School Bus Biodiesel (B20) NOx Emissions Testing

TEXAS TRANSPORTATION INSTITUTE
THE TEXAS A&M UNIVERSITY SYSTEM
COLLEGE STATION, TEXAS

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SCHOOL BUS BIODIESEL (B20) NOx EMISSIONS TESTING

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ABSTRACT

This study investigated the impact of biodiesel (B20: 20 percent biodiesel, 80 percent conventional diesel) on the oxides of nitrogen (NOx) emissions emitted from diesel school buses. Two drive cycles were developed based on the real rural and urban drive cycle data collected using a global positioning system (GPS). The developed synthetic drive cycles captured the important characteristics of real world driving conditions for replication on a test track. Five buses were selected according to the current model year mix in Texas and were driven following the developed drive cycles for three fuel blends — Texas Low Emissions Diesel as base fuel, B20 market blend, and B20 all soy. A state-of-the-art portable emission measurement system (PEMS) unit was used to measure the NOx emission along with other emissions, ambient weather condition, GPS readings, and vehicle engine data. The data were cleaned and aggregated to represent the current Texas school bus fleet and rural/urban mix of miles driven. The results of statistical analysis showed that using B20 had no significant effect on the level of NOx emissions emitted by the school buses.

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INTRODUCTION

The Capital Area Council of Governments (CAPCOG), Capital Metropolitan Planning Organization (CAMPO), CLEAN AIR Force of Central Texas, Central Texas Clean Cities Coalition, and the Texas Department of Agriculture formed a workgroup to examine the possibility of local school district using biodiesel fuel (B20: 20 percent biodiesel, 80 percent conventional petroleum diesel) to operate their school buses. While there are a number of studies that show using B20 has the potential to lower health-harming particulate matter and air toxins significantly from the emissions of ordinary diesel fuel, U.S. Environmental Protection Agency (EPA) studies have shown that B20 use may increase oxides of nitrogen (NOx) emissions by an average of 2 percent (*1*). In EPA's study approximately 98 percent of the data were collected on 1997 or earlier model year engines. Because of this, the researchers expressed concern that their estimates of biodiesel impact on emissions may be less accurate for future fleets than the current fleet. The Texas Commission on Environmental Quality (TCEQ) has adopted the EPA's position, and as recently as February 2006, TCEQ staff have publicly stated that there is a presumption that use of B20 increases NOx emissions.

However, other, more recent research shows that B20 may decrease NOx emissions depending on the application. The National Renewable Energy Laboratory (NREL) conducted a series of tests on buses in Denver using a chassis dynamometer. The tests showed that NOx emissions fell 4 percent using B20 fuel (*2*). A CTE–North Carolina Department of Transportation study on dump trucks in North Carolina illustrated that using B20 fuel reduced NOx emissions by 10 percent compared to conventional petroleum diesel (*3*). Researchers at Rowan University in New Jersey also found that using B20 fuel in school buses helped reduce NOx emissions (*4*).

Due to the ozone attainment/nonattainment status in central Texas, CAPCOG and members of the workgroup are hesitant to encourage the expanded use of B20 without further study on school bus NOx emissions resulting from the use of B20 fuel. This study investigates the issue of school bus NOx emissions. An overview of the project proposed by Texas Transportation Institute (TTI) to study NOx emissions from school buses fueled with B20 follows.

APPROACH

The general approach of the study consisted of measuring tailpipe emissions of five sample school buses for three study fuels using portable emission measurement system (PEMS) equipment and analyzing the results. Researchers developed two simple and consistent drive cycles, one for rural conditions and one for urban conditions, for use in the study. For each fuel and bus combination, data including emissions measurements, engine parameters, and global positioning system (GPS) information were collected on a second-by-second basis while driving the developed cycles on a test track. These data were cleaned, converted to the appropriate format, and analyzed. The following sections explain the various components of the study.

TEST SITE

The data collection part of the study took place at TTI's test track located at Riverside Campus of Texas A&M University, Bryan, Texas. The Riverside campus is a 2,000-acre former Air Force base which is used for research and training purposes. The available test roads consist of a roadway network surrounding former barracks and other base buildings plus the former runways (longest straightaway 7,500 feet) which were used for testing in this study. Figure 1 shows an aerial view of available road network at the Riverside Campus.

Figure 1. Aerial View of the Riverside Campus at Texas A&M University.

TEST VEHICLES

The Caldwell, Texas, Independent School District (CISD) provided five school buses as test vehicles for the study. Each bus belonged to a different model year group, which was adopted from TTI's report on *School Bus Emissions Reduction Program*, prepared for Texas Department of Transportation (TxDOT) (*5*). Each group represented a different emissions control and engine technology category. Using this approach, the composed average fleet emissions were calculated based on Texas' school bus group mix provided in the TTI report (*5*). Table 1 shows information about the school buses used in this study along with their share of the Texas school bus fleet.

Table 1. Age Distribution of School Buses in the Nonattainment and Early Action Compact Areas in Texas

Group [x1]	Percent of Texas Fleet [x1]	Bus Numbers	Model Year
1978-1989	24%	Bus 3	1987
1990-1993	17%	Bus 21	1990
1994-1998	28%	Bus 20	1997
1999-2000	14%	Bus 30	2000
2001-2006	17%	Bus 6	2004

All the buses were equipped with in-line, six-cylinder International engines (Series D466 and D466E). All buses were type C's based on their passenger seat capacity (*6*, *7*). Each bus was loaded with 56 50-lb. sand bags (2,800 lbs) to replicate an average loading situation (approximately equal to 30 children on-board).

TEST DATES

The preparation phase was performed Tuesday July 11 to Friday July 14, 2006. The testing phase was conducted Monday June 17 to Friday June 28, 2006. These testing dates are typical summer days in central Texas. The conditions were mostly humid and sunny with temperatures in the mid/upper 90 degrees Fahrenheit.

TEST FUELS

The three fuel blends examined in this study included:

- Base fuel (Fuel 1): Texas Low-Emissions Diesel (TxLED) Ultra Low Sulfur Diesel (ULSD) provided by Valero's Three Rivers Refinery;
- B20 market blend (Fuel 2): 80 percent base fuel, 20 percent market blend biodiesel obtained from Austin Bio Fuels, LLC; and
- B20 all soy (Fuel 3): 80 percent base fuel, 20 percent biodiesel made from soy obtained from Austin Bio Fuels, LLC.

The biodiesel fuels were obtained in form of B100 (100 percent biodiesel) and were mixed (splash-blended) in appropriate proportion at the test site.

DRIVE CYCLES

Researchers developed two drive cycles, one for rural regions and one for urban areas, for this study. The drive cycles were developed based on three criteria – each drive cycle should reflect typical school bus driving cycles, each cycle must be easy to follow, and each cycle must fit in the available test track.

Prior to the test, four CISD school buses were equipped with GPS units for a complete school day to track morning and afternoon bus routes. The first two bus routes covered mainly rural areas, while the other two bus routes serviced urban areas. Researchers analyzed the speed profiles of all the buses and each cycle was separated into different sub-cycles corresponding to different driving conditions. Each sub-cycle was further examined and average time spent in cruise, average speed, average idle duration, number of stops, and total time spent in the sub-cycle was calculated. This information was then used in conjunction with the synthetic cycle developing method illustrated by Dion et al. (*8*) and the constraint of the maximum available straight test track (6,000 ft.) to build the drive cycles. Figures 2 and 3 show the developed cycles used in this study for the rural and urban conditions, respectively.

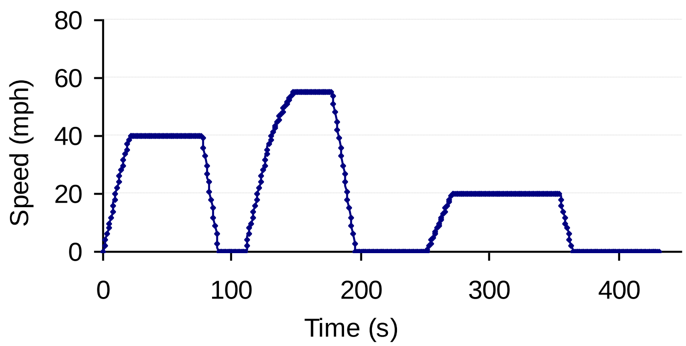

Figure 2. Synthetic Driving Cycle Representing Rural Driving Conditions.

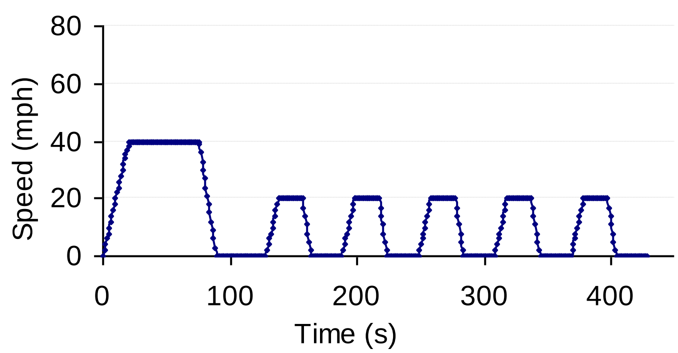

Figure 3. Synthetic Driving Cycle Representing Urban Driving Conditions.

Both cycles consisted of three components; 1) cruising, 2) acceleration and deceleration, and 3) idling. The cruising portion of the rural cycle included a 40 mph cruise segment, a 55 mph segment, and a 20 mph segment. The 55 mph component reflected driving on a highway. The 55 mph maximum speed is set by law and some of the buses were equipped with a governor that does not allow the bus to go faster than 55 mph. The 40 mph element represented driving on rural arterials and the 20 mph component represented driving conditions on rural access roads (possibly dirt roads). The cruising part of the urban cycle consisted of a 40 mph component for urban arterials/streets and five short 20-mph elements reflecting driving short distances in a neighborhood and picking up schoolchildren.

Since only one driver was used in the test, the driver's natural acceleration and deceleration behavior was considered close to real world driving behavior. The driver was instructed to accelerate and decelerate as he/she would usually do while safely driving on a street or highway. The idling portions of the cycles reflected the amount of time that buses remained idle due to traffic control, congestion, and picking up children. A researcher on board the bus provided instructions to the driver for following the target driving profile. These instructions included: 1) the starting of acceleration and the target speed, 2) the time interval of each cruising speed and when to begin deceleration, and 3) the duration of idle period. The researcher was checking the speed at each step periodically to ensure that the driver was following the instructions.

Texas Transportation Institute's study of *School Bus Emission Reduction Programs* [5] indicated that 28% of total miles driven by school buses in Texas occurred in rural areas and the rest (72%) were in urban areas. These proportions were used to build up the Texas' representative emission rates.

TEST EQUIPMENT

The PEMS unit used in this study was the state-of-the-art SEMTECH-DS manufactured by SENSORS Inc. The SEMTECH-DS unit includes a set of gas analyzers, an engine diagnostic scanner, a GPS, an exhaust flow meter, and embedded software. Figure 4 shows the SEMTECH-DS system and the exhaust flow meter installed on a school bus.

Figure 4. Components of the SEMTECH-DS Unit Installed on a School Bus.

Gas analyzers measured the concentrations of NOx (NO and nitrogen dioxide[NO_2]), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO_2), and oxygen (O_2) in the vehicle exhaust. The engine scanner was connected to the vehicle engine control module (ECM) via a vehicle interface (VI) and provided speed, engine speed (RPM), torque, and fuel flow. SEMTECH-DS used the Garmin International, Inc. GPS receiver model GPS 16 HVS to track the route, elevation, and ground speed of the vehicle under test on a second-by-second basis. The SEMTECH-DS used the SEMTECH EFM electronic exhaust flow meter to measure the vehicle exhaust flow. The SEMTECH-DS and the post-processor application software used this exhaust mass flow information to calculate exhaust mass emissions for all measured exhaust gases. The SEMTECH-DS used embedded software, which controlled the connection to external computers via a wireless or Ethernet connection to provide the real-time control of the instrument. A Panasonic Toughbook laptop was used to connect to the SEMTECH-DS and to control the unit.

TEST PROTOCOL

The study team developed a test protocol that would provide the best opportunity to test emissions differences resulting from using different fuel mixes. The effect of fuel mix was captured by driving the test vehicles equipped with each fuel mix using the developed synthetic rural and urban cycles. To maintain consistency between each run, a professional school bus driver working for CISD was used for all the test runs. Each test scenario included three runs and for each of the runs the emissions, engine, and speed data were collected on a second-by-second basis. Figure 5 shows a flow diagram illustrating the test protocol used in this study. Each test scenario was repeated three times resulting in 90 total runs (3 runs × 5 buses × 3 fuels × 2 cycles = 90).

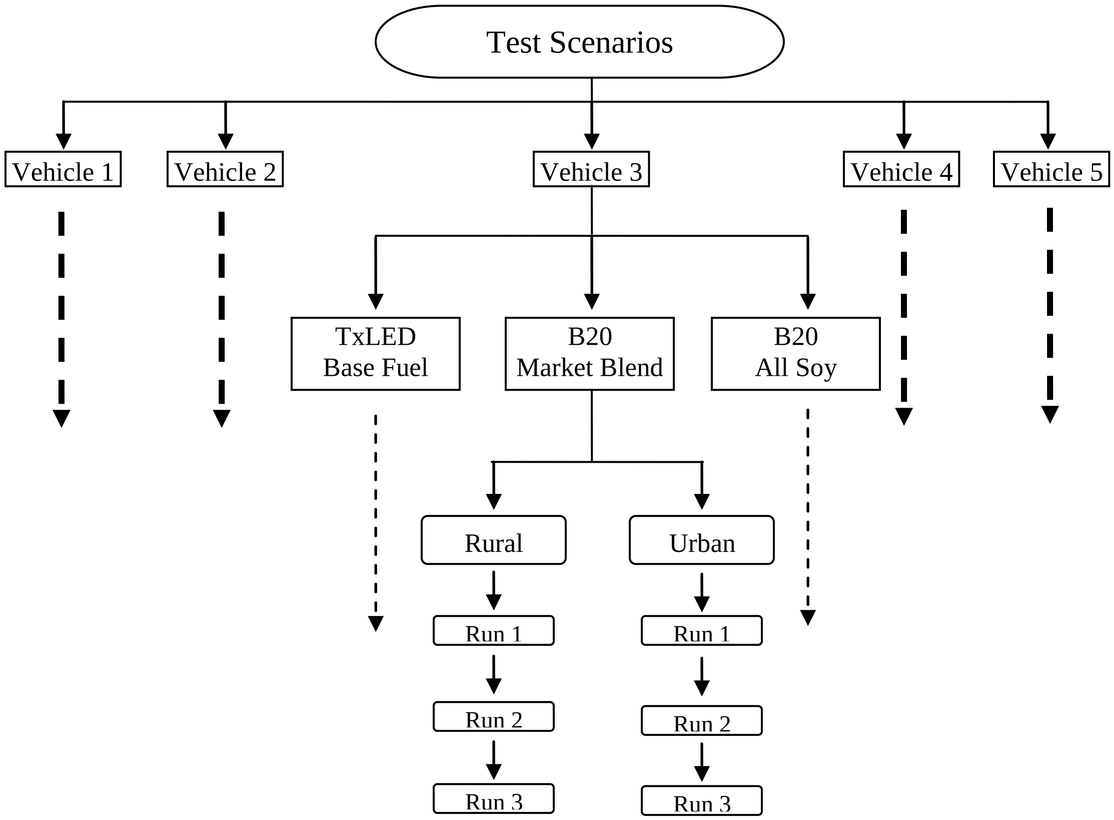

Figure 5. Flow Chart of the Test Protocol.

RESULTS

The data recorded by SEMTECH-DS were in second-by-second format. From the entire array of information that SEMTECH-DS recorded in its output (emissions, ambient conditions, and vehicle parameters) the following information was extracted and used in this study:

- engine parameters (if a VI was available) such as engine speed, throttle position, and engine load for data quality checking;
- second-by-second vehicle speed from GPS in mph; and
- emission mass rates in grams per second (g/s).

The data were then cleaned and observations that were not part of the desired drive cycles were removed. The length of the idle segments for each section of the cycles were examined and the extra records (i.e., the extra data recorded beyond the number of seconds in target driving cycles) were eliminated to provide cycles which were comparable to each other.

NOx Emissions

The NOx emissions mass rates (g/s) were converted to accumulated emissions rates (grams per mile [g/mi]) for each run and cycle. Table 2 shows these rates. The weighted averages of these accumulated rates were then calculated for each fuel according to Texas school bus model year mix provided in TTI's school bus report (*5*). These results were subsequently weighted based on rural/urban miles covered (rural 28 percent, urban 72 percent) (*5*) to provide the estimated average mass emissions rates for the Texas school bus fleet (see Table 3).

Table 2. NOx Mass Rate for Individual Buses (g/mi)

	Rural Driving Cycle			Urban Driving Cycle		
Bus/Run	**TxLED**	**B20 market**	**B20 soy**	**TxLED**	**B20 market**	**B20 soy**
Bus 3 / Run1	17.31	16.53	17.08	19.14	19.05	19.92
Bus 3 / Run2	16.90	16.58	16.76	19.14	18.73	19.51
Bus 3 / Run3	16.17	16.12	15.89	18.78	18.18	18.73
Bus 6 / Run1	10.44	10.17	10.08	11.45	12.18	11.63
Bus 6 / Run2	9.85	10.40	10.12	11.63	11.91	11.40
Bus 6 / Run3	9.53	9.89	10.12	11.77	11.72	11.77
Bus 21 / Run1	18.14	18.41	18.27	20.52	20.11	20.56
Bus 21 / Run2	17.77	17.54	17.54	20.38	19.88	21.80
Bus 21 / Run3	17.50	17.27	16.99	19.65	19.60	20.75
Bus 30 / Run1	10.53	10.08	10.17	10.49	10.53	10.49
Bus 30 / Run2	10.08	9.57	9.66	10.72	10.63	10.76
Bus 30 / Run3	10.03	9.98	9.43	10.95	10.53	10.76
Bus 20 / Run1	11.36	11.18	11.36	12.50	11.04	13.60
Bus 20 / Run2	12.78	10.26	10.95	11.72	12.32	invalid
Bus 20 / Run3	10.67	9.43	10.40	11.72	12.23	12.05

Table 3. Average NOx mass rate for Texas fleet (g/mi)

	TxLed	**B20 market**	**B20 soy**
Average (g/mi)	14.43	14.19	14.53
Change from TxLed (%)	0.0%	-1.6%	+0.7%

Table 3 clearly demonstrates that on the average B20 does not significantly affect NOx emissions for the Texas fleet mix and the Texas rural/urban composition (in both cases they are less than 2 percent).

To support this conclusion, a statistical analysis was performed on the individual bus data. For each of the rural and urban cycles, a paired t-test was utilized for this purpose on the weighted (according to Texas fleet mix) differences between Texas Low-Emissions Diesel fuel emissions and the two biodiesel fuels. In all cases, it was found that the differences were insignificant at a 99 percent significance level.

Overall Findings

- The buses older than 1994 emitted approximately 1.6 times the amount of NOx as buses manufactured after 1994. The NOx emissions level for buses newer than 1994 were almost equal.
- In terms of HC, benefits of using B20 were significantly higher for older buses. B20 had slight or no effect on HC for buses newer than 2000.
- The effect of B20 on CO was found to be inconclusive. This is because there was no consistent pattern (i.e., mixed increasing and decreasing effects).
- For all the buses, the urban cycle resulted in higher NOx emissions rate (g/mi) than for the rural cycle, despite the higher average speed of rural driving cycle. This is possibly the result of more transient driving profiles in urban driving conditions (i.e., more stops, more acceleration/deceleration periods, and shorter cruising intervals).
- For almost all the cases (with exception of the Texas Low-Emissions Diesel fuel for Buses 30 and 20), the CO and CO_2 emissions were higher for the urban cycle.
- With exception of TxLED for Bus 30, the HC emissions were higher for the urban driving cycle.

Appendix B includes graphs showing the results of the individual bus and fleet-level emissions. Figures B1 through B4 show different emissions rates in g/mi for each individual bus using each fuel blend. Specifically, Figure B1 confirms that the impact of using B20 on the NOx emissions rate is insignificant. Figure B5 shows the NOx emissions rates in g/s for different stable components of the drive cycles (i.e., the acceleration and deceleration sections are removed). The figure demonstrates that higher speeds result in higher NOx emissions and the effect of speed difference is more significant for higher speeds (e.g., the difference of NOx rates between 20 and 40 mph is significantly larger than the differences between idle and 20 mph). Figures B6 through B9 show the NOx emissions rates (g/s) for individual buses at each stable condition speed. In general, these figures display the effect of a vehicles' age on how a test vehicle reacted to different fuel mixes at different stable driving conditions. In general, Figures B6 through B9 demonstrate that differences between NOx emissions using different fuel blends are relatively small for almost all cases. The only exception to this pattern is Bus 20 with all soy biodiesel fuel at 20 mph in the urban cycle. Further investigation on the available data did not reveal the cause of this variation for Bus 20.

CONCLUSIONS

This study intended to determine what effect using a 20 percent biodiesel blend (B20) has on school bus NOx emissions. Based on the test results and the available estimation of the school bus model year mix in Texas, the researchers developed the following conclusions.

- On average for Texas school bus fleet, the effect of B20 from both sources (market blend and all soy) on the emitted NOx emissions is insignificant.
- Older buses (older than 1994) are producing higher rates of NOx. Retiring these older buses from the fleet can potentially reduce NOx emissions significantly.
- The benefit of using B20 for reducing HC is significantly higher for older buses (older than 1994). For buses newer than the model year 2000, the change in HC from using B20 is either insignificant or slightly increasing.

Any study has some limitations that could be used to expand the scope of the analysis or to apply improved methods for future work. A few limitations of this study imply recommendations for future work:

- The overall vehicle sample size of 5 is relatively small compared to the in-use fleet. Although the researchers do not expect that it would make a significant difference in the results, having a bigger sample size (e.g. 3 buses from each age group, total 15 school buses) would increase the statistical confidence in the results.
- Due to the budgetary and time constraints only three repetitions for each test were performed. More repetitions would provide more statistical strength to the analysis. It is not expected that having more repetitions would have changed the results significantly.
- The study used Texas representative driving cycles and fleet mix and the test site was located in central Texas. The researchers would not recommend generalizing the results without carefully taking into account the regional differences in climatic and school bus fleet parameters.
- This study investigated only school buses using school bus specific parameters and assumptions, and one should not generalize the results beyond school buses. Each vehicle class should be studied separately in order to develop conclusions for those classes.

ACKNOWLEDGEMENTS

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- Capital Area Metropolitan Planning Organization (CAMPO); and
- Texas Commission on Environmental Quality (TCEQ).

Our CAPCOG contacts, Bill Gill and Mike Fishburn, were valuable colleagues throughout the project. The Authors would like to thank Hazel Barbour representing the Clean School Bus Program of Central Texas for providing insightful comments on the study scope and project report.

A number of other organizations and individuals contributed to the success of this effort. The support of the Caldwell ISD was critical. Randall Berryhill, Bill Broaddus, Pam Nichols, Henry Washington, Craig Ayers, and Rhonda Homeyer were especially helpful. Technical support was provided by our colleagues John Storey and Doh-Won Lee, of Oakridge National Laboratory. The fuels used for testing were provided by Valero’s Three Rivers Refinery and Austin Bio Fuels.

Editorial support was provided by Gary Lobaugh of TTI. Finally, the authors thank the following TTI staff for their hard work in collecting the data used in this analysis: Ed Brackin, Mark Ojah, A. J. Rand, and Meghan Wieters.

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APPENDIX A: BIODIESEL LITERATURE REVIEW

Literature Review Relating to the Fuel Economy, Maintenance Impacts, and Emissions of Biodiesel Fuel Alternatives

OVERVIEW

As noted, the focus of this study was the empirical testing of various alternative fuel (biodiesel) blends in replications of real school bus drive cycles using actual school bus fleet vehicles. The duration and scope of the study did not allow for the direct measurement of either fuel economy or vehicle maintenance impacts. Instead, a review of the available research literature is provided. Since the research that addressed fuel economy and maintenance typically also addressed emissions, a summary of the findings relating to emissions is also provided.

Ultimately, studies that examined biodiesel emissions and other effects (fuel economy, maintenance impacts) are not unanimous in their conclusions. As reported below, some studies suggest that the use of biodiesel may produce increases in NOx emissions concurrent with reductions in other pollutants, promoting the need for additional research and studies. Of course, these and similar findings form the basis for the present study.

Results of school bus tests indicate the overall operating costs were identical for B20 and B100 fueled engines. The majority of studies reported that use of biodiesel in either "neat" or blended forms resulted in similar fuel economy and power output, however, one study did report use of B100 produced loss of fuel efficiency. Regarding soy and animal blended biodiesel, one study reported beef tallow performed similar to petroleum-based diesel manufactured from other feedstock such as soybean oil.

In most instances, researchers found that overall B20 and ULSD reduced CO and particulate matter (PM) emissions but increased NOx emissions. In particular, EPA findings indicate biodiesel impacts on emissions vary depending on the type of biodiesel and on the type of conventional diesel to which the biodiesel was added. Department of Defense (DoD) test results showed no statistically significant emissions differences between biodiesel fuels manufactured from yellow grease or soybean oil feedstocks, nor was there a statistically significant increase in NOx emissions (using a military fleet). For heavy-duty diesel trucks, the emissions rates varied among operating modes. The distinction between real-world duty cycles as opposed to arbitrary test cycles was critical to the estimation of emissions, especially nitric oxide (NO).

REGULATORY AGENCY TESTING

In October 2002, in connection with the increasing interest in the use of biodiesel, the EPA published the draft Technical Report, *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions (*EPA420-P-02-001), after conducting a comprehensive analysis of the emissions impacts of biodiesel using publicly available data. The investigation made use of statistical regression analysis to correlate the concentration of biodiesel in conventional diesel fuel with changes in regulated and unregulated pollutants. Since the majority of available data was collected on heavy-duty highway engines, this data formed the basis of the analysis.

One of the most common blends of biodiesel contains 20 percent biodiesel and 80 percent conventional diesel. Biodiesel is also predicted to reduce fuel economy by 1 percent to 2 percent for a 20 percent biodiesel blend. Aggregate toxics are predicted to be reduced, but the impacts differ from one toxic compound to another. The researchers were unable to identify an unambiguous difference in exhaust CO_2 emissions between biodiesel and conventional diesel. More importantly, the authors noted, the CO_2 benefits commonly attributed to biodiesel are the result of the renewability of the biodiesel itself, not the comparative exhaust CO_2 emissions. An investigation into the renewability of biodiesel was not addressed in the current study.

The study was accurate for estimates in the current fleet, however, the database contained no engines equipped with exhaust gas recirculation (EGR), NOx absorbers, or PM traps. In addition, approximately 98 percent of the data was collected on 1997 or earlier model year engines. The researchers expressed concern that their estimates of biodiesel impacts on emissions may be less accurate for future fleets than for the current fleet.

The investigation also discovered that biodiesel impacts on emissions varied depending on the type of biodiesel (soybean, rapeseed, or animal fats) and on the type of conventional diesel to which the biodiesel was added. With one minor exception, emissions impacts of biodiesel did not appear to differ by engine model year. The highway engine-based correlations between biodiesel concentration and emissions were also compared to data collected on nonroad engines and light-duty vehicles. On the basis of this comparison, the researchers could not say with confidence that either of these groups responded to biodiesel in the same way that heavy-duty highway engines do. Finally, the EPA researchers were unable to predict the impacts of biodiesel use on emissions from light-duty diesel vehicles or diesel-powered nonroad equipment.

DEPARTMENT OF DEFENSE

In May 2006, Holden et al. published a report describing a three-year project led by the Naval Facilities Engineering Service Center (NFESC) to obtain emissions factors (i.e., tailpipe air pollution emissions data) from 10 types of DoD-operated diesel-powered engines. Emissions data was obtained from eight vehicles, primarily buses and trucks, and two portable generators. All testing was performed with the engines installed in the vehicles/portable equipment. Emissions factors were determined for the engines fueled with various blends/types of biodiesel as well as a baseline fuel, either California Air Resources Board-(CARB) certified ULSD (15 parts-per-million [ppm] sulfur maximum) or JP-8. CARB USLD was used since it will be required within California for on-road vehicles beginning in June 2006. Biodiesel blends from 20 percent to 70 percent were tested along with 100 percent biodiesel. For the blended biodiesel testing, the biodiesel was mixed with ULSD. Although several blends were tested, the project focused on B20 (20 percent biodiesel) blends, since this is the primary blend of biodiesel used in military vehicles.

Testing performed on B20 fuels identified three significant results: 1) there were no consistent trends over all engines tested, 2) there were no statistically significant emissions differences found between biodiesel fuels manufactured from yellow grease or soy bean oil feedstocks, and 3) extensive statistical analyses indicated no statistically significant differences in HC, CO, NOx, or PM emissions between a B20 biodiesel manufactured at the naval base in Ventura County from yellow grease and CARB ULSD petroleum diesel.

Although their testing was unable to identify statistically significant air pollution benefits for use of B20 biodiesel, what they did find is that from a lifecycle cost standpoint, the use of B20 is the most cost effective method for DoD fleets to meet their alternative vehicle requirements. According to the authors, using B20 in place of petroleum diesel involves neither new infrastructure requirements nor additional environmental compliance costs – the only cost is the $0.14 higher cost per gallon to purchase the fuel.

The researchers reported the results from the project were significantly different than those previously reported by the EPA. In particular, for actual DoD fleet diesel engines, there were no statistically significant increases in NOx emissions.

UNIVERSITY-AFFILIATED STUDIES – HEAVY-DUTY DIESEL TRUCKS

A 2005 study conducted by North Carolina State University (NCSU) demonstrated a decrease in emissions of NO (a precursor to NOx) using soy-based B20. Researchers Frey and Kim conducted a pilot study to demonstrate the use of B20 biodiesel fuel on approximately 1,000 vehicles in selected areas of North Carolina. Real-world, in-use, on-road emissions of selected heavy-duty diesel vehicles, including those fueled with B20 biodiesel and petroleum diesel, were measured during normal duty cycles using a PEMS. Four categories of dump trucks were selected for testing, including: 1) single rear axle with Tier 1 engines, 2) single rear axle with Tier 2 engines, 3) tandems with Tier 1 engines, and 4) tandems with Tier 2 engines. A total of 12 vehicles were tested. Each vehicle was tested for one day on B20 biodiesel and for one day on petroleum diesel, for a total of 24 days of field measurements. The vehicles were operated by drivers assigned by the North Carolina Department of Transportation. Each test was conducted over the course of an entire workshift, and on average there were 4.5 duty cycles per shift. Each duty cycle is comprised of a uniquely weighted combination of nine operating modes (idle, three levels of acceleration, three levels of cruise, deceleration, and dumping).

Average emissions rates on a mass-per-time basis varied substantially among the operating modes. Average fuel use and emissions rates increased 26 to 35 percent when vehicles were loaded versus unloaded. Average fuel use and CO_2 emission rates were approximately the same for the two fuels, but average emission rates of NO, CO, HC, and

PM decreased by 10, 11, 22, and 10 percent, respectively, for B20 biodiesel versus petroleum diesel. The average emissions rates from the PEMS data were compared with engine dynamometer data. The two data compared reasonably well and appropriately. The role of real world duty cycles, as opposed to arbitrary test cycles, was found to be critical with respect to accurate estimation of emissions, especially for NO.

Factors that were responsible for the observed variability in fuel use and emissions include: operating mode, vehicle size, engine type, vehicle weight, and fuel. In some cases, the type of engine clearly had a significant role. In particular, NO and PM emissions rates were typically lower for Tier 2 engines than for Tier 1 engines. Recommendations were made regarding operating strategies to reduce emissions, choice of fuel, and the need for future work to collect real world duty cycle data for other vehicle types.

Transit and School Buses

MARK-IV Consulting, Inc. and Kansas State University (1998) collaborated to determine if beef tallow provided a suitable feedstock for producing biodiesel. Although many miles of on-road testing have been performed with biodiesel produced from soybean oil, this project represented the first transit fleet test with biodiesel manufactured from beef tallow.

The Kansas City beef tallow based biodiesel test program found that a 20 percent beef tallow based biodiesel blend performs similar to petroleum based diesel, as well as biodiesel manufactured from other feedstock such as soybean oil. The test results validate the use of beef tallow as a feedstock for biodiesel production by documenting operating performance compared to petroleum-based diesel fuel. Four buses fueled with a B20 blend and four control buses fueled with 100 percent conventional diesel fuel (D2) were operated for 10 months. Operational data was collected and compared for the eight test buses. Oil samples were taken throughout the duration of the project and tested as part of the standard Kansas City Area Transportation Authority (KCATA) maintenance program. Results of the engine oil analysis indicate that performance with biodiesel blends is at least as good as that of petrodiesel, if not better. Reduced wear on engine components may ultimately result in decreased maintenance costs.

Repairs and fuel economy were also monitored and documented throughout the test program. No repairs attributed to the use of biodiesel blends were made during the test. Fuel economy, which was ultimately tracked based on fuel consumption and engine hours, was similar for both the biodiesel and petrodiesel buses. Drivers reported no differences in power output and felt the biodiesel blends performed similar to the petrodiesel buses. KCATA considered the program a complete success.

The researchers found that, in addition to the ease of use, positive performance attributes and potential positive economic impacts, the use of biodiesel has positive environmental impacts by reducing pollutants such as PM, CO, smoke, HC, and other air toxics. Further, the authors recommended KCATA use the research findings to evaluate the benefits of biodiesel use against the various goals and responsibilities it must address to provide reliable and safe transportation services, while simultaneously supporting the use of alternative fuels and cleaner air.

In 2003, for his Master's thesis at Rowan University, Hearne provided the results of an investigation performed to measure school bus idle emissions in a controlled environmental chamber. At that time, the New Jersey Department of Transportation was sponsoring a research study at Rowan to develop strategies for reducing diesel emissions from mobile sources such as school buses and Class 8 trucks. Hearne's research identified the results of mobile school bus testing performed to quantify the emission reduction capabilities of various alternative fuels, such as biodiesel, ULSD, and a blend of the two, when used to fuel school buses representative of those in use in the state of New Jersey.

Hearne tested ULSD and ULSD/20 percent biodiesel and compared them to No. 2 diesel fuel in three different school buses. Test results showed that the ULSD/20 percent biodiesel mixture alone has the ability to provide emissions reductions and potential to combine with other emissions reduction technologies for further reductions. The first school bus mobile emissions cycle to represent rural, urban, and suburban region of New Jersey was also created.

From the school buses tested in this study, the following table is a summary of Hearne's results on NOx emissions:

Table A1. Percentage of Change in NOx Emissions for Tested Alternative Fuel Compared to #2 Diesel.

	NOx	
Fuel	**Engine International T444-E**	**Engine International T466**
B20	3.03%	-2.46%
ULSD	3.96%	-14.04%
ULSD/20%Bio	14.22%	-20.18%

In the effort to obtain additional alternative fuel mobile emissions data, Hearne tested three alternative fueled buses (1. B20, 2. ULSD, and, 3. Biodiesel ULSD) and one #2 petroleum diesel fueled bus on-road within the Medford, NJ school district. In addition, Hearne tested three buses at the Aberdeen Test Center using the same three alternative fuels and a baseline No. 2 petroleum diesel. The following conclusions were drawn.

- CO_2 emissions were not affected by the alternative fuels tested; however biodiesel provides CO_2 benefits because it is a renewable fuel.

- NOx emissions were slightly affected by the alternative fuels tested, however ULSD and ULSD/20 percent biodiesel allow for use of NOx reduction technologies.
- HC emissions were significantly reduced for all buses by all alternative fuels by 7 to 43 percent.
- B20 and ULSD reduced CO and PM emissions by an average of 30 to 40 percent for the T444E and Cummins engines.
- ULSD/20 percent biodiesel provided significant reductions in CO and PM emissions by 70 percent and 50 percent, respectively, for the T444E engine.
- ULSD/20 percent biodiesel reduced PM emissions by 22 percent for the DT466E engine.
- There was no affect of alternative fuels on CO emissions for the DT466E engine.
- B20 had no affect on PM emissions for the DT466E engine.
- ULSD raised PM emissions by 22 percent for the DT466E engine.

STATE AND LOCAL GOVERNMENT SPONSORED PROJECTS

In June, 1997, the Medford (New Jersey) Township Board of Education, in conjunction with the New Jersey Board of Public Utilities, Office of Clean Energy, began conducting a biodiesel school bus demonstration program involving the district-owned school buses. Half of the school bus fleet (approximately 22 buses), as well as one dump truck, operated on a blend of 20 percent biodiesel and 80 percent diesel, known as B20, while the remaining “control” vehicles operated on 100 percent petroleum diesel. After bidding the fuel and installing a separate biodiesel storage tank, refueling with B20 began in November, 1997. (A separate tank was installed, due to the need to continue refueling the control vehicles on diesel fuel). The length of time individual vehicles participated in the project ranged from 8 months to 56 months, due to the regular replacement of aging buses with newer vehicles.

Medford Township tracked each of the vehicles throughout the life of the project. Records were kept on mileage accumulated, fuel used, and oil added. Vehicles were divided into two categories — Type 1 (17 – 54 passenger capacity) and Type 2 (10 – 16 passenger capacity) buses. As there was no control vehicle for the dump truck operating on B20, results are also presented for that one truck, with no comparison to diesel vehicles.

Operating costs were divided into three main categories — maintenance, fuel, and “other”. The “other” category included licenses, insurance and depreciation. During the 56 months of the project period that involved refueling with biodiesel, the Medford

Township school district used approximately 180,000 gallons of B20. The buses operating on B20 logged nearly 1.185 million miles during this period, with no difference in basic performance between the project vehicles and the control group.

A review of the data shows that, for Type 1 buses, while the miles per gallon were slightly lower for the B20 buses (5.90 vs. 6.65), and the fuel costs slightly higher ($0.14/mile vs. $0.12/mile), the maintenance costs were lower ($0.10/mile vs. ($0.12/mile) and overall costs identical ($0.55/mile) when compared to the diesel group. For Type 2 buses, the miles per gallon were actually slightly higher for the B20 buses (10.06 vs. 9.12) when compared to the diesel buses. While fuel costs were higher ($0.09/mile vs. $0.07), other costs were lower ($0.20/mile vs. $0.22/mile) and overall costs were identical ($0.35/mile).

Public acceptance of the project was high, and it was well received by bus drivers and students. No change in daily operations was required. Both drivers and students reported a reduction in the noxious odor typically associated with standard diesel exhaust. Since the official end of the demonstration project in June 2002, Medford Township has continued to fuel its buses with B20. Because of the success of the Medford Township project, in July 2003, the State of New Jersey initiated a Biodiesel Fuel Rebate Program, geared toward local governments, state colleges and universities, and school districts.

Montreal BIOBUS Project

Biodiesel blends of B5 to B20 were tested on 155 transit buses in downtown Montreal, Canada as part of the one year BIOBUS project, from March 2002 to March 2003. The study was designed to test the use of biodiesel as a source of supply for public transit, to assess the viability of the fuel as part of the routine operation of a bus fleet, particularly in cold weather, and measure biodiesel's environmental and economic impact. The project was a joint effort by the Canadian Renewable Fuels Association, the Fédération des producteurs de cultures commerciales du Québec (FPCCQ), Rothsay/Laurenco and the Société de transport de Montréal (STM).

Over the duration of the BIOBUS project, Frontenac terminal buses consumed 550,000 liters of pure biodiesel (24 percent based on vegetable oil, 28 percent on animal fat, and 48 percent on used cooking oil) in 5 percent (B5) and 20 percent (B20) blends with petrodiesel. Despite three interruptions in blend delivery during the year, the STM did not encounter any major problems from either maintenance or a customer service standpoint.

The report includes the following findings and recommendations regarding fuel supply, emissions, maintenance and operations:

Recommendations Regarding Fuel Supply

- Follow strict multi-step filtering to prevent clogging of refueling pump filters and bus fuel system filters (suppliers must use filters whose performance has been proven by documented test procedures).

Findings Regarding Emissions Measurements

- Reduced polluting emissions, greenhouse gases (GHGs), and urban smog
- Biodiesel has the overall effect of reducing polluting and GHG emissions), be they regulated (PM, CO, total HC and NOx) or unregulated (sulfate [SO_4], polycyclic aeromatic HCs [PAH], CO2 and PM2.5), and helps reduce urban smog.
- Direct tailpipe CO_2 emissions produced with petrodiesel – Engines with mechanical and electronic fuel injection
  - Baseline GHG emissions for both engine types are roughly 2.59 kg of CO_2 per liter of STM-reference petrodiesel. Direct GHG emissions are, for all intents and purposes, only comprised of CO2 since despite their high global warming potential, direct nitrous oxide (N_2O) and methane (CH_4) emissions were negligible and completely overshadowed by CO_2.)
- Direct CO_2 Emissions Produced with Biodiesel
  - The researchers hypothesized that for every liter of pure biodiesel (B100) used to replace a liter of petrodiesel GHGs are reduced by 2.33 kg of CO_2. Based on this hypothesis, it is possible to calculate how much GHGs are reduced for each liter of B100 used to replace a liter of petrodiesel.
- Impact of Biodiesel on Urban Smog
  - Regardless of concentration or source, biodiesel can help reduce urban smog formation. Using biodiesel does not increase NOx emissions, and can even reduce them. It also substantially lowers the mass of particulate emissions and, depending on the measures taken, reduces sulfur dioxide (SO_2) emissions. This is in part because biodiesel, not containing sulfur, dilutes the proportion of sulfur in the blend the engine burns.
  - Another family of emissions that act as ozone precursors in smog formation are non-methane organic compounds, a major component of smog. Ozone-forming potential was lowered the most with animal-fat-based B5 and cooking-oil-based B20, the two blends for which the most significant NOx reductions were observed. N_2O also contributes to ozone formation though not an organic compound.
- Impact of Engine Type

- Biodiesel had the overall effect of reducing polluting emissions both for the engine with mechanical fuel injection and for the one with electronic fuel injection.

- Impact of the concentration of biodiesel in the blend.
    - Test data does not establish that emissions reductions are proportional to the concentration of biodiesel in the blend. With B20, significant reductions were generally noted.
- Impact of the Source of Biodiesel
    - Each source of biodiesel has its advantages and limitations, depending on the type of emissions considered. In other words, all sources were on a par from the emissions standpoint. Emissions tests alone do not provide sufficient basis for selecting any given source of biodiesel over another.

Findings/Recommendations Regarding Maintenance

- A training program should be implemented to instruct technical staff on the transition from petrodiesel to biodiesel. Its content should emphasize the importance of identifying the true source of a problem, particularly during the cleansing period, to achieve a correct diagnosis.
- Follow a multi-step filtering process to assure that potential blend quality issues do not affect buses. Analysis of the cause of incidents arising with 10-µm filters highlights the importance of a consistent multi-step filtering process. The determining value is the pore size of the finest filters equipping buses.
- Make effective plans for converting to B20; it is better to shift to the desired concentration from the outset rather than gradually phasing in biodiesel using weaker blends (to avoid prolonging the cleansing period).
- Biodiesel caused no bus-related mechanical problems, notably with the fuel injection system. Most buses, particularly those with 25-µm filters (and Detroit Diesel engines), went through the cleansing period without any problems. The cleansing period was longer than predicted for buses with 10-µm filters, longer still because B5 was used for three months before converting to B20.
- In certain bus models, some mechanical failures can result in symptoms similar to those associated with plugged fuel filters; it is therefore important to single out the source of the problem.

Findings Regarding Operations

- Dependability of biodiesel as a winter fuel
    - No significant change in engine efficiency was noted. The two buses having engines with electronic fuel injection used during the winter

months each were driven over 10,000 km on B20. They did not prove any more prone to problems on biodiesel than did other vehicles, even during very cold weather.

BIODIESEL EFFECTS ON ENGINES (EMISSIONS, FUEL EFFICIENCY, ECONOMICAL, ETC.)

Graboski and McCormick (1998) researched the combustion of fat and vegetable oil derived fuels in diesel engines. The fuels considered were primarily the methyl esters of fatty acids derived from a variety of vegetable oils and animal fats, and referred to as biodiesel. The economics of biodiesel production are discussed by the authors, and it is concluded that the price of the feedstock fat or oil is the major factor determining biodiesel price.

According to the researchers, the use of biodiesel in neat or blended form has no effect on the energy-based engine fuel economy. The lubricity of these fuels is superior to conventional diesel, and this property is imparted to blends at levels above 20 percent. PM emissions can be reduced dramatically through use of biodiesel in engines that are not high-lube oil emitters. NO emissions increase significantly for both neat and blended fuels in both two- and four-stroke engines. The increase may be lower in newer, lower NO, emitting four-strokes, but additional data are needed to confirm this conclusion.

Among the most important recommendations is the need for all future studies to employ biodiesel of well-known composition and purity and to report detailed analyses. The purity levels necessary for achieving adequate engine endurance, compatibility with coatings and elastomers, cold flow properties, stability and emissions performance must be better defined.

Canakci and Van Gerpen (2003) investigated the effect of the biodiesel produced from high free-fatty acid feedstocks on engine performance and emissions. Two different biodiesels were prepared from animal fat–based yellow grease with 9 percent free-fatty acids and from soybean oil. The neat fuels and their 20 percent blends with No. 2 diesel fuel were studied at steady-state engine operating conditions in a four-cylinder turbocharged diesel engine. Although both biodiesel fuels provided significant reductions in PM, CO, and unburned HC, the NOx emissions increased by 11 percent and 13 percent for the yellow grease methyl ester and soybean oil methyl ester, respectively. The conversion of the biodiesel fuel’s energy to work was equal to that from diesel fuel.

In 1995, Ahouissoussi and Wetzstein researched developing a dynamic control model for determining the present value of operating costs of biodiesel buses and its competitors, diesel, methanol, and compressed natural gas (CNG). Accordingly, their analysis aimed at comparing the expected life cycle costs of operating a transit bus fleet fueled with these alternative fuels.

The authors used a nested fixed-point algorithm model for estimating marginal operating cost for four fleets fueled with alternative fuels, biodiesel, diesel, methanol, and CNG. The method assumes that transit authorities have developed a procedure for optimally determining when a bus engine should be rebuilt or replaced. Given this optimal timing, the model estimates what the marginal cost per month should be to obtain this optimal timing. Knowledge of this marginal cost along with information on infrastructure, refueling, and any incremental bus capital costs, allows the comparison of net present value for alternative fueled buses with diesel buses. Such a comparison accounts for not only the explicit cost such as maintenance but also the opportunity cost, including loss of goodwill, associated with bus failure. Assuming a 35 percent blend, biodiesel fuel can comply with regulatory emission standards. Biodiesel fuel at prices as high as $3.00 per gallon are competitive with the other alternative fuels. A constraint on the robustness of these results is the limited data on both number of buses and months of bus operations.

> The authors' analyses revealed that biodiesel is competitive with compressed natural gas(CNG)/Diesel (dual fueled engine) and methanol fuels. However, they found it less competitive compared with petroleum diesel fuel. In summary, biodiesel fuels are less competitive to conventional fuels, but *are* competitive to other alternative fuels, i.e., CNG, LNG, fuel cells, etc. Bearing in mind this study was in 1995, the researchers believed that for biodiesel to have a likelihood of controlling a major portion of fuels markets, on-going test programs should develop a biodiesel-fueled engine that achieves PM and NOx reductions beyond those attainable from using low-sulfur diesel and catalytic converters in new engines and/or low-sulfur diesel and standard rebuild kits in existing engines.

The City of Toronto, Fleet Services Division prepared a Technology Testing Report in July 2003 concerning biodiesel fuel. The report found that B100 biodiesel fuel reduces total emissions produced, however, it can be an expensive fuel compared to regular diesel fuel depending on market conditions, and, the loss of 11.4 percent fuel efficiency increases the cost of implementing B100. In addition, information on the effect of extended use of B100 fuel on rubber seals in older diesel engines and fuel pumps suggests that a mix of petroleum diesel and biodiesel fuel may be a better choice. The reason for this, according to the University of Kentucky – College of Agriculture, Cooperative Extension Service, biodiesel blends higher than B20 can cause problems with natural rubber engine components, such as seals and hoses…however, biodiesel blends of B20 or below should not cause problems with natural rubber components, but do need periodic review to verify they are not degrading or getting hard. To summarize – B100 can damage seals and hoses made of natural rubber, while blends of B20 or below are less likely to cause damage. Nevertheless, there are total emissions reductions achieved through the use of B100 biodiesel, and the estimated price of emissions reduced is lower by using blends of biodiesel and petrodiesel.

Industry Statements/Research

In February 2003, the U.S. Engine Manufacturers Association prepared a Technical Statement on the *Use of Biodiesel Fuel in Compression Ignition Engines*. Their findings include the following.

- Depending on the biomass feedstock and the process used to produce the fuel, B100 fuels should meet the requirements of either ASTM D 6751 or an approved European specification.
- Biodiesel blends up to a maximum of B5 should not cause engine or fuel system problems, provided the B100 used in the blend meets the requirements of ASTM D 6751, DIN 51606, or EN 14214. Engine manufacturers should be consulted if higher percentage blends are desired.
- Biodiesel blends may require additives to improve storage stability and allow use in a wide range of temperatures. In addition, the conditions of seals, hoses, gaskets, and wire coatings should be monitored regularly when biodiesel fuels are used.
- Although the actual loss will vary depending on the percentage of biodiesel blended in the fuel, the net effect of using B100 fuel is a loss of approximately 5 to 7 percent in maximum power output.
- Neat biodiesel and biodiesel blends reduce particulate, HC and CO emissions and increase NOx emissions compared with petroleum-based diesel fuel used in an unmodified diesel engine.
- Biodiesel fuels have generally been found to be nontoxic and are biodegradