuel and advanced transportation technologies that aim to reduce U.S. dependence on foreign oil while improving the nation's air quality. The FT&E team's role is to bridge the gap between research and development (R&D) and the commercial availability of alternative fuels and advanced vehicle technologies. FT&E supports DOE's Vehicle Technologies Program by examining market factors and customer requirements, evaluating the performance and durability of alternative fuel and advanced technology vehicles, and assessing the performance of these vehicles in fleet applications.

The FT&E team supports vehicle research activities at NREL by conducting medium- and heavy-duty vehicle evaluations. The team's tasks include selecting appropriate technologies to validate, identifying fleets to evaluate, designing test plans, gathering on-site data, preparing technical reports, and communicating results on its Web site and in print publications. NREL has completed numerous light- and heavy-duty vehicle evaluations based on an established data collection protocol, known as the General Evaluation Plan,[1] developed with and for DOE. This project supports DOE's Nonpetroleum Based Fuels (NPBF) activity.

Objectives

The objective of this project is to evaluate the extended in-use performance of B20 fuel. Specific objectives are to compare fuel economy, vehicle maintenance, engine performance, component wear, and lube oil performance against ULSD.

St. Louis Metro Fleet Operations and Facilities

Operations

St. Louis Metro (Metro) was created in 1949 through a compact between the states of Missouri and Illinois and ratified by the United States Congress. Metro's broad powers enable it to cross local, county, and state boundaries to plan, construct, maintain, own, and operate specific facilities in its efforts to enhance the quality of life in the region. Its service area encompasses 200 municipalities.

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

[1] Available on the Web at www.nrel.gov/vehiclesandfuels/fleettest/pdfs/32392.pdf.

Metro Call-A-Ride, a paratransit van system. Metro also oversees the operations of the St. Louis Downtown Airport and surrounding industrial business park, the Gateway Arch Revenue Collections Center, the Gateway Arch Transportation System, the Gateway Arch Riverboats, and the Gateway Arch Parking Facility.

In FY 2005, Metro transported over 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.

Facilities

Metro maintains four garage facilities (Main, Brentwood, Debaliveire and Illinois), two of which are the focus of this evaluation. The Brentwood Garage (BW) dispatches and maintains the B20-fueled buses and the Debaliveire Garage (DB) is the diesel bus control group.

Buses at each garage are fueled daily, to every other day at two indoor fueling dispensers. As part of service and cleaning operations, the buses are washed and fueled in the evening hours as buses 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 for maintenance operations. Depending on the service required, buses are lifted on hoists or driven over pits to perform necessary repairs or inspections. Maintenance work is recorded electronically by mechanics, capturing data on repair codes, parts, and labor hours.

Approach

Vehicle Selection

Fifteen identical buses are included in this evaluation project. Eight of the buses operate on B20 fuel and seven operate on ULSD to serve as a control group. Basic vehicle attributes are presented in Table 1, and detailed vehicle specifications can be found in Appendix A. Operation and maintenance data is collected during normal operation and analyzed to evaluate performance.

Table 1. Metro B20 Transit Bus Basic Description

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

Additional information regarding the study vehicles is presented in Table 2.

Table 2. Study Bus Information

Bus Unit Number	VIN	ESN	Date of Acquisition	Evaluation Start Mileage	Fuel
3401	15GCD211741112498	35088747	2/3/2004	110,990	ULSD
3402	15GCD211941112499	35088751	2/4/2004	98,042	ULSD
3403	15GCD211141112500	35088755	2/5/2004	113,496	ULSD
3404	15GCD211341112501	35088748	2/9/2004	87,056	ULSD
3405	15GCD211541112502	35088754	2/3/2004	110,583	ULSD
3406	15GCD211741112503	35088750	2/3/2004	103,929	ULSD
3407	15GCD211941112504	35088752	2/3/2004	129,510	ULSD
3408	15GCD211041112505	35088746	2/3/2004	127,467	B20
3409	15GCD211241112506	35090107	2/3/2004	125,630	B20
3410	15GCD211441112507	35090103	2/3/2004	127,825	B20
3411	15GCD211641112508	35090106	2/3/2004	123,374	B20
3412	15GCD211841112509	35090105	2/16/2004	133,231	B20
3413	15GCD211441112510	35090104	2/23/2004	129,086	B20
3414	15GCD211641112511	35088753	2/18/2004	125,081	B20
3415	15GCD211841112512	35088749	2/3/2004	129,530	B20

Route / Duty-Cycle Selection

Several comparative routes were considered to evaluate B20- and ULSD-fueled buses. Options were limited in selecting routes of similar characteristics, from different garages, which are specific to 40-foot transit buses. 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

Throughout this study, eight of the 15 study buses operate on B20, and seven on petroleum ULSD as a control group. Fueling records are submitted to NREL by Metro, reviewed for accuracy, and analyzed for fuel economy comparison of the B20 and diesel groups.

The fueling regime at both Brentwood and Debaliveire garages is very similar. Brentwood fuels with B20 and Debaliveire with petroleum ULSD.

Fuel is generally delivered to each garage daily, to every four or five days. Rack-blended (in-line proportional blending) B20 is delivered to Brentwood by Hartford Wood River Terminal (HWRT). ULSD is 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 located behind the garage, and are connected to three interior fuel dispensers by about 1,000 feet of underground supply line. There is a 30 um filter downstream of the supply pump, and a 10 um filter at the fuel dispenser. There are three dispensers, two are actively being used and one is kept as a spare. All USTs are monitored by a leak- and water-detection system manufactured by Veeder-Root. In addition, the Veeder-Root system performs a tank tightness test (pressure test) once a month.

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 odometer reading, fueling volume, and lube oil requirements are uploaded to M5. These fueling records are transferred to NREL for evaluation and analysis.

Vehicle Reliability

A road call (RC) is defined as a call-in to dispatch reporting a mechanical problem. Depending on the nature of the problem, dispatch may instruct operators to continue driving their routes. However, an RC may stem from an issue that requires the bus to stop driving, allowing for roadside mechanical repair or towing back to the maintenance facility. 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 the occurrence of an RC was recorded as such, regardless of its relative severity.

Vehicle Maintenance and Data Collection

For the B20 fueled buses in this evaluation, routine maintenance is performed identically to the diesel buses. Scheduled maintenance is performed by Metro personnel at the Brentwood and Debaliveire garages, and preventative maintenance (PM) events are conducted every 6,000 miles of driving. 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.

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. Maintenance records are submitted electronically to NREL by Metro, reviewed for accuracy, and analyzed for maintenance cost per mile comparison of the B20 and diesel groups. For vehicle subsystems that may be impacted by B20 fuel use, maintenance cost per mile figures were calculated specific to these subsystems. These subsystems and specific components of interest include:

- Vehicle Subsystems
  - Engine
  - Fuel
- Components
  - Fuel supply system—fuel tank, fuel pumps, fuel lines, fuel injectors, fittings, sensors, etc.
  - Fuel filters and housings

Vehicle Warranty Repairs

Data on warranty repairs are collected in a similar manner as data on normal maintenance actions. However, the cost data are not included in the operating cost calculation. Labor costs may be included depending on the mechanic (operator or manufacturer) and whether those hours were reimbursed under the warranty agreement. (Warranty maintenance information is collected primarily for an indication of reliability and durability.)

Biodiesel Fuel Analysis

Collecting and analyzing samples of B100 and B20 is useful in establishing and recording fuel quality. In addition, should equipment maintenance or reliability issues give reason to suspect poor quality or off-spec fuel, retained samples can be analyzed for corroboration.

NREL coordinated with HWRT to obtain samples of B100 used to blend each new batch of B20 delivered to Metro. These samples were stored in a cool, dark location before they were shipped to NREL. Fuel samples were analyzed by NREL and Southwest Research Institute (SwRI). Analyses performed are presented in Table 4.

Table 4. Biodiesel Fuel Analyses

B100 Load Sample Analysis		
Description	**Method**	**Performed By**
Free & Total Glycerin	ASTM D6584	SwRI
Flash Point	ASTM D93	SwRI
Na/K/Ca/Mg	ASTM D5185	SwRI
B20 Load Sample Analysis		
Description	**Method**	**Performed By**
Biodiesel Content	FTIR in-house	NREL
Cloud Point	ASTM D2500	SwRI

Lube Oil Analysis

Seven ULSD and seven B20 buses were selected for lube oil analysis over the course of the evaluation. Analyses included:

- TBN decay

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

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

Evaluation Results

These final evaluation results are based on a 12-month evaluation period of October 2006 – September 2007.

Bus Use

During the evaluation period, the B20 and ULSD study bus groups accumulated 394,116 and 325,407 miles, respectively. Table 5 presents the average monthly mileage per bus during the evaluation period. The overall 12-month average monthly miles per bus for the B20 buses at BW depot is about 6% higher than for the ULSD buses at DB. This is primarily a function of depot size and routes served.

Table 5. Average Miles Driven per Month per Bus by Study Group

Bus Group	Average Miles per Month
B20	4,105
ULSD	3,874

Figure 1 shows cumulative average monthly miles per bus for each study group. Bus average usage declined slightly during the evaluation period.

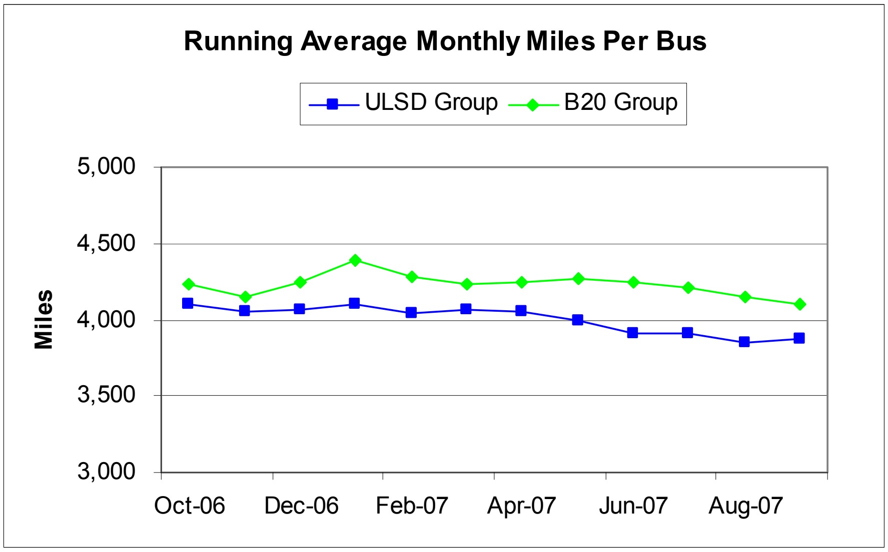

Figure 1. Cumulative Average Monthly Mileage per Bus

Fuel Economy and Cost

Metro's implementation of ULSD (less than 15 ppm sulfur) fuel coincided with the start of this evaluation in October 2006, and the start of B20 use at Metro. ULSD was required in most areas of the United States beginning in October 2006.

The B20 and ULSD study fleet fuel consumption and economy data are presented in Table 6. The calculated 12-month average fuel economy for the B20 buses is 1.7% lower than that of the ULSD buses. This difference is expected due to the approximately 2% lower energy content in a gallon of B20. The 12-month fuel economy for each bus was used to compare ULSD and B20 groups in a two-tailed, paired t-test. By conventional criteria, the difference between the two groups is not statistically significant with a high degree of confidence (P = 0.3).

Table 6. Bus Fuel Use and Economy

Bus	Fuel	Mileage Total	Fuel Used (gallons)	Fuel Economy (mpg)
3401	Diesel	50,154	14,043	3.57
3402	Diesel	45,786	12,797	3.58
3403	Diesel	44,019	12,092	3.64
3404	Diesel	45,252	12,729	3.55
3405	Diesel	42,695	12,397	3.44
3406	Diesel	48,650	13,785	3.53
3407	Diesel	48,851	13,140	3.72
Total	**Diesel**	**325,407**	**90,983**	**3.58**
3408	B20	55,456	15,638	3.55
3409	B20	57,531	15,742	3.65
3410	B20	50,588	14,785	3.42
3411	B20	47,881	14,176	3.38
3412	B20	46,514	12,918	3.60
3413	B20	48,695	14,264	3.41
3414	B20	45,312	12,457	3.64
3415	B20	42,139	12,136	3.47
Total	**B20**	**394,116**	**112,115**	**3.52**

Figure 2 shows average monthly fuel economy for the two study groups for the 12-month evaluation period. This trend exhibits a continuous slight decline in fuel economy.

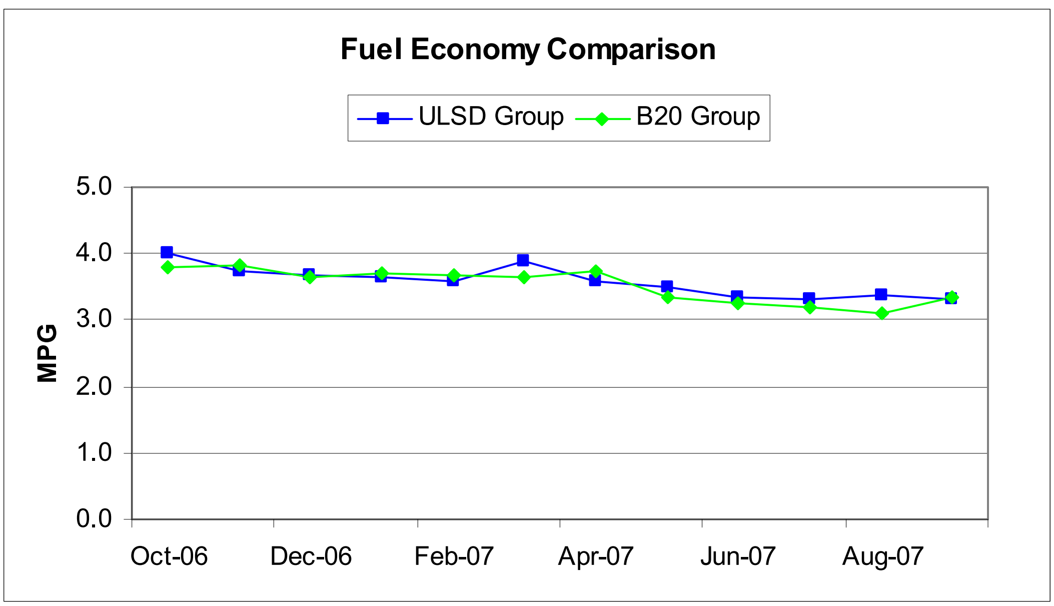

Figure 2. Average Fuel Economy

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 2,375 and 2,627 for ULSD and B20 groups, respectively.

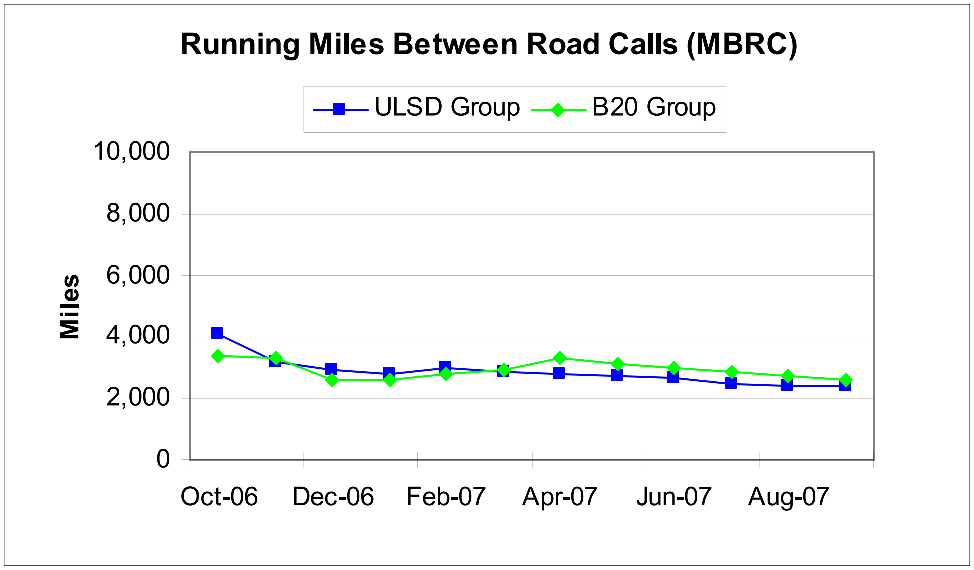

Figure 3. Cumulative MBRCs

In addition, reliability as measured in MBRCs is assessed for the engine and fuel systems. Figure 4 shows the cumulative MBRC for all RCs for the ULSD and B20 groups. The ULSD group had a three month run of exceptionally high MBRC numbers, but by the end of the 12-month evaluation the B20 buses exhibited higher reliability, with engine and fuel system MBRC values of 6,924 and 8,211 for ULSD and B20 groups, respectively.

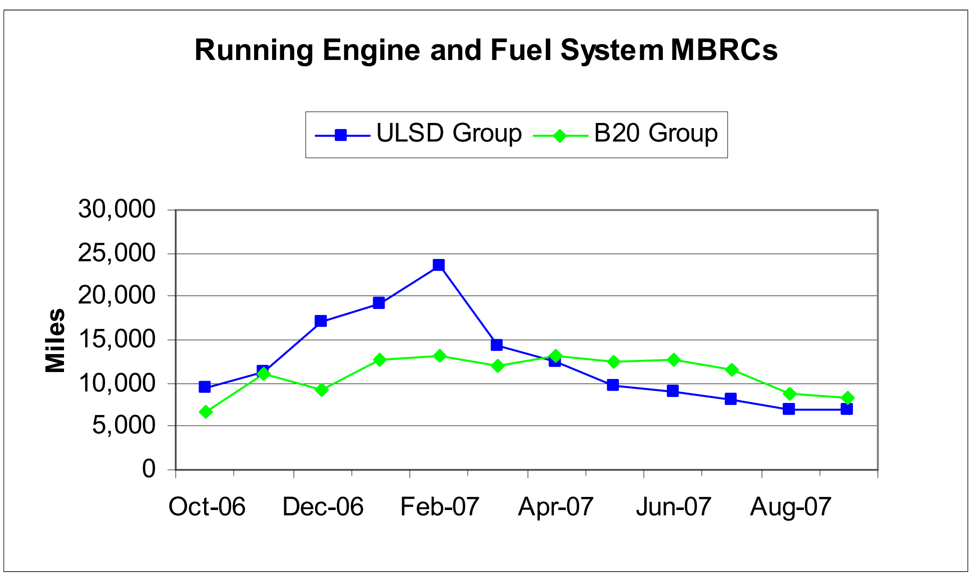

Figure 4: Cumulative MBRCs, Engine and Fuel System

Maintenance Cost Analysis

The maintenance costs have been collected in a similar way for each study group. The duty cycle and maintenance practices at BR and DB depots are similar. All work orders and parts information available were collected for the study buses.

Total Maintenance Costs

This cost category includes the costs of parts, assumes hourly labor costs of $50 per hour, but does *not* include warranty costs. Cost per mile is calculated as follows:

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

The labor rate has been artificially set at a constant rate of $50 per hour so that other analysts can change this rate to one more similar to their own. This rate does not directly reflect Metro's current hourly mechanic rate.

Table 7 shows total maintenance costs for the study buses during the evaluation period. The total maintenance cost per mile was 0.32% higher for the B20 buses than the ULSD buses. The 12-month total maintenance cost/mile for each bus was used to compare ULSD and B20 groups in a two-tailed, paired t-test. By conventional criteria, the difference between the two groups is not statistically significant with a high degree of confidence (P = 0.8).

Table 7. Total Maintenance Costs

Total Maintenance Cost Comparison					
Bus	**Fuel**	**Mileage Total**	**Labor Hours**	**Parts Cost**	**Cost ($/mile)***
3401	Diesel	50,154	459	$ 12,923	$ 0.716
3402	Diesel	45,786	324	$ 5,842	$ 0.482
3403	Diesel	44,019	364	$ 8,361	$ 0.604
3404	Diesel	45,252	293	$ 7,876	$ 0.498
3405	Diesel	42,695	305	$ 4,283	$ 0.457
3406	Diesel	48,650	442	$ 9,498	$ 0.649
3407	Diesel	48,851	332	$ 9,430	$ 0.533
Total	**Diesel**	**325,407**	**2,520**	**$ 58,214**	**$ 0.566**
3408	B20	55,456	501	$ 12,762	$ 0.682
3409	B20	57,531	440	$ 8,092	$ 0.523
3410	B20	50,588	423	$ 11,574	$ 0.647
3411	B20	47,881	398	$ 7,540	$ 0.574
3412	B20	46,514	404	$ 9,673	$ 0.642
3413	B20	48,695	317	$ 4,369	$ 0.415
3414	B20	45,312	316	$ 8,221	$ 0.530
3415	B20	42,139	318	$ 5,778	$ 0.514
Total	**B20**	**394,116**	**3,116**	**$ 68,010**	**$ 0.568**

* Assumed labor cost of $50/hour

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 gain parity with the diesel group by the ninth month of the evaluation.

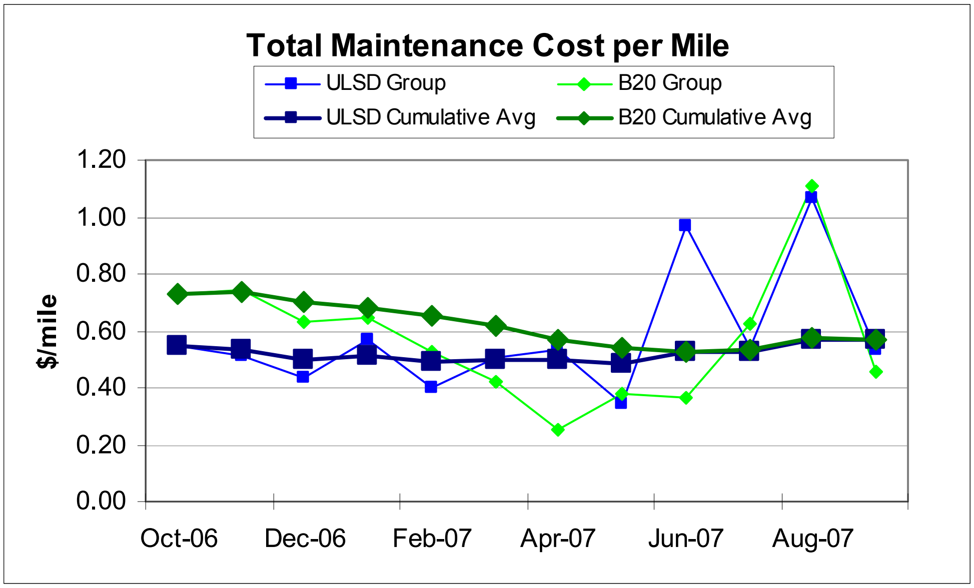

Figure 5. Total Maintenance Costs

Engine and Fuel System Maintenance Costs

The impact of B20 on the vehicle fuel delivery system is of considerable interest to NBB, OEMs, and end users. Consequently, this analysis also includes a maintenance cost comparison specific to the engine and fuel system.

Metro codes and categorizes labor events and parts replacements according to vehicle subsystem or maintenance activity. For example, maintenance performed on the engine, fuel system, or as part of a preventative maintenance program is coded differently. Using these codes, the maintenance and repair data were analyzed in more detail to assess differences at the engine and fuel system level—the systems that B20 use might be expected to impact.

Bus maintenance costs during the evaluation period related to the engine and fuel system are presented in Table 8. The engine and fuel system maintenance cost per mile was 35% higher for the B20 buses than the ULSD buses. These higher costs for the B20 study group were driven primarily by an elevated number of fuel injector replacements (see *Fuel System Component Replacements*). Nevertheless, the bus to bus variability is so high that this difference is not statistically significant. The 12-month engine and fuel system maintenance cost/mile for each bus was used to compare ULSD and B20 groups in a paired t-test. The difference between the two groups is not statistically significant with a high degree of confidence (P = 0.21).

Table 8. Engine and Fuel System Maintenance Costs

Engine and Fuel Systems Maintenance Cost Comparison					
Bus	Fuel	Mileage Total	Labor Hours	Parts Cost	Cost ($/mile)*
3401	Diesel	50,154	36	$ 448	$ 0.045
3402	Diesel	45,786	59	$ 108	$ 0.067
3403	Diesel	44,019	59	$ 356	$ 0.075
3404	Diesel	45,252	54	$ 342	$ 0.067
3405	Diesel	42,695	27	$ 15	$ 0.032
3406	Diesel	48,650	21	$ 11	$ 0.022
3407	Diesel	48,851	66	$ -	$ 0.067
Total	**Diesel**	**325,407**	**322**	**$ 1,281**	**$ 0.053**
3408	B20	55,456	84	$ 657	$ 0.088
3409	B20	57,531	28	$ 459	$ 0.032
3410	B20	50,588	67	$ 1,740	$ 0.101
3411	B20	47,881	50	$ 608	$ 0.065
3412	B20	46,514	74	$ 1,696	$ 0.116
3413	B20	48,695	21	$ 862	$ 0.039
3414	B20	45,312	48	$ 882	$ 0.073
3415	B20	42,139	49	$ 455	$ 0.069
Total	**B20**	**394,116**	**421**	**$ 7,360**	**$ 0.072**

* Assumed labor cost of $50/hour

The monthly and running average of engine and fuel system maintenance costs for the diesel and B20 groups are compared in Figure 6. 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 the monthly maintenance costs. These engine and fuel system maintenance costs are higher through the first several months for the B20 group, driven by the elevated number of fuel filter and fuel injector replacements. Although the B20 group engine and fuel system related maintenance cost is $0.02/mile higher than the ULSD group, the B20 group total maintenance cost is only $0.002/mile higher. Thus, engine and fuel system related maintenance was not a significant driver in total maintenance costs.

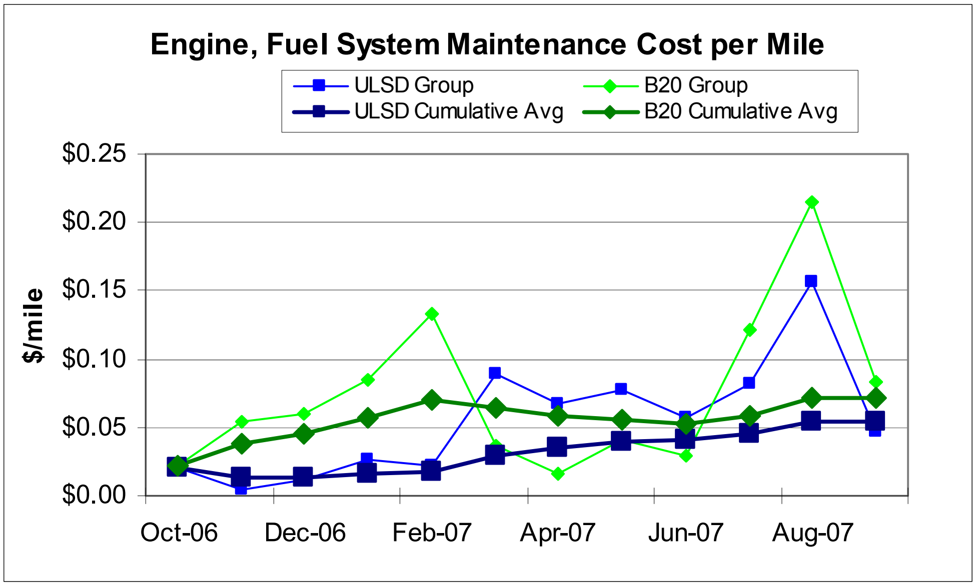

Figure 6. Engine and Fuel System Maintenance Costs

Fuel System Component Replacements

Looking specifically at fuel system parts that may be considered potentially susceptible to B20 use, maintenance items found in the data include the following:

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

The fuel filter and fuel system flush are grouped with a suite of preventative maintenance repair checks and part replacements. A fuel system flush is performed every 50,000 miles. The occurrence of a fuel system flush outside of this interval could indicate fuel system diagnostic activities to 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 by fleets switching over to a biodiesel blend, but we are not aware of data to support this change in practice.

Table 9 presents fuel system part replacement frequency for the ULSD and B20 groups over the evaluation period. Fuel filter replacements listed are those that occurred outside of PM activities, and may indicate a fuel-related issue. All fuel system flush events occurred as part of 50,000-mile PM events.

Table 9. Fuel System Part Replacements

Fuel	Part Replaced	Oct-06	Nov-06	Dec-06	Jan-07	Feb-07	Mar-07	Apr-07	May-07	Jun-07	Jul-07	Aug-07	Sep-07	Total
ULSD	Fuel Filter		2	1	1		1	1	2	3	1		1	13
	Fuel Injector					2						1		3
	Fuel Pump													0
	Fuel Sys Flush				2									2
B20	Fuel Filter	7	5		1	10	1	3			1			28
	Fuel Injector		1	1	2	3			1	1	2	2	2	15
	Fuel Pump													0
	Fuel Sys Flush			1	2		1							4

The higher replacement frequency of fuel filters in the first two months of B20 use is due to Metro's implementation of a 3:1 change frequency. The reasons for the replacement of ten fuel filters on B20 buses in February 2007 are not completely understood. During February 2007, St. Louis experienced unseasonable cold temperatures dropping below the cloud point of their B20. This could indicate that cold flow issues contributed to the increase in fuel filter changes that month. Four of the ten are listed as part replacements during a PM event, but not all correspond to a PM activity in Metro's work order database. The other six fuel filter replacements are coded as "test", but Metro does not have record of conducting a test involving fuel filters during this period. Data indicate there was one RC related to a plugged fuel filter during February 2007.

The bulk of this analysis focuses on the high incidence of fuel injector replacements with B20 use. Fuel injectors are a costly item, and their long-term durability with B20 use is unknown. According to Metro, injectors on this order group of buses have been observed to fail as early as 100,000 miles. Table 10 presents the miles accrued on buses with injector replacements during this evaluation. It is unknown how many miles had been driven on these injectors prior to the start of the study. Of note is the wide range of miles driven on B20 prior to injector failure, suggesting that total injector mileage may be a more important factor than exposure to a specific fuel. Also note the higher evaluation starting mileage (by about 20,000 miles) of the B20 group.

Table 10. Fuel Injector Failure Mileages

Unit No	Fuel	Evaluation Start Mileage	B20 Miles Before Failure	Injectors Replaced	Unit No	Fuel	Evaluation Start Mileage	ULSD Miles (*Before Failure*)	Injectors Replaced
3408	B20	127,467	55,355	2	3401	ULSD	110,990	***45,072***	1
3409	B20	125,630	47,270	1	3402	ULSD	98,042	45,786	0
3410	B20	127,825	3,865	1	3403	ULSD	113,496	44,019	0
3410	B20	127,825	18,635	2	3404	ULSD	87,056	***19,101***	1
3411	B20	123,374	10,364	1	3405	ULSD	110,583	***14,128***	1
3411	B20	123,374	12,332	1	3406	ULSD	103,929	48,650	0
3412	B20	131,582	13,180	1	3407	ULSD	129,510	48,851	0
3412	B20	131,582	33,403	1					
3412	B20	131,582	40,406	1					
3413	B20	128,805	35,542	1					
3413	B20	128,805	40,444	1					
3414	B20	124,923	20,950	1					
3415	B20	129,530	38,204	1					
Average Miles		127,392	29,596		Average Miles		107,658	26,100	
Standard Deviation		2,664	16,717		Standard Deviation		13,305	16,617	

Gateway Cummins, Inc. is the local Cummins supplier for Metro. According to Metro, fuel injectors have been covered under warranty by this supplier for this particular bus group even beyond the 100,000 miles normal warranty. Table 11 presents the labor and parts costs associated with injector replacements for all study buses. Parts costs that are blank are indicative of warranty replacements. Metro maintains a field in their maintenance database for "job reason", which sheds some light on why a repair occurred. The "job reason" can range from a driver report of suspected malfunction or diminished performance, to a scheduled maintenance event. Table 11 includes this information when known, which in some cases qualifies fuel injector replacements.

Table 11. Fuel Injector Replacement Costs, Job Reasons

Unit No	Fuel	Injectors Replaced	Labor Hours	Part Cost	Total Cost	Job Reason
3408	B20	2	4.2	$ 480	$ 690	Unplanned visit
3409	B20	1	6.2	$ 452	$ 760	Unplanned visit
3410	B20	1	4.9	$ -	$ 246	Yard Grief
3410	B20	2	5.7	$ 1,106	$ 1,392	Driver Report x2
3411	B20	1	2.5	$ 604	$ 728	Unplanned visit
3411	B20	1	0	$ -	$ -	Unplanned visit
3412	B20	1	7.7	$ -	$ 383	Driver Report
3412	B20	1	4.2	$ -	$ 209	Unplanned visit
3412	B20	1	2.7	$ -	$ 137	Unplanned visit
3413	B20	1	2.8	$ 398	$ 539	Inspection Grief
3413	B20	1	0.2	$ 452	$ 464	Inspection Grief
3414	B20	1	8.4	$ 565	$ 983	Unplanned visit
3415	B20	1	0	$ 448	$ 448	Unplanned visit
3401	ULSD	1	0	$ 448	$ -	Planned Visit
3404	ULSD	1	0	$ -	$ -	Driver Report
3405	ULSD	1	0	$ -	$ -	Not Listed

As presented above, the ULSD-fueled buses had one known scheduled fuel injector inspection and replacement out of three. However, the B20-fueled buses had injectors replaced under circumstances that suggest operational problems. Table 12 presents fuel filter replacements (10) and fuel injector replacements (3) for B20 buses in February 2007. The two shaded regions show date ranges in which fuel filter replacements were followed by fuel injector replacements.

At the onset of this project, NREL and Metro agreed to employ a "part retention program" for fuel system parts, which would allow tear-down analysis and identification of the root cause of failure. This effort was not executed by depot maintenance staff as planned. A retroactive investigation into fuel injector replacements was initiated by NREL and led by Metro staff, but did not yield any additional information as to the cause of these maintenance events. Given the large number of buses in Metro's garages undergoing engine repairs, replacing injectors without significant analysis of the root cause of failure is not abnormal.

Table 12. Fuel Filter-Injector Successive Replacements, February 2007

Unit No	Fuel	Date	Part Replaced
3408	B20	02/08/07	Fuel filter
3410	B20	02/13/07	Fuel filter
3410	B20	02/14/07	Fuel injector
3410	B20	02/14/07	Fuel injector
3410	B20	02/22/07	Fuel filter
3410	B20	02/23/07	Fuel filter
3411	B20	02/05/07	Fuel filter
3411	B20	02/25/07	Fuel filter
3412	B20	02/26/07	Fuel filter
3413	B20	02/26/07	Fuel filter
3414	B20	02/27/07	Fuel injector
3414	B20	02/27/07	Fuel filter
3415	B20	02/27/07	Fuel filter

Fuel analysis was conducted in part to determine if fuel system durability issues were connected with poor fuel quality. Biodiesel fuel analysis and results are presented below.

Based on the available data, the cause of the higher rate of fuel injector replacement for the B20 buses cannot be determined with certainty. On the one hand, exposure to B20 may have been the cause, but on the other hand, the higher mileage of the B20 buses might also have lead to a higher number of injector failures. This is not atypical for a 12-month evaluation, as a significantly longer time is generally required to fully understand fuel impacts on engine durability and maintenance. Note that the evaluation is being continued for a second year, and the additional data will hopefully clarify the situation.

Biodiesel Fuel Analysis and Results

Fifteen B100 and 19 B20 samples were analyzed by NREL or SwRI. These samples represented fuel consumed by Metro from late January through July 2007.

B100 analysis results are summarized in Table 13. Only one sample was off-spec (flashpoint), and two additional samples were borderline (flashpoint). A sample is off-spec if flashpoint is <130C, but >93C and methanol content is >0.200% by mass; or if flashpoint is <93C. Generally, a flashpoint result in the 93 to 130C range warrants methanol analysis to confirm if the sample was off-spec. While free and total glycerin results are within specification, the absence of acid number results does not allow decoupling of fuel quality and fuel injector failures in B20 buses.

Table 13. Summary of B100 Fuel Analytical Results

Sample Date	Free Glycerin (weight %)	Total Glycerin (weight %)	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	P (ppm)	Flashpoint (degC)
01/29/07	<0.005	0.078	<5	<5	<1	<1	<1	117.8
02/05/07	<0.005	0.071	<5	<5	<1	<1	<1	160.6
02/12/07	<0.005	0.178	<5	<5	<1	<1	<1	143.9
02/19/07	<0.005	0.135	<5	<5	<1	<1	<1	160.6
02/26/07	<0.005	0.182	<5	<5	<1	<1	<1	162.8
03/05/07	<0.005	0.173	<5	<5	<1	<1	<1	157.8
03/12/07	<0.005	0.159	<5	<5	<1	<1	<1	163.3
05/07/07	<0.005	0.112	<5	<5	<1	<1	<1	138.9
05/14/07	<0.005	0.112	<5	<5	<1	<1	<1	73.3
05/21/07	<0.005	0.085	<5	<5	<1	<1	<1	147.2
06/04/07	<0.005	0.179	<5	<5	<1	<1	<1	146.1
06/11/07	<0.005	0.159	<5	<5	<1	<1	<1	145
06/18/07	<0.005	0.173	<5	<5	<1	<1	<1	99.4
07/02/07	<0.005	0.160	<5	<5	<1	<1	<1	145
07/09/07	<0.005	0.178	<5	<5	<1	<1	<1	155

(red): Off-spec
(yellow): Borderline off-spec; require methanol content (EN14110) to confirm.

B20 analysis results are summarized in Table 14. The B20 samples had consistent cloud point results; however during February 2007, St. Louis experienced unseasonable cold temperatures dropping below the cloud point of their B20. This could indicate that cold flow issues contributed to the increase in fuel filter changes that month.

Table 14. Summary of B20 Fuel Analytical Results

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

NA: Not Analyzed

Lube Oil Analysis and Results

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.

Figure 7 presents weight percent soot in oil. Ideally, soot should be below 3.0% by weight. 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 8 presents the kinematic viscosity of oil at 100C. Viscosity can be used as an indication of fuel dilution. 15W-40 oils, as used by Metro, have a minimum value of 12.5 cSt, thus this viscosity value should be above 12.5 cSt. Viscosity remains "in-grade" throughout the oil drain period for both groups. Figure 9 presents total base number (TBN) of oil. Ideally, TBN should be above 2.5 mg KOH/g. TBN appears slightly lower with B20, but both show sufficient TBN retention at end of drain. Figure 10 presents iron in oil; an indication of engine wear. Wear appears slightly lower with B20, especially at high mileage. Figure 11 presents lead in oil; an indication of engine corrosion. Corrosion appears slightly higher with B20, especially at high mileage. However, the oil is still “in-grade” throughout the oil drain period.

In general, there appeared to be no harm to lube oil with B20 use, and some potential benefits. Both soot in oil and wear metals were lower with B20 use as compared to ULSD. TBN, kinematic viscosity, and corrosion were slightly compromised with B20 use, but oil was still “in-grade” throughout the 6,000 mile oil interval.

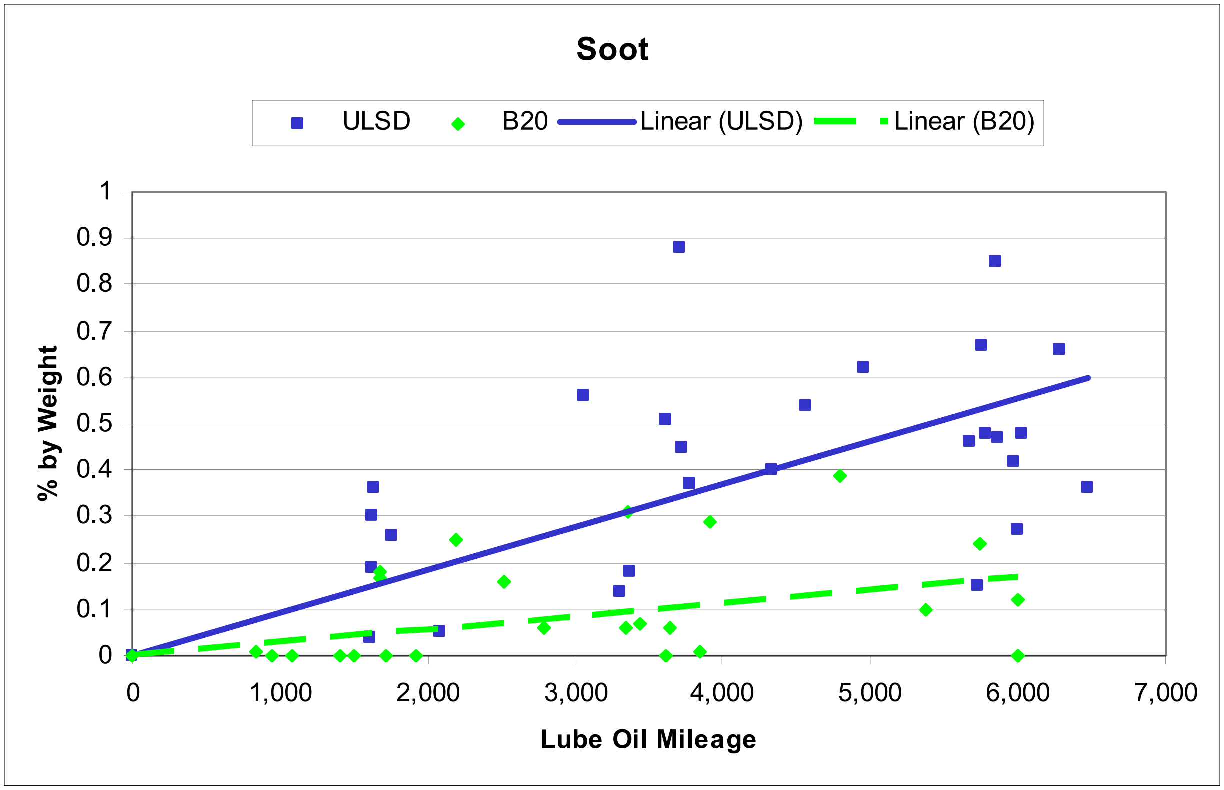

Figure 7. Soot in Lube Oil

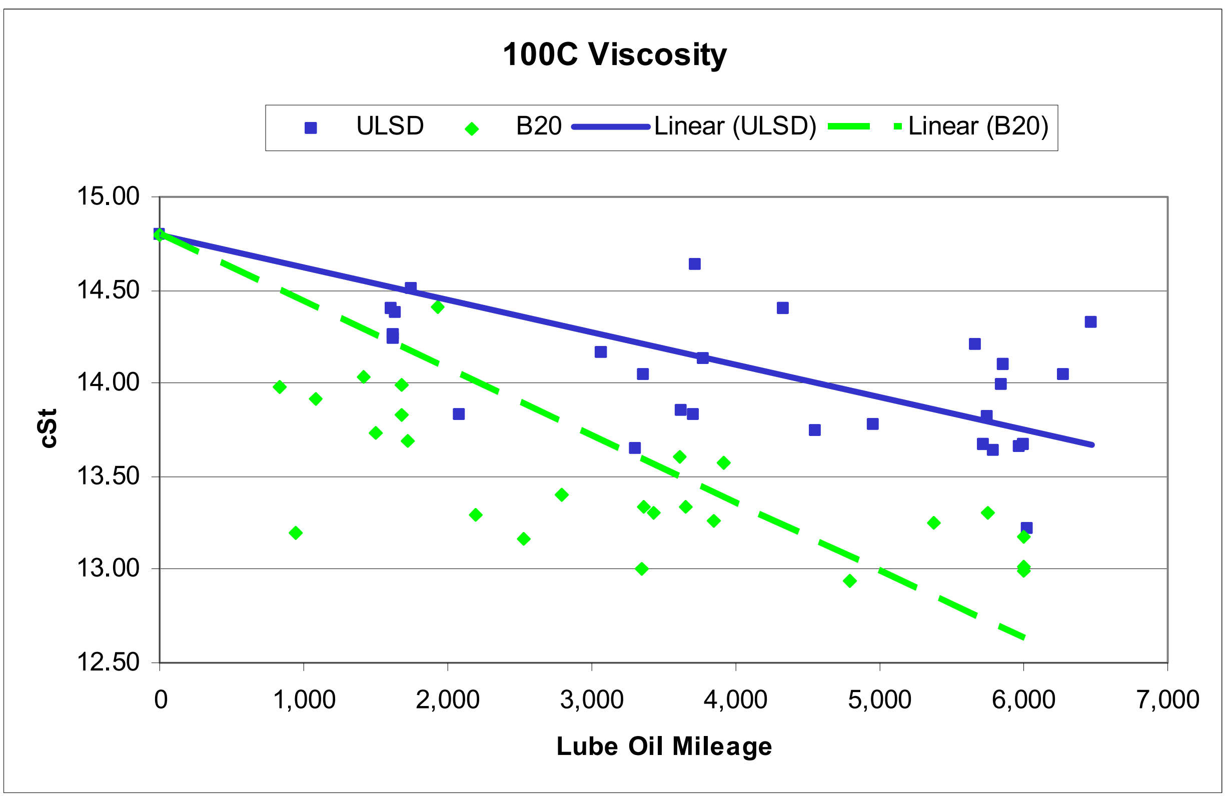

Figure 8. 100C Viscosity of Lube Oil

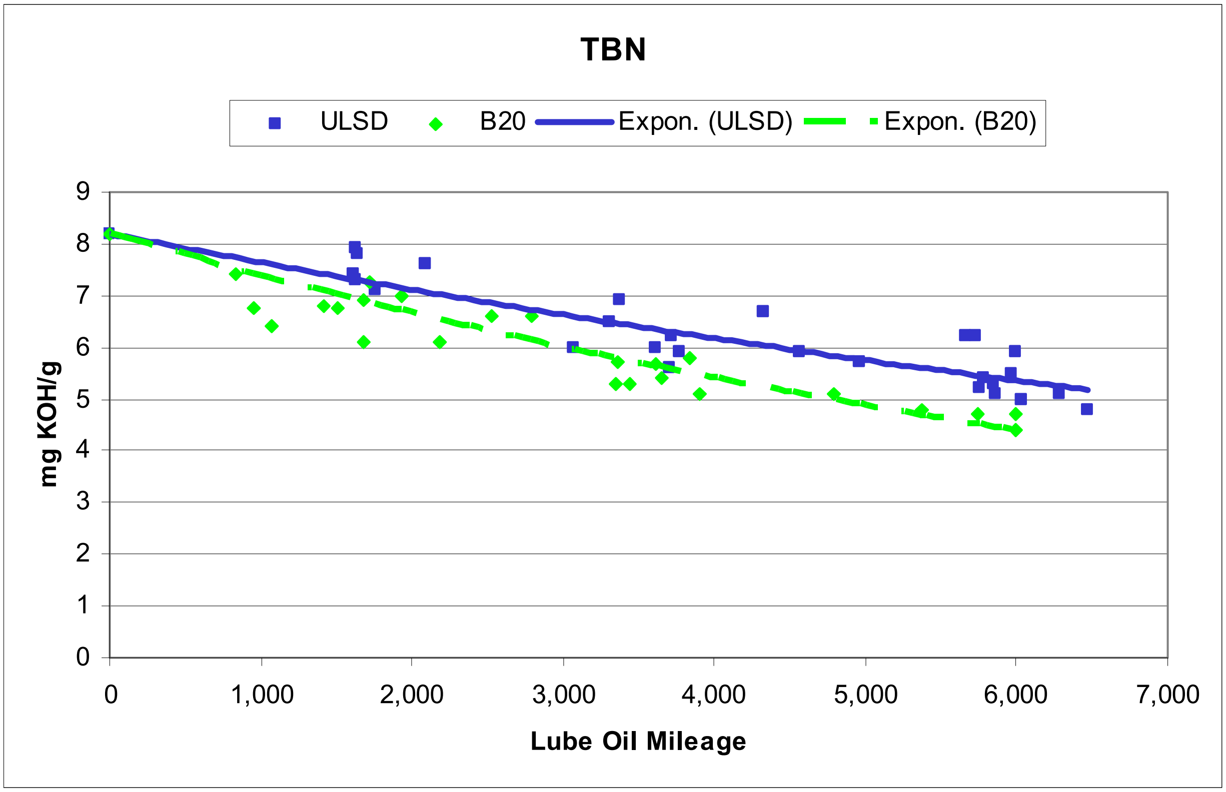

Figure 9. TBN of Lube Oil

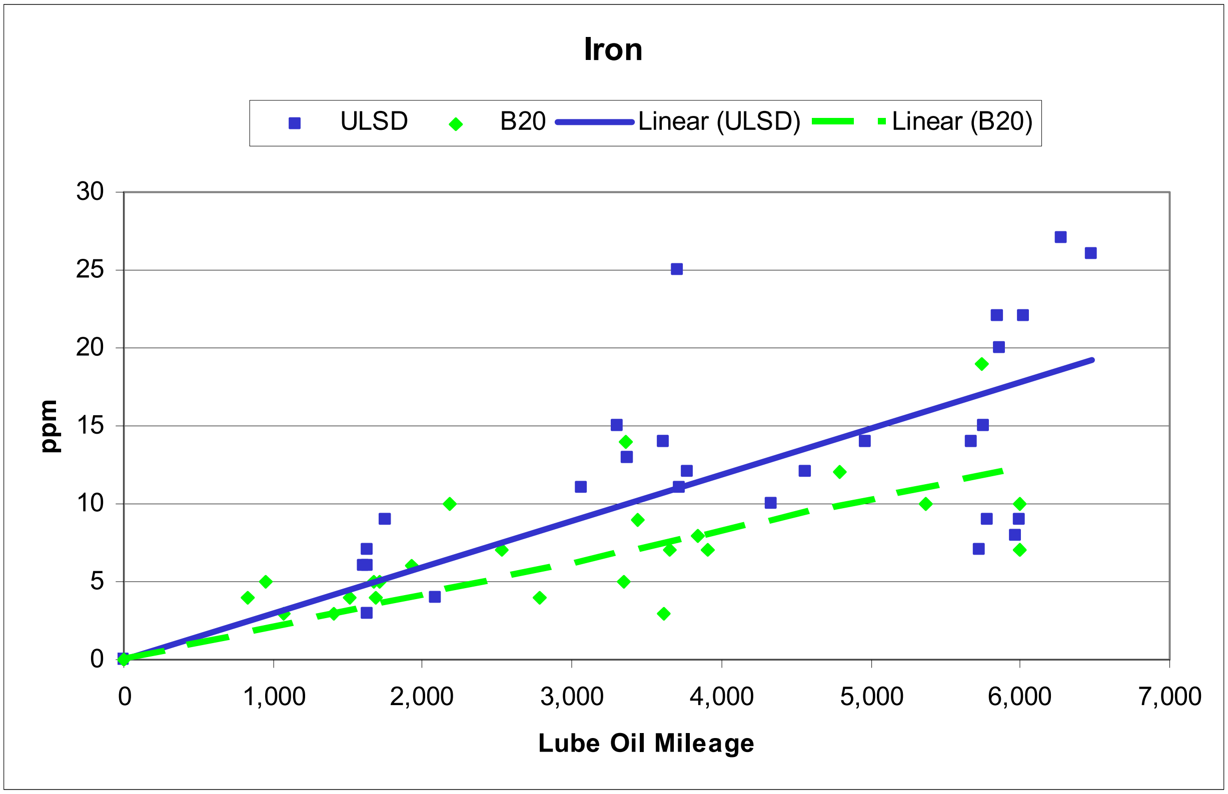

Figure 10. Iron in Lube Oil

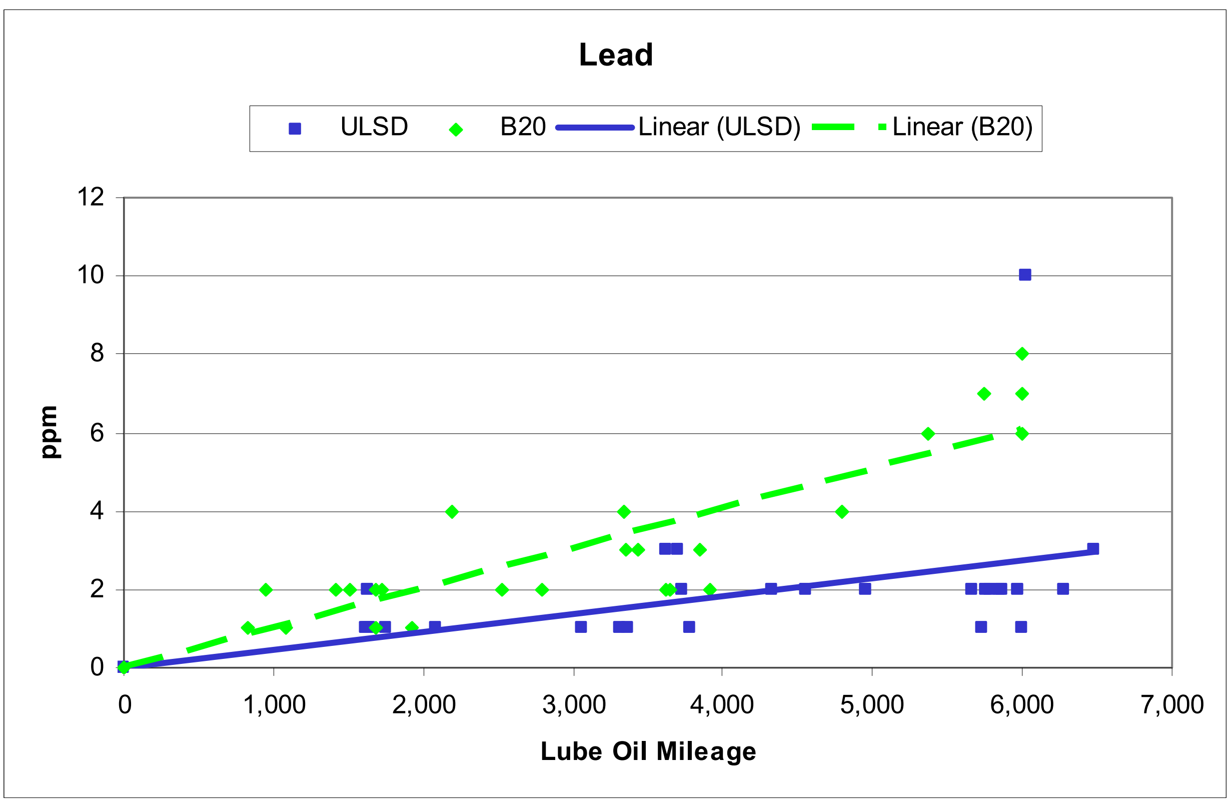

Figure 11. Lead in Lube Oil

Conclusions

- With similar usage and duty cycle, the B20 study group exhibited a 1.7% lower fuel economy than the ULSD study group. This difference is expected due to the lower energy content of B20 fuel. However, this difference is considered to be not statistically significant ($P = 0.3$).
- The B20 study group exhibited similar reliability (as measured in MBRC) to the ULSD study group.
- There was no significant difference in total maintenance cost per mile between the two study groups; engine and fuel system related maintenance was not a significant driver in total maintenance costs.
- The engine and fuel system maintenance cost per mile was 35% ($P = 0.21$) higher for the B20 study group than the ULSD study group, but the difference is not statistically significant because of high vehicle to vehicle variability in engine and fuel system maintenance costs.
- The B20 study group had a higher incidence of fuel filter replacements. Initially, fuel filters were intentionally replaced at a 3:1 ratio on B20 buses, as a proactive effort to avoid filter plugging due to loosening of fuel system deposits. The reason for the replacement of ten fuel filters on B20 buses in February 2007 is unknown, but extremely cold temperatures (below cloud point) could be to blame.
- The B20 study group experienced an elevated number of fuel injector replacements.
- Metro's maintenance database indicates that operational problems led to fuel injector replacements on B20 buses. No additional qualifying information is available. However the bus group, which includes the study buses, is the subject of ongoing warranty replacement of injectors by the local Cummins distributor. All fuel injector failures occurred within the expected mileage range of failure for this group, and no obvious pattern exists in terms of miles driven on B20 prior to injector replacement.
- Although analysis of B100 fuel samples did not indicate poor fuel quality as measured by free and total glycerin, no fuel injectors were retained for tear-down analysis to determine failure mode and cause.
- Lube oil analysis indicates no harm, and some potential benefits, with B20 use; notably, soot and wear metals were lower with B20 use. Viscosity, total base number, and corrosive metals were generally more positive with ULSD use, but these qualities were still "in-grade" for the B20 buses throughout the oil drain interval.

Appendix

Evaluation and Vehicle Specifications

Evaluation Technology	Biodiesel (B20)
Operating Company	Metro St. Louis
Evaluation Period	10/1/06 - 9/30/07

Bus Unit Number	VIN	Date of Acquisition	Evaluation Start Mileage	Fuel
3401	15GCD211741112498	2/3/2004	110,990	ULSD
3402	15GCD211941112499	2/4/2004	98,042	ULSD
3403	15GCD211141112500	2/5/2004	113,496	ULSD
3404	15GCD211341112501	2/9/2004	87,056	ULSD
3405	15GCD211541112502	2/3/2004	110,583	ULSD
3406	15GCD211741112503	2/3/2004	103,929	ULSD
3407	15GCD211941112504	2/3/2004	129,510	ULSD
3408	15GCD211041112505	2/3/2004	127,467	B20
3409	15GCD211241112506	2/3/2004	125,630	B20
3410	15GCD211441112507	2/3/2004	127,825	B20
3411	15GCD211641112508	2/3/2004	123,374	B20
3412	15GCD211841112509	2/16/2004	133,231	B20
3413	15GCD211441112510	2/23/2004	129,086	B20
3414	15GCD211641112511	2/18/2004	125,081	B20
3415	15GCD211841112512	2/3/2004	129,530	B20

Vehicle Dimensions	
Manufacturer	Gillig
Model	Phantom 4102
Length, ft.	39' 10"
Width, in.	101.75"
Height, in.	121"
Ground clearance, in.	9" (at axles), 13" (excluding axles)
Wheel Base	280"
Front overhang (axle to vehicle front), in.	90.75"
Number of axles	2
Number of driven axles	1
Gross Vehicle Weight Rating, lb.	
Front Axle	14,600
Total	40,600
Curb Weight, lb.	
Front Axle	10,000
Rear Axle	18,800
Total	29,000
Seated Load Weight	
Front Axle	12,407
Rear Axle	22,843
Total	35,250
Rear Axle	26,000

Passenger Seats	
Number of Passenger Seats with no Wheelchairs on Board	43
Number of Wheelchair Positions	2
Number of Passenger Seats with all Wheelchair Positions Occupied	37
Maximum Number of Standees	30.41

Fuel	
Type(s)	ULSD, B20
Necessary Additives	None reported

Power Plant	
OEM or Retrofit?	OEM
Power Plant Type (engine, turbine, fuel cell)	Engine
Manufacturer	Cummins
Model Number	ISM 280
Year of Manufacture	2002
2 Cycle or 4 Cycle?	4 Cycle
Compression Ratio	16.1:1
Power Plant, continued	
Ignition Aids Used? (Yes/No)	No
Type of Ignition Aid (Spark Plug, Glow Plug, Pilot Ignition, Other)	NA
EPA Certified? (Yes/No)	Yes
CARB Certified? (Yes/No)	
Power Rating	
Max. bhp	280 hp
RPM of Max. bhp	2100

Power Plant (continued)	
Max. Torque (ft. lbs.)	900
RPM of Max. Torque	1200
Displacement (L)	661 cu in
Engine Oil	
Type(s) Used	Chevron RPM 15W40
Necessary Additives	Proprietary
Oil Capacity (qts.)	40
Blower? (Yes/No)	No
Turbocharger? (Yes/No)	Yes
Liquid Fuel Delivery Systems	
Mechanical or Electronic Fuel Injectors?	Electronic
Injector Manufacturer	Cummins / ISM
Injector Model Number	3411756
Number of Fuel Filters	2
Fuel Filter Manufacturer	Fleetguard, Davco
Fuel Filter Model	FS1022, 382
Gaseous Fuel Delivery Systems	NA
Direct Injection or Fumigation?	NA
Throttle for Intake Air? (Yes/No)	NA
OEM or Retrofit?	NA

Power Plant Accessories	
Mechanical or Electric Drive Accessories?	Mechanical
Generator	Delco Remy
Output at Normal Idle	200A
Maximum Rating	270A
Starter Type (Electrical/Air)?	Electrical
Manufacturer	Nippondenso
Model	42800-070
Hydraulic Pump	
Manufacturer	Saugr Sundstrand
Model	
Output (gpm @ psi)	
Heating	
Heating System Type	Forced Air
Capacity, BTU/hr	120,000 BTU
Air Conditioning	
Manufacturer	Carrier
Model	68RM35-604-48
Capacity, BTU/hr	108,000 BTU
Air Compressor	
Manufacturer	WABCO
Model Number	
Capacity, Cubic Ft./Min.	

Drivetrain	
Transmission/Gearbox	
Manufacturer	Voith
Model Number	D.864.3
Model Year	2002
Manual or Automatic?	Automatic
Number of forward speeds	4
Gear Ratios	
Torque conversion ratio	
Additional features	
Retarder	
Manufacturer	Voith
Model Number	
Drive Axle	
Manufacturer	Rockwell Meritor
Model Number	61153-WX
Axle ratio(s)	4.1
Tires	
Manufacturer	Goodyear
Model Number	Metro Miler
Size	
Torque converter	
Manufacturer	
Model Number	
Type (hydraulic, other)	

Fuel Storage System	
Number of Tanks	1
Maximum Working Pressure (Gaseous Fuels Only)	NA
Total Useful Amount of Fuel	125 gallon
Tank Manufacturer	Mancor Canada
Tank Model(s)	
Total Empty Weight of Tank(s)	
Safety Equipment	
Fire Detection (Y/N)?	Yes
Manufacturer	
Model Number	
Year of Manufacture	
Sensor Type	
Number of Sensors	
Fire Suppression (Y/N)?	No
Manufacturer	
Model Number	
Year of Manufacture	
Amount of Agent	
Type of Agent	
Number of Discharge Points	
Vapor Detection (Y/N)?	NA
Manufacturer	NA
Model Number	NA
Year of Manufacture	NA
Sensor Type	NA
Number of Sensors	NA
Alarm Threshold (% LEL)	NA

Other Attributes or Features (Wheelchair lifts, wheelchair position, bicycle racks, any items that make this bus different from the other test or control buses)	No differences

Emission Control	
Catalytic Converter (Y/N)?	No
Manufacturer	
Model Number	
Type	
Length of pipe from engine to catalyst	
Diesel Particulate Control Device (Y/N)?	No
Manufacturer	
Model Number	
Type	
Special Requirements (Low sulfur diesel, specific regeneration temperatures, etc.)	
Power Plant Emissions Certification Data	

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14. ABSTRACT *(Maximum 200 Words)*
The St. Louis Metro Biodiesel Transit Bus Evaluation project is being conducted under a Cooperative Research and Development Agreement between NREL and the National Biodiesel Board to evaluate the extended in-use performance of buses operating on B20 fuel. The objective of this research project is to compare B20 and ultra-low sulfur diesel buses in terms of fuel economy, vehicles maintenance, engine performance, component wear, and lube oil performance.

15. SUBJECT TERMS
transit bus; St. Louis Metro; CRADA; B20; biodiesel; diesel particulate filter; ultra-low sulfur diesel; ULSD

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