

100,000-Mile Evaluation of Transit Buses Operated on Biodiesel Blends (B20)

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ABSTRACT

Nine identical 40-ft. transit buses were operated on B20 and diesel for a period of two years – five of the buses operated exclusively on B20 (20% biodiesel blend) and the other four on petroleum diesel. The buses were model year 2000 Orion V equipped with Cummins ISM engines, and all operated on the same bus route. Each bus accumulated about 100,000 miles over the course of the study. B20 buses were compared to the petroleum diesel buses in terms of fuel economy, vehicle maintenance cost, road calls, and emissions. There was no difference between the on-road average fuel economy of the two groups (4.41 mpg) based on the in-use data, however laboratory testing revealed a nearly 2% reduction in fuel economy for the B20 vehicles. Engine and fuel system related maintenance costs were nearly identical for the two groups until the final month of the study. Component replacements near the end of the study on one B20 bus caused average maintenance costs to be higher for the B20 group (\$0.07 vs. \$0.05 per mile). However, engine and fuel system maintenance costs varied widely from bus-to-bus so the \$0.02 per mile average difference between the two groups is not statistically significant. There was no significant difference in miles between road calls. Analysis of B20 samples during the study period revealed early problems with fuel blending. There also were occasional fuel filter plugging events for the B20-fueled buses that were likely caused by out of specification biodiesel, however the exact cause could not be conclusively determined. Oil analysis results indicate no additional wear metals from the use of B20, with similar rates of TBN and ZDDP decay. Soot levels in the lubricant were significantly lower for the B20 vehicles. Laboratory chassis emissions tests comparing the in-use B20 and petroleum diesel on the CSHVC cycle showed reductions in all measured pollutants, including a reduction in nitrogen oxides.

INTRODUCTION

Biodiesel is a diesel fuel blending component made from vegetable oil, waste cooking oil, or animal fat by reaction with methanol to form methyl esters. Biodiesel blends are used to reduce petroleum consumption as well as greenhouse gas and pollutant emissions, and to comply with mandates for the use of alternative fuels. Reductions of particulate matter (PM), carbon monoxide (CO), and total hydrocarbon emissions (THC) can be achieved with biodiesel use [1]. Based on life-cycle analysis, the use of biodiesel produces real reductions in petroleum consumption and carbon dioxide (CO₂) emissions [2]. Energy content per gallon is slightly lower resulting in minor reductions in peak torque and fuel economy, but thermal efficiency is unchanged [3].

There are few quantitative studies of in-use operational performance. Bickel and Strebig [4] report a two-year field trial of B20 use in road maintenance vehicles in Minnesota. Nearly 25,000 gallons of B20 were consumed over roughly 135,000 miles of operation. The B20 vehicles exhibited the same average fuel economy (in miles per gallon) as the diesel control vehicles. Oil analysis conducted at 5,000-mile intervals indicated no unusual engine wear or fuel dilution.

Chase et al. [5] described operation of a heavy-duty, line-haul truck on a blend of 50% biodiesel and 50% No. 2 diesel (B50) for more than 200,000 miles. No operational problems were reported, inspection of the engine at the conclusion of the study showed no excessive wear, and tests indicated no injector degradation.

The BIOBUS project was conducted in Montreal from March 2002 to March 2003 [6]. Biodiesel from vegetable oil, animal fat, and waste cooking oil was tested as B5 and B20 in over 150 buses. Engines included primarily mechanically governed 2-stroke and 4-stroke engines

manufactured by Detroit Diesel Corporation and Cummins, Inc., respectively. The study found no impact of biodiesel on fuel economy or on the cost to maintain fuel pumps and fuel injectors. Problems with low temperature fuel filter plugging were noted for a few specific vehicles. Pollutant emission measurements revealed reductions in THC, CO, and PM with no effect or a small increase for NO_x.

Fraer et al. [7] compared operation of cargo vans and truck tractors on B20 and petroleum diesel and performed teardown and analysis of engines and components. After four years of operation and 600,000 miles accumulated on B20, no differences in wear were noted. In comparing maintenance costs between the two groups, only minor differences could be attributed to B20 use.

In this study, nine identical 40-ft. transit buses were operated on B20 and diesel for a period of two years – five of the buses operated exclusively on B20 and the other four on petroleum diesel. The buses operated in the Regional Transportation District (RTD) fleet in Boulder, Colorado. A quantitative comparison of mileage accumulation, fuel use, road calls, maintenance costs and events, fuel analysis, oil analysis, and pollutant emissions is reported.

OBJECTIVE

The objective of this study is to compare vehicles operating on B20 and conventional diesel in terms of engine performance, fuel economy, vehicle maintenance, and emissions. The results will help RTD—and other potential biodiesel users—understand the costs and benefits of B20 use, and any changes to maintenance and operating procedures that might be required. The results also will help engine manufacturers in exploring the effects of B20 on engine durability.

Additionally, RTD has specific objectives for its participation in the project. Located at a mile above sea level, RTD operates and maintains a fleet of over 1000 heavy-duty transit buses serving the transportation needs of over 2.5 million people in the Denver Metropolitan area. The high altitude plus the high desert climate—very low humidity, hot in the summer, and cold and snowy in the winter—create unique challenges for RTD bus propulsion systems. Some of the common problems experienced at this area are low vehicle power, incomplete combustion due to lack of oxygen, and engine overheating due to reduced airflow through the radiators.

RTD is working to reduce exhaust emissions from its buses. In evaluating biodiesel, RTD expects to obtain information on the operation of biodiesel to help its planning of a strategy for improving RTD fleet operating conditions and public image through vehicle emissions reduction, use of renewable fuel, and fleet reliability. This information includes:

- Verification of the emissions benefits of biodiesel
- Performance changes in buses operating on biodiesel
- Fuel consumption changes with biodiesel
- Effects of biodiesel on bus mechanical reliability and service availability
- High altitude and cold weather performance and stability of biodiesel
- Drivers and passengers acceptance of biodiesel.

B20 has typically cost more than No. 2 diesel, and at the time of the evaluation, averaged \$0.17 higher in the Denver, Colorado, area. As of August 24, 2006, B20 averaged \$2.62 in the United States compared to \$2.44 for No. 2 diesel (taxes not included) [8]. RTD must weigh this additional cost against potential benefits.

APPROACH

VEHICLE SELECTION

The vehicles chosen for this study are 40-ft Orion V transit buses and seat 43 passengers. These buses were selected in part because they operate on a dedicated route. They operate in Boulder, Colorado, on RTD's "Skip" route, a 16.1-mile roundtrip route that provides high-frequency bus service along a heavily traveled corridor. The Skip route is served by the nine buses, which have special exterior graphics showing they are dedicated for the route (Figure 1). Table 1 provides a summary description of the Skip buses.



Figure 1. RTD Skip Bus in Service

VEHICLE FUELING

During this study, five of the nine buses operated on B20, and four operated on standard petroleum diesel as a control group. All buses were fueled daily at which time the hubodometer reading, fuel amount, and amounts of any other fluids added were logged. Diesel buses were fueled at an indoor fueling island, whereas the B20 buses were fueled at a temporary fueling facility located just outside the bus garage (Figure 2). The B20 fueling station contained a 6,000-gallon, above ground storage tank and a pedestal-mounted dispenser.

Table 1. RTD B20 Evaluation Transit Bus Description Summary

Vehicle Information	Evaluation Buses (B20 and Diesel)
Number of Buses	5 B20, 4 Diesel
Chassis Manufacturer/Model	Orion V
Chassis Model Year	2000
Engine Manufacturer/Model	Cummins ISM
Engine Model Year	2000
Engine Ratings Max. Horsepower Max. Torque	280hp @ 2,100 rpm 900 lb-ft @ 1,200 rpm
Diesel Fuel System Capacity	125 gal
Transmission Manufacturer/Model	ZF Ecomat 5HP592
Curb Weight	28,800 lb
Gross Vehicle Weight Rating (GVWR)	40,600 lb

quality and compare oil degradation. On-road fuel economy, maintenance, and road call calculations were based upon records provided by RTD and were reviewed for accuracy by the National Renewable Energy Laboratory (NREL). Each individual event was examined for missing or incomplete information. For example, each fuel record was first checked for data entered in all fields, then for an accurate hubodometer reading (in sequence for a given date), and finally for fuel economy (further examination if grossly out of range). Records that were recorded or entered incorrectly, thereby casting doubt upon their accuracy, were removed from the calculations, thus improving the level of confidence in the on-road data. Results are typically reported as a running or cumulative average, that is, the average results from the beginning of the study to any given point in the study.

CHASSIS DYNAMOMETER EMISSIONS TESTING

Chassis dynamometer testing allows emissions to be accurately measured in g/mile while the vehicle is driven over a reproducible duty cycle in the laboratory. The dynamometer system simulates the vehicle payload as well as aerodynamic drag and rolling resistance. Driving cycles consist of a speed versus time schedule that is followed by the vehicle driver. This study employed a chassis dynamometer consisting of twin 40" rolls connected via gears to a 380 hp DC dynamometer and to 47" diameter flywheels. The base inertia of the dynamometer system as configured for this testing was approximately 32,000 lbs. Additional vehicle inertia, drag, and rolling resistance were simulated using load applied electrically by the dynamometer.

The emissions measurement system employs full scale dilution with constant volume sampling for mass flow measurement. Gaseous emissions—including CO₂, nitrogen oxide (NO_x), THC, and CO—are measured continuously. PM emissions are measured gravimetrically for samples collected onto 47 mm Teflon filters and weighed on a microbalance in a clean room environment. The emission measurement system meets the requirements of the current code of federal regulations for heavy-duty engine emissions certification (40 CFR, part 86). In addition, direct mass flow fuel consumption is measured in line with a high accuracy (+/-0.5% of reading) fuel metering system, which comprises a volume flow meter and in-line density meter to measure fuel mass flow.

The Skip buses have a rated gross vehicle weight of 40,600 lb. For chassis dynamometer testing, a vehicle inertia of 35,000 lb was employed with estimated rolling resistance and drag coefficients set at C_{RR}=0.01 and C_D=0.5. The test driving cycle selected was the City-Suburban Heavy-Vehicle Cycle (CSHVC). This cycle was chosen because certain parameters of the cycle are a close match with the typical Skip bus route, as shown in Table 2. The CSHVC speed-time trace is shown in Figure 3.



Figure 2. B20 Fueling Station

The buses were fueled using a dry-lock nozzle manufactured by Emco-Wheaton, but to separate fuel types, the B20 buses used a nonstandard connector. The fueling nozzle at the B20 station was identical in appearance and operation to the standard diesel fuel nozzle, but it used a four-pin instead of the standard three-pin connector. This different pin configuration ensured that the test buses were only fueled with B20, and B20 was dispensed only into these buses.

PERIOD OF OPERATION

RTD has 303 Orion buses in its fleet that entered service beginning in late 2000. In the summer of 2001, nine of the buses were dedicated to the Skip route, and B20 fueling began in July 2004 with each of the buses at about 160,000 miles. By late July 2004, controlled fueling of the five B20 buses and continuous data collection were in place. The data collection period reported is from August 1, 2004 through July 31, 2006.

DATA COLLECTION AND ANALYSIS

Operation and maintenance data were collected for 24 months during normal operation and analyzed to evaluate performance. Periodic fuel and used oil samples were collected and analyzed to verify fuel

Table 2. Comparison of Parameters for CSHVC and Skip Bus Route

	CSHVC	Skip Route
Average Speed, mph	14.2	15.6
Maximum Speed, mph	44	40
Stops per Mile	0.75	0.78

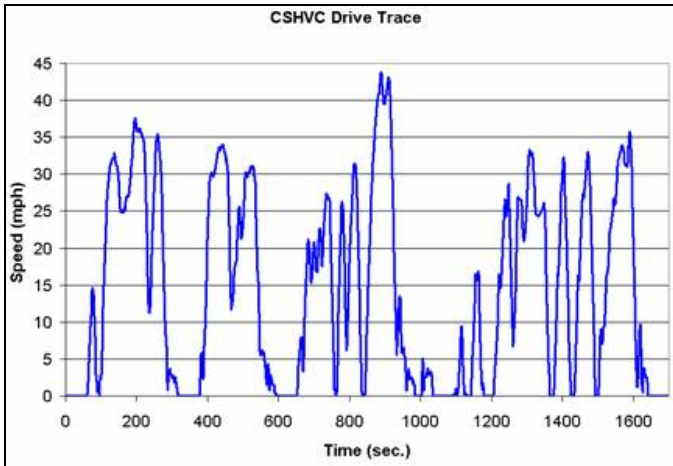


Figure 3. Speed-Time Trace for the CSHVC.

RESULTS

MILEAGE ACCUMULATION AND FUEL USE

In the 24 months of data collection, about 100,000 miles were driven by each of the study vehicles. For the B20 buses, more than 100,000 gallons were consumed in total during the study. Table 3 provides mileage accumulation details. The B20 buses had about the same use as the diesel comparison buses. Accumulated mileage numbers are very similar, and both groups averaged over 4,000 miles per bus per month (Figure 4).

Table 3. Accumulated Mileage Details

Bus Number	VIN	Total Data Period Mileage
Diesel Group		
2203	1VH5H3H2XY6501249	105,499
2204	1VH5H3H2XY6501250	106,788
2205	1VH5H3H2XY6501251	110,133
2206	1VH5H3H2XY6501252	105,981
B20 Group		
2207	1VH5H3H2XY6501256	102,614
2208	1VH5H3H2XY6501258	100,484
2209	1VH5H3H2XY6501259	95,358
2210	1VH5H3H2XY6501260	101,815
2211	1VH5H3H2XY6501261	100,962

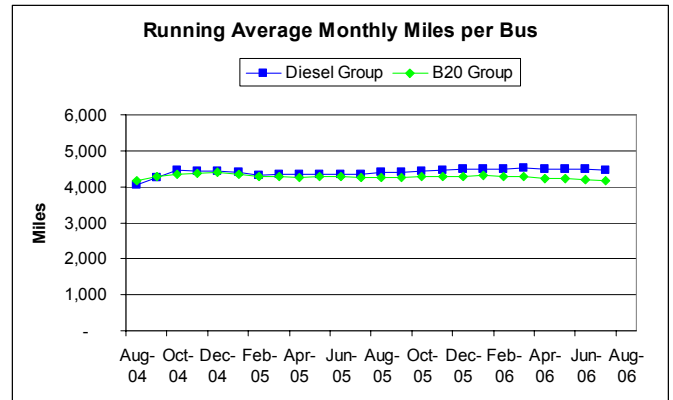


Figure 4. Running Average Monthly Miles

FUEL ECONOMY

Individual bus fuel economy over 24 months is shown in Table 4. Fuel economy values are calculated by dividing total miles driven by total gallons of fuel used. Buses are grouped by fuel type (B20 or diesel), and fuel economy results presented in Figure 5.

Although diesel bus 2205 exhibited a fuel economy consistently about 5% lower than the rest of the diesel baseline group, there is no apparent basis for removing it from this dataset as an outlier. As a result, there is no difference (4.41 mpg diesel vs. 4.41 mpg B20) between the diesel and B20 study group fuel economies.

If diesel bus 2205 were removed as an outlier, the 24-month average fuel economy for the diesel group becomes 4.46 mpg. In this case, the fuel economy for the B20 buses is 1.2% lower than that of the diesel buses (p-value = 0.02). A small fuel economy reduction is expected due to the lower energy content of B20 as compared to diesel fuel.

Table 4. Individual Bus Fuel Economy

Bus Number	Fuel Economy (mpg)
Diesel Group	
2203	4.46
2204	4.46
2205	4.25
2206	4.46
Average	4.41
B20 Group	
2207	4.37
2208	4.40
2209	4.41
2210	4.45
2211	4.41
Average	4.41

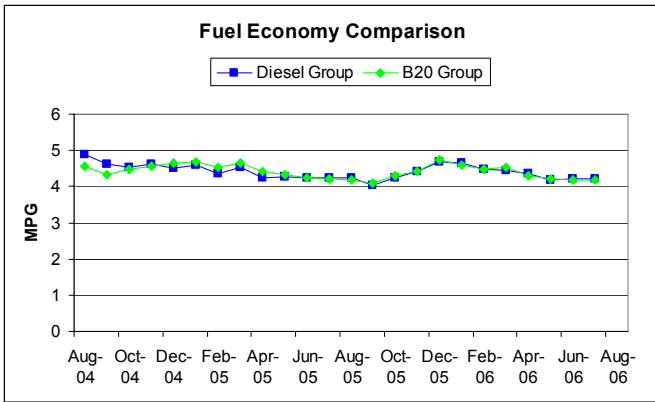


Figure 5. Fuel Economy Comparison by Fuel Group

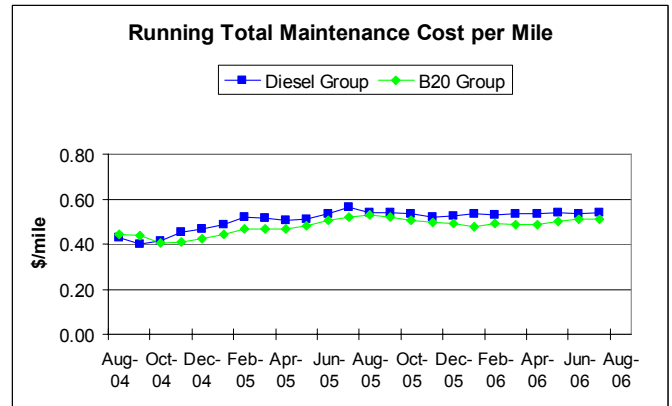


Figure 6. Running Total Maintenance Cost Comparison by Fuel Group

MAINTENANCE

This analysis examines both total maintenance costs, as well as maintenance costs related to the engine and fuel system. Total maintenance costs include the costs of parts and labor, but do not include warranty costs (the five-year extended warranty expired in 2005). The labor rate for maintenance has been arbitrarily set at \$50 per hour and is not intended to reflect RTD's current labor mechanic rate. Cost per mile is calculated as follows:

$$\text{Cost per mile} = ((\text{labor hours} * \$50) + \text{parts cost}) / \text{mileage}$$

Bus maintenance costs over 24 months are presented in Table 5. The running average of maintenance costs for the diesel and B20 groups are compared in Figure 6. This running average or cumulative presentation of maintenance costs shows the average of the costs up to a given month and smooths occasional monthly spikes in maintenance. The total maintenance cost per mile for the B20 group was 5.2% lower than for the diesel group (p-value = 0.27). This difference will be explored in further discussion regarding maintenance cost breakdown by vehicle system.

Table 5. Bus Maintenance Costs

Bus Number	Miles Driven	Labor Hours	Parts Cost	Total Cost (\$/mile)
Diesel Group				
2203	105,499	892	\$11,965	\$0.54
2204	106,788	835	\$14,254	\$0.52
2205	110,133	965	\$14,178	\$0.57
2206	105,981	852	\$13,555	\$0.53
Totals	428,401	3,544	\$53,951	\$0.54
B20 Group				
2207	102,614	770	\$7,366	\$0.45
2208	100,484	888	\$11,507	\$0.56
2209	95,358	844	\$8,647	\$0.53
2210	101,815	757	\$11,957	\$0.49
2211	100,962	800	\$13,145	\$0.53
Totals	501,233	4,059	\$52,622	\$0.51

RTD 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 over 24 months related to the engine and fuel system are presented in Table 6. The running average maintenance costs for the diesel and B20 groups are compared in Figure 7. The engine and fuel system maintenance cost per mile for the B20 group is 39% higher than for the diesel group (p-value = 0.16). Engine and fuel system maintenance costs are very similar for most of the test period. However, during the last 3 months of the study, average B20 maintenance costs increased due to component replacements on Bus 2211 in May and June of 2006 (details to follow). The 5.2% lower total maintenance cost per mile exhibited by the B20 group is not attributable to fewer engine and fuel system repairs. In calculation of the total maintenance costs, the higher engine and fuel system repair costs for the B20 group were offset by higher maintenance costs for transmission repairs in the diesel group (unrelated to fuel use).

Table 6. Bus Engine and Fuel System Maintenance Costs

Bus Number	Miles Driven	Labor Hours	Parts Cost	Total Cost (\$/mile)
Diesel Group				
2203	105,499	48	\$3,427	\$0.06
2204	106,788	38	\$3,227	\$0.05
2205	110,133	57	\$3,205	\$0.05
2206	105,981	29	\$3,234	\$0.04
Totals	428,401	171	\$13,093	\$0.05
B20 Group				
2207	102,614	25	\$2,910	\$0.04
2208	100,484	81	\$3,402	\$0.07
2209	95,358	80	\$3,474	\$0.08
2210	101,815	27	\$4,104	\$0.05
2211	100,962	70	\$7,118	\$0.11
Totals	501,233	284	\$21,008	\$0.07

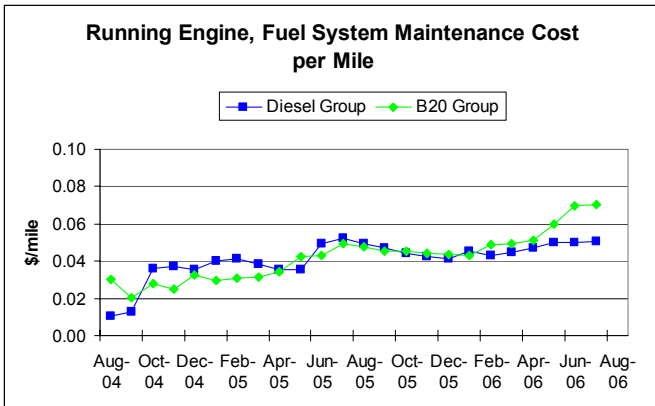


Figure 7. Running Engine and Fuel System Maintenance Cost Comparison by Fuel Group

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

- Fuel pump
- Fuel pump gasket
- Fuel injector
- Fuel injector O-ring
- Fuel lines
- Fuel filter.

These parts are all categorized as fuel system parts, with the exception of the fuel filter. The fuel filter is grouped with a suite of preventative maintenance repair checks and part replacements. Preventative maintenance events are scheduled by RTD to occur every 6,000 miles of use.

The fuel system replacement parts installed during the study are shown in Table 7 for both diesel and B20 buses. During the evaluation period, fuel pumps were replaced for two diesel buses (2203 and 2206), and a fuel pump was replaced for a B20 bus (2209). A single fuel injector was replaced for one diesel bus (2205) and one B20 bus (2208). However, B20 Bus 2211 had all six injectors replaced due to a “no-start” condition in May 2006. In June 2006, Bus 2211 had a cylinder head replacement due to a “burnt valve” and all six injectors were again replaced as part of the rebuilt cylinder head replacement, although it does not appear that this second replacement of 6 valves was actually necessary. The labor and parts costs associated with the May – June 2006 fuel injector and cylinder head replacements of Bus 2211 make up the difference in engine and fuel maintenance costs between the B20 and diesel groups in this study. Further analysis of the replaced parts is ongoing to determine if B20 use is related to their failure.

These results highlight certain challenges inherent in controlled fleet evaluations, and in particular the high variability in maintenance costs from vehicle to vehicle, independent of the fuel used. For this group of vehicles transmission repairs that were unrelated to fuel use caused the total maintenance costs for the diesel group to be higher. At the same time, a single maintenance

event for Bus 2211 caused the running average engine and fuel system maintenance costs for the B20 group to spike during the last few months of the study. To mitigate the impact of the high variability in maintenance costs between vehicles, future studies will need to assess a larger fleet or a similar sized fleet for a significantly longer period of time.

Table 7. Replacement Fuel System Parts

Bus Number	Part Description	Date Replaced	Quantity	Total Cost
Diesel Group				
2203	Gasket Fuel Pump	07/13/05	1	\$4.81
2203	Gasket Fuel Pump	07/14/05	1	\$4.91
2203	Fuel Pump	07/14/05	1	\$622.67
2203	Tube Fuel Supply	01/24/05	1	\$15.31
2204	Gasket Fuel Pump	07/15/05	1	\$4.91
2205	Fuel Injector	01/27/06	1	\$548.49
2206	Gasket Fuel Pump	10/21/04	1	\$1.76
2206	Fuel Pump	10/21/04	1	\$555.37
2206	Gasket Fuel Pump	02/20/06	1	\$4.94
			Total	\$1,763
B20 Group				
2208	Fuel Injector	07/08/05	1	\$709.2
2208	Fuel Solenoid S/Off	07/08/05	1	\$36.47
2208	Oring Injector	07/11/05	1	\$1.59
2208	Oring Injector	07/11/05	1	\$1.61
2208	Oring Injector	07/11/05	1	\$1.78
2209	Gasket Fuel Pump	10/26/04	1	\$1.76
2209	Fuel Pump	10/26/04	1	\$555.37
2209	Tube Fuel Supply	10/13/05	1	\$15.82
2211	Oring Injector	05/24/06	6	\$10.32
2211	Fuel Injector	05/24/06	6	\$2,479.14
2211	Fuel Injector	06/14/06	6	\$2,479.14
			Total	\$6,293

ROAD CALLS

A road call 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, a road call may stem from an issue that requires the bus to stop driving, allowing for roadside mechanical repair or towing back to the maintenance facility. Road calls and average miles (driven) between road calls (MBRC) are an important reliability indicator for the transit industry. For the purposes of this analysis, data received from RTD indicating the occurrence of a road call was recorded as such, regardless of its relative severity.

Figure 8 shows the cumulative MBRC for all road calls for the B20 and diesel baseline groups. Average MBRC values over 24 months are 3,197 and 3,632 for diesel and B20 groups, respectively. The B20 buses are apparently 14% higher, but the difference is not significant (p -value = 0.59) and there is no evidence in the data to suggest this improvement is attributable to fuel use. Differences during the first months of the study are related to the variability of MBRC month-to-month, with a few months required for the running average of each group to settle. After 24 months of evaluation, there is no negative impact on MBRC from the use of B20.

However, in April 2005 two buses reported road calls for engine misfiring and stalling caused by plugged fuel filters. The first incident happened with Bus 2210 on April 8, 2005. The plugged fuel filter was removed from the vehicle and cut open for examination. A brown “grease-like” material was found in the filter pleats and was the suspected cause of the filter plugging (Figure 9).

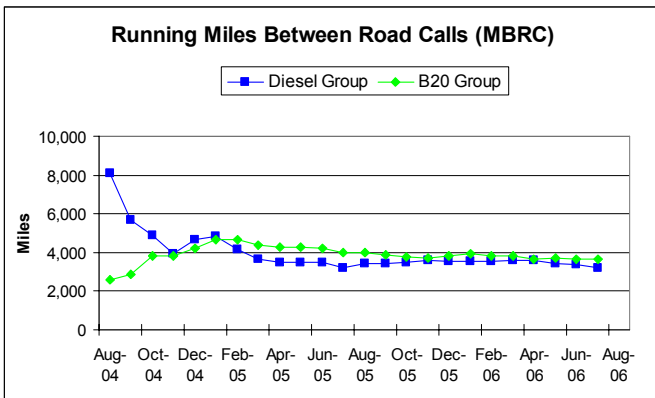


Figure 8. Running Average MBRC Comparison by Fuel Group



Figure 9. Bus 2210 Plugged Filter Examination

The second incident with Bus 2208 occurred three days later on April 11, 2005. The plugged filter from this bus also contained the brown material. The filters on the other three B20 buses were changed as a precautionary measure, and inspection of these used filters also revealed signs of the brown material, but not of the quantity and consistency of the plugged filters.

Fuel was removed from the vehicle fuel tanks and tested for several properties as shown in Table 8. None of the fuel samples exhibited excessively high levels of biodiesel or cold filter plugging point (CFPP, determined by ASTM D6371). Water determined by Karl Fischer method (ASTM D6304) indicated higher levels than typical of a No. 2 diesel fuel but not excessively high. The Bug Alert™ ATP test for microbial growth does not indicate that microbial contamination is an issue.

Table 8. Vehicle Fuel Testing Results (April 2005)

Sample	Percent Biodiesel	CFPP °C	Water, ppm	Bug Alert™ ATP
2207	18.4	-24	72	139 (med)
2208	16.9	-25	77	27 (low)
2209	19.2	-25	88	57 (low)
2210	20.3	-25	97	1 (very low)
2211	15.0	-30	78	93 (low-med)

The dark brown gelatinous residue coating RTD fuel filter No. 2210 was analyzed by gas chromatography mass spectrometry (GC-MS) (Agilent 6890 GC equipped with a 5890 MSD mass selective detector). The sample was prepared by scraping 23 mg of residue from a filter pleat and dissolving this in 1.0 mL of toluene. 1.0 μ L of the solution was injected into the GC-MS using a split injection (100:1) onto a 30m x 0.25mm column, (0.50 μ m DB-5 film).

The resulting chromatographic data are shown as the total ion current (TIC) signal from the MSD, as a function of component elution time in Figure 10. The multiple peaks in the 8-17 minute region are identified as diesel hydrocarbons. The larger peaks in the 18-23 minute region are fatty acid methyl esters (FAME) from the soybean derived biodiesel. The presence of these components is due to the fact that no attempt was made to extract them from the sampled filter residue.

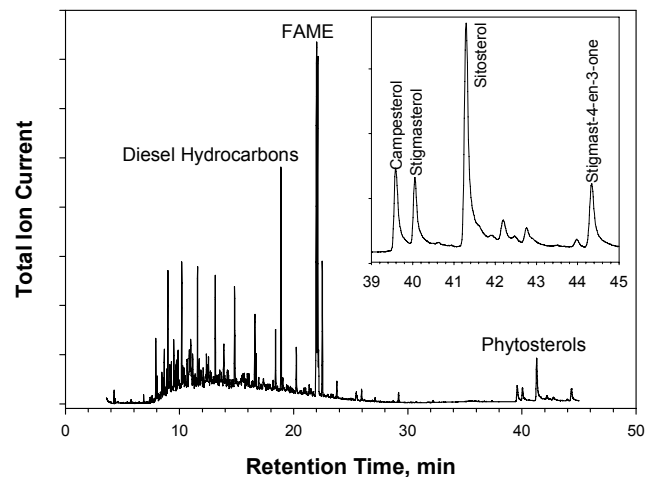


Figure 10. GC-MS results for brown material found on plugged fuel filter from Bus 2210

Plant (or phyto) sterols were detected in the 39-45 minute region. The compounds were identified by matching mass spectra of the peaks with library spectra.

Campesterol, stigmasterol, sitosterol and stigmast-4-en-3-one were the major species identified at retention times 39.59, 40.06, 41.30 and 44.34 minutes, respectively. The relative amounts are in rough agreement with those reported in soybean oil [10]. While this analysis is semi-quantitative, the total level of sterols is significantly higher than expected for B20. Thus, this analysis suggests that high levels of plant sterols might be responsible for the filter plugging. These sterols are much higher molecular weight (≥ 400 amu) and would have a higher freezing point than typical of FAME or diesel fuel components. However, based on this analysis alone we cannot rule out other potential causes.

Two other filter plugging events occurred during the remaining study period. One happened about two months later on June 14, 2005. Bus 2209 filled from the B20 dispenser with a report of slow fueling by the dispenser operator. The fuel filter on Bus 2209 plugged shortly thereafter. It was later discovered that the B20 tank was nearly empty. Bus 2209 required several fuel filter changes and vehicle tank drainage to correct the plugging problem. The remaining B20 was also drained from the storage tank, the tank cleaned, and then refilled for continued B20 service.

A final plugging event happened during the last month of the study period. Two buses, 2207 and 2211, were road called for plugged fuel filters on July 7, 2006. The fuel storage tank was again near empty in anticipation of completion of the study and removal of the tank. Because the tank is drawn from the bottom, this implies that a material less dense than biodiesel was floating on top and was pumped into the vehicles as the tank became nearly empty. One well known quality issue with biodiesel is the presence of soap, which in large enough concentration will float on top of a fuel tank.

As mentioned previously, fuel filters are not included in the analysis of engine and fuel system labor and parts costs because they are considered preventative maintenance. Due to fuel filter plugging events fuel filters were replaced on the B20 buses in excess of their preventative maintenance schedule. Table 9 lists the number of extra fuel filters replaced, and indicates the associated labor and parts cost. In addition, labor for diagnosis and related work (draining and refilling fuel tanks) amounted to \$712.50 for a total cost of \$1,054.81. These additional fuel filter replacements were not significant additions to the maintenance analysis, adding an additional maintenance cost per mile to the B20 group of only \$0.002. However, disruptions in transit service and related costs (bus substitution, affected ridership) are not captured in the maintenance costs, and were considered significant to RTD.

Table 9. Extra Fuel Filter Maintenance Costs

Bus Number	Extra Fuel Filters	Labor Hours	Parts Cost	Total Cost
B20 Group				
2207	3	1	\$19.45	\$69.45
2208	3	0.8	\$18.84	\$58.84
2209	4	1	\$25.12	\$75.12
2210	2	0.5	\$12.56	\$37.56
2211	4	1.5	\$26.34	\$101.34
Totals	16	4.8	\$102.31	\$342.31

FUEL TESTING

Fuel delivery load samples were collected for analysis of biodiesel blend content. Fuel was delivered about twice a month with samples starting in September 2004. Biodiesel content was determined by infrared spectroscopy (FTIR). The fuel blender employed splash blending to mix biodiesel with petroleum diesel to make the required B20 blend. Biodiesel from a heated storage tank was loaded into the delivery truck and then driven to the fuel terminal where No. 2 diesel fuel (or both No. 2 and No. 1 diesel in the winter months) was typically bottom loaded to make the blend. From the terminal, the delivery truck would drive to the RTD Boulder facility and offload all of the B20 into the outdoor storage tank (typically 2,500 gallons per delivery). Load samples were taken from the top of the delivery truck tank at the terminal, prior to delivery.

In examining the delivery load samples for biodiesel content, blend levels were found to range from less than 1% to over 80% (Figure 11). After the discovery of erratic blend levels from the first group of samples tested in May 2005, the blender reported changing its blending procedure to include recirculation of fuel within the delivery truck tank prior to delivery. Later samples seemed consistently B20 for a short period then again became erratic.

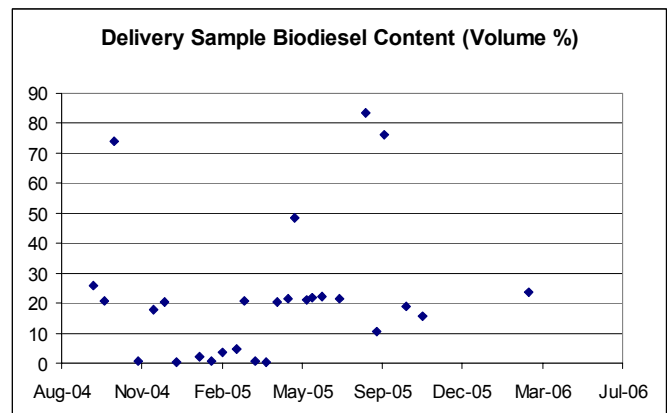


Figure 11. B100 Content of Delivery Load Samples

Inconsistent blend levels for B20 fuel are not uncommon. A survey of 50 B20 samples taken across the United States indicated varying blend levels and noted problems with splash blending [9]. In the RTD study however, all

the fuel from each delivery truck was offloaded into the storage tank, and it appeared to have been completely blended in this process as evidenced by vehicle tank samples taken in April 2005 (Table 8) and March 2006 at or near B20 (Table 10).

In addition to blend level, several other properties were tested to examine fuel quality in March 2006. Acid value, peroxides, and aldehydes (or alkanals) were determined using the Saftest™ method. Acid and peroxides are consistently low in comparison to levels observed in the B20 quality survey [9]. Alkanals indicate some oxidative degradation of the biodiesel but are not high.

Table 10. B20 Vehicle Sample Testing March 2006

Vehicle Number	B100 Content Volume %	Acid Value mgKOH/g	Peroxide Saftest™ ppm	Aldehyde Saftest™ nmol/mL
2207	20.3	<0.1	--	58.212
2208	18.4	<0.1	13.22	57.902
2209	17.4	<0.1	11.59	55.696
2210	18.7	<0.1	16.75	73.35
2211	19.7	<0.1	11.42	61.546

Samples collected in March 2006 from both the diesel and biodiesel vehicle fuel tanks were combined to produce composite diesel and B20 samples. These were subjected to more detailed analysis as shown in Table 11. These results show the reduction of fuel sulfur content caused by blending in of biodiesel as well as the 2.4% reduction in energy content. The B20 blends exhibit significantly higher cetane number.

Table 11. Results of Testing of B20 and Diesel Composite samples Obtained from Vehicles March 2006

		B20 Composite	Diesel Composite
Water & Sediment vol %	D2709	0.01	0.01
Cloud Point °C	D2500	-13	-14
Sulfur ppm	D5453		324.1
Sulfur ppm	D2622	272	
Aromatics vol %	D1319		25.6
Olefins vol %			1.3
Saturates vol %			73.1
C mass%	D5291	84.71	86.6
H mass%		12.88	13.21
Derived Cetane Number	D6890	51.0	47.9
LHV BTU/lb	D240	17859.7	18306.6

OIL TESTING

Oil was sampled from several of the test vehicles during oil drain intervals in March through June of 2006 and at the mileage indicated in Table 12. These data provide a snapshot of oil performance for the two fuels in terms of ZDDP (zinc dialkyldithiophosphate) decay, TBN (total

base number) decay, oxidation, fuel dilution, viscosity, soot loading, and wear metals).

ZDDP decay and lubricant oxidation were assessed using FTIR. For ZDDP the strengths of the C-O-P stretching band at 957 cm⁻¹ and of the P=S stretching band at 670 cm⁻¹ were measured. The decay of these bands with mileage for all samples listed in Table 12 is shown in Figure 12. This indicates exponential decay with mileage:

$$C = C_0 \exp(-\alpha m) \quad (1)$$

$$\ln(1 + (C - C_0)/C_0) = -\alpha m \quad (2)$$

Where m = mileage

C_0 = initial intensity

C = intensity at mileage m

α = exponential decay constant

Table 12. Oil Samples Taken for Analysis, Miles Indicate Mileage Since Last Oil Change

Vehicle No.	Sample Date	Miles
Diesel Group		
2203	3/14/06	1295
2203	4/26/06	7770
2203	6/8/06	5375
2204	3/14/06	1392
2204	4/22/06	6850
2204	6/6/06	6035
2205	5/17/06	7463
2206	6/1/06	5840
B20 Group		
2207	3/14/06	2900
2207	6/6/06	7256
2208	3/14/06	1834
2208	4/25/06	7314
2209	4/25/06	802
2210	4/29/06	3634
2211	5/24/06	8800

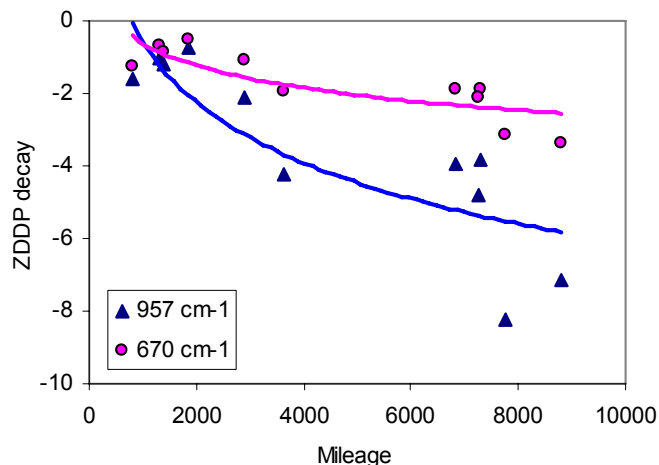


Figure 12. ZDDP Decay in Lubricants from All Vehicles. C-O-P Monitored at 957 cm⁻¹ and P=S Monitored at 670 cm⁻¹

Fitting of the data to equation 2 (Figure 13) yields exponential decay constants of 0.00007/mile for the C-O-P stretch and 0.0001/mile for the P=S stretch, which are consistent with previous testing at Cummins and with expectations for oil decay for this engine. Differences between the fuels for ZDDP decay were small and probably not significant. The buildup of oxidation products was monitored via the acid carbonyl IR band at 1700 cm^{-1} . Oxidation products grow exponentially with mileage as shown in Figure 14. Lubricants contain over-based detergent, which neutralize acids by formation of carboxylate. The formation of carboxylate was also monitored via the IR band at 1640 cm^{-1} which also shows exponential growth. As seen in Figure 14, both acid and carboxylate growth has essentially the same slope or exponential growth constant. This indicates that the acids being formed are being adequately neutralized by the detergent. No difference was observed between diesel and B20.

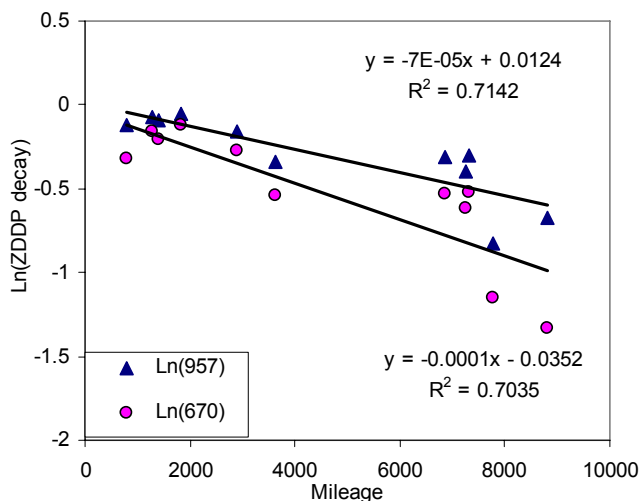


Figure 13. Results of Fitting ZDDP Decay Data to Linearized Exponential Law, Equation 2

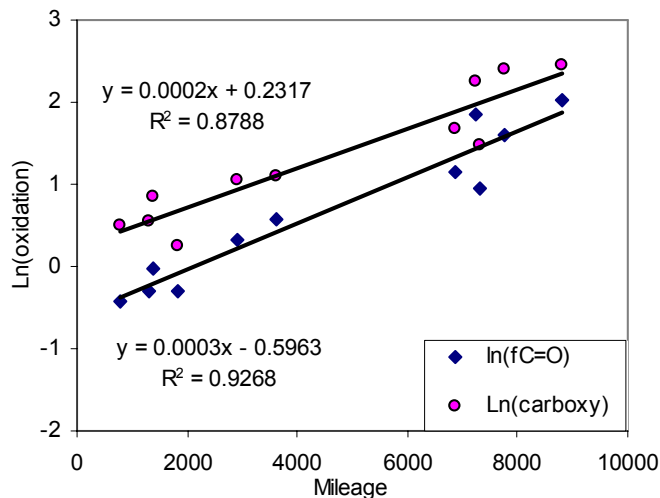


Figure 14. Results of Fitting Acid Carbonyl and Carboxylate Growth Data to Linearized Exponential Law, Equation 2

TBN also decays exponentially with mileage, as shown in Figure 15. The decay constant is consistent with Cummins experience for conventional diesel fuel. TBN is a sensitive function of fuel sulfur content. As noted, biodiesel dilutes the sulfur content of the diesel fuel. Table 13 lists TBN values and other oil properties as a function of mileage. Examination of these values suggests that TBN decay is occurring more slowly for the B20 blends; however, this cannot be proven based on this limited dataset.

Fuel dilution of the lubricant was examined by a gas chromatography method for some samples. This method yields the amount of petroleum diesel fuel in the lubricant and results are shown in Table 13. Fuel dilution by lubricant is low in all cases, and even lower for the B20 blends. Additionally, lubricant dilution by methyl ester from the biodiesel fuel blend was examined by FTIR. No ester was detected in the lubricant from the B20 buses except for the 7314 mile sample from bus 2208, which contained 0.6% methyl ester.

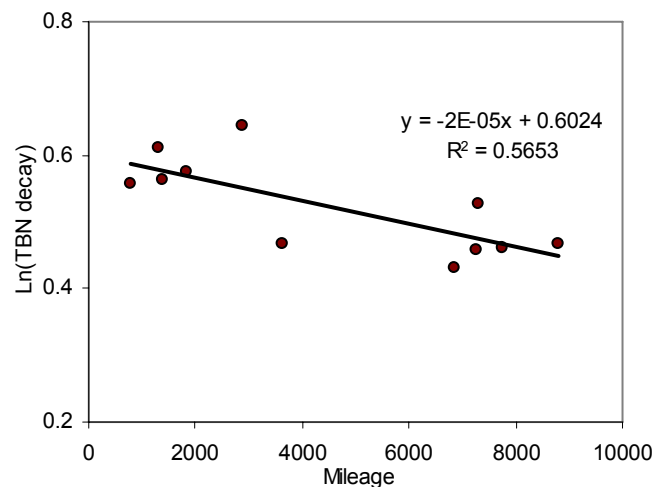


Figure 15. Results of Fitting TBN Decay Data to Linearized Exponential Law, Equation 2

Metals analysis was performed by ICP-AA (inductively coupled plasma/atomic absorption). Calcium, zinc, and phosphorus increase in concentration as the lubricant is consumed by evaporation, thus can be used to track oil consumption. However for these oil samples the concentrations of these metals do not exhibit any trend with mileage and show no discernable difference for diesel and B20. Iron, copper, and chromium are indicators of engine wear. There is no discernable difference for oil samples from the diesel and B20 buses. Finally, sodium levels are low in all cases indicating no coolant leak or contamination with high soap content biodiesel.

Soot in oil was determined by a thermogravimetric analysis method, and these values are also shown in Table 13. Soot levels are low in all cases but about 50% lower on average in the B20 lubricant samples. This lower soot loading for B20 is a significant potential advantage that should be examined in more detail in

Table 13. Lubricant Properties at Various Mileage

Vehicle No.	Miles	TBN	Fuel % by GC	Ca, ppm	Zn, ppm	P, ppm	Fe, ppm	Cu, ppm	Cr, ppm	Na, ppm	Soot, wt%
Unused Oil	0	9.27	0	3261	1246	1215	2	0	0	0	0
Diesel Group											
2203	1295	8.4	0.70	3265	1265	1177	5	0	0	1	--
2203	5375	4.21	--	3213	1259	1111	24	1	1	3	3.83
2203	7770	5.86	--	3421	1323	1173	21	1	2	4	3.09
2204	1392	7.57	0.70	3411	1312	1234	7	6	1	2	--
2204	6035	4.64	--	3385	1299	1178	22	3	3	3	4.16
2204	6850	5.37	0.30	3731	1401	1255	23	10	3	4	3.42
2205	7463	4.7	--	3399	1297	1168	20	1	1	4	3.9
2206	5840	4.73	--	3293	1311	1171	25	1	2	4	4.27
B20 Group											
2207	2900	7.75	0	3684	1286	1210	6	2	3	3	--
2207	7256	5.82	--	3213	1268	1144	13	3	5	3	1.9
2208	1834	9.03	0.20	3508	1258	1208	3	0	0	1	--
2208	7314	6.95	0	3802	1413	1277	13	1	1	6	1.75
2209	802	7.47	--	3405	1295	1237	4	0	0	1	0.32
2210	3634	5.93	--	3367	1327	1179	20	2	2	4	3.72
2211	8800	5.93	--	3330	1319	1181	20	1	1	4	2.53

lubricant performance tests. The lubricant samples were also tested for viscosity and viscosity index. These values did not decay significantly during the oil drain interval for lubricant from either group of vehicles.

Overall the lubricant analysis indicates no negative impact from the use of B20 and suggests some potential benefits. To quantify these potential benefits will require additional study.

CHASSIS EMISSION TESTS

Emission testing was conducted on two vehicles: bus numbers 2208 and 2211. The buses were tested using both the in-use No. 2 diesel and the in-use B20 fuels. Properties of these fuels are listed in Table 14. At the time of this testing, the B20 was being blended with the same diesel fuel used by the diesel buses. The B20 shows significantly higher cetane number, in part because of the relatively high cetane number of biodiesel which is typically 54 [9], but this can only account for a cetane number increase of about 3. The additional increase is caused by the multifunctional diesel additive used by the biodiesel supplier, which includes a cetane improving additive. The aromatic content of the B20 appears to be slightly higher than the aromatic content of the diesel fuel; however biodiesel is known to interfere in method D1319 [11] and may provide falsely high values for B20 blends. Two drivers were used to perform the test cycles. Testing was performed so that each driver performed the same number of test runs on each bus, per fuel.

Six to eight total repeated test cycle runs were driven for each bus on each fuel, results for each test run are reported in Appendix A; and summary results analyzed statistically for each bus and for both buses combined

are reported in Table 15. The data show that for these vehicles on this test cycle, operation on B20 reduced all regulated pollutants, including NO_x. Fuel economy on a mpg basis was decreased by roughly 2%, in agreement with the lower energy content of B20. In most cases p<0.05, indicating changes are significant with 95% or better confidence.

Table 14. Fuel Properties of Fuel Used for Emissions Testing

	B20	Diesel
B100 Content (Vol %)	21.1	NA
Distillation T90, °F (D86)	644.4	617.4
Flash Point, °F (D93)	159	151
Copper Corrosion (D130)	1a	1a
Kinematic Viscosity, cSt@40°C (D445)	2.726	2.438
Ash, %Mass (D482)	0	0
Carbon Residue, %mass (D524)	<0.010	0.04
Cetane Number (D613)	47	40
Cloud Point, °F (D5773)	6	0
Total Sulfur, ppm (D5453)	280	364
Water & Sediment, %Vol (D2709)	0	0
Aromatics, %Vol (D1319)	28.5	27.1
Heat of Combustion, BTU/gal (D240)	134,650	137,720
Acid Number, mg KOH/gram (D664)	0.16	0.01
Peroxide Number, ppm (D3703)	8.1	0

Clearly the oxygen content provided by the biodiesel is primarily responsible for the reductions in THC, CO, and PM; in agreement with previous studies [1]. The situation for NO_x emissions is less clear. B20 exhibited a cetane

number of 47 versus 40 for the in-use diesel fuel. For fuels that are otherwise identical, increasing cetane number from 40 to 47 could produce a NO_x reduction of 3% [12]. However, in testing of a third mechanically identical transit bus where neither fuel contained additives we have observed NO_x reductions ranging from 2 to 5% [13]. Thus it seems unlikely that additive effects are the main cause of the NO_x reduction observed here.

By testing two buses, with two drivers each, on both fuels, some information regarding variability between vehicles and between drivers can also be acquired. This analysis can be useful to evaluate whether the results can be interpreted to likely apply generally to the Skip bus fleet or if vehicle-to-vehicle variability prevents such a generalized conclusion.

The data show good agreement between the two test vehicles, with no statistically significant difference (at alpha of 0.05), between the two buses for any of the regulated emissions. There was a statistically significant difference between the two buses for fuel economy with bus 2211 achieving approximately 3% better fuel economy than bus 2208, on average.

There was no statistically significant difference between drivers (alpha of 0.05) for NO_x emissions, THC emissions, or fuel economy. There was a statistically significant difference between drivers for CO and PM emissions, with these emissions from driver A averaging about 22%-23% higher than driver B.

Table 15. Summary Results for Bus Emission Testing

Bus	NO _x g/mile	THC g/mile	CO g/mile	PM g/mile	FE mpg
2211					
Base	19.81	0.871	3.60	0.274	4.70
B20	18.65	0.625	2.63	0.226	4.59
%Δ	-5.8	-28.2	-26.8	-17.3	-2.4
p-value	<0.001	0.001	<0.001	0.042	0.032
2208					
Base	19.44	0.807	3.44	0.2648	4.60
B20	18.67	0.571	2.73	0.2150	4.45
%Δ	-3.9	-28.0	-20.3	-19.9	-2.1
p-value	0.039	0.002	0.071	0.153	0.018

CONCLUSIONS

In the 100,000-mile evaluation of transit buses operated on B20, the following operational differences were found related to vehicle fuel:

- The fuel economy for both petroleum diesel and B20 groups was 4.41 mpg based on in-use fleet data. An approximately 2% reduction in fuel economy for B20 was measured in laboratory emission testing.
- Total maintenance costs per mile were \$0.54 for the diesel group and \$0.51 for the B20 group, and maintenance costs specific to the engine and fuel

systems were \$0.05 and \$0.07 per mile, respectively. Because of high variability in maintenance costs between vehicles, the engine and fuel system maintenance costs for the two groups are not significantly different with a high degree of confidence (p~0.5). The increased engine and fuel system costs for the B20 group were due to fuel injector and cylinder head replacements on Bus 2211. Further study will be required to determine if B20 fuel use caused these failures.

- Miles between road calls averaged 3,197 for the diesel group and 3,632 for the B20 group. There is no evidence in the data to suggest this difference is related to fuel use.
- Fuel filter plugging on the B20 buses caused road calls, and required extra filter replacements in the B20 group. Although the additional maintenance cost was small, adding only \$1,054.81 to the B20 group or \$0.002 per mile, the events were significant to the transit district because of resulting disruptions to normal bus service. Fuel filter plugging may have been caused by the presence of high levels of plant sterols in the biodiesel or other fuel quality issues.
- Measurement of biodiesel blend level showed erratic biodiesel content for delivery load samples. Vehicle samples, however, were consistently at or near B20 indicating complete blending had occurred during delivery and offloading of the fuel.
- Oil analysis results indicate no additional wear metals from the use of B20, with similar rates of TBN and ZDDP decay, oxidation, fuel dilution, and viscosity. Soot levels in the lubricant were significantly lower for the B20 vehicles. Quantifying potential benefits will require additional study.
- Laboratory chassis testing on the CSHVC cycle using the in-use fuels found that B20 reduced emissions of all regulated pollutants and caused a small fuel economy decrease.

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CONTACT

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AA:	Atomic absorption
ASTM:	ASTM International
B20:	A blend of 20% biodiesel with diesel fuel
CFPP:	Cold filter plugging point
CFR:	Code of Federal Regulations
CSHVC:	City-suburban heavy-vehicle cycle
CO:	Carbon monoxide
CO₂:	Carbon dioxide
DC:	Direct current
FAME:	Fatty acid methyl esters
FE:	Fuel economy
FTIR:	Infrared spectroscopy
GCMS:	Gas chromatography mass spectrometry
ICP:	Inductively coupled plasma
MBRC:	Miles between road calls
NO_x:	Oxides of nitrogen
NREL:	National Renewable Energy Laboratory
PM:	Particulate matter
RC:	Road call
RTD:	Regional Transportation District
TBN:	Total base number
THC:	Total hydrocarbon
VIN:	Vehicle identification number
ZDDP:	Zinc dialkyldithiophosphate

APPENDIX A

Table A1. Chassis Emissions Test Data

Bus 2211	Fuel	Run	NOx g/mile	THC g/mile	CO g/mile	PM g/mile	Fuel Economy mpg
	Base	332	19.90	0.906	4.18	0.2380	4.68
	Base	333	20.56	1.033	3.74	0.2185	4.70
	Base	337	19.69	0.816	3.48	0.3055	nm
	Base	338	19.81	0.854	3.08	0.2616	4.68
	Base	339	19.33	0.789	3.78	0.3263	4.67
	Base	340	19.54	0.829	3.32	0.2940	4.77
Average			19.80	0.871	3.60	0.2740	4.70
Standard deviation			0.42	0.09	0.39	0.04	0.04
Coefficient of variation			2.1%	10.2%	10.8%	15.2%	0.9%
	B20	326	18.78	0.604	2.48	0.2421	nm
	B20	328	18.54	0.598	2.94	0.2200	4.54
	B20	329	18.83	0.581	2.69	0.2365	4.50
	B20	345	18.36	0.485	2.97	0.2603	4.55
	B20	346	18.83	0.729	2.35	0.1961	4.65
	B20	347	18.57	0.754	2.36	0.2037	4.69
Average			18.65	0.625	2.63	0.2264	4.59
Standard deviation			0.19	0.10	0.28	0.02	0.08
Coefficient of variation			1.0%	16.0%	10.6%	10.8%	1.7%
Percent difference with base:			-5.8%	-28.3%	-26.8%	-17.4%	-2.4%
Bus 2208	Fuel	Run	NOx g/mile	THC g/mile	CO g/mile	PM g/mile	Fuel Economy mpg
	Base	364	19.81	0.806	2.84	0.2178	4.67
	Base	365	19.86	0.818	2.77	0.2001	4.67
	Base	366	19.24	0.724	3.64	0.2901	4.57
	Base	367	19.08	0.938	3.60	0.2804	4.60
	Base	372	18.68	0.747	4.35	0.3358	4.52
Average			19.34	0.807	3.44	0.2648	4.60
Standard deviation			0.50	0.08	0.65	0.06	0.06
Coefficient of variation			2.6%	10.3%	18.9%	21.0%	1.4%
	B20	358	19.01	0.542	3.18	0.2583	4.24
	B20	359	18.75	0.566	2.37	0.1933	4.33
	B20	360	18.47	0.546	2.93	0.2439	4.37
	B20	362	19.17	0.564	2.43	0.1581	4.44
	B20	377	18.33	0.533	3.61	0.3261	4.45
	B20	378	18.38	0.597	2.38	0.1868	4.59
	B20	379	18.20	0.616	2.53	0.1821	4.62
	B20	380	19.08	0.608	2.42	0.1714	4.55
Average			18.67	0.571	2.73	0.2150	4.45
Standard deviation			0.38	0.03	0.46	0.06	0.13
Coefficient of variation			2.0%	5.6%	16.9%	26.4%	3.0%
Percent difference with base:			-4.11	-38.94	-25.54	-49.29	-2.08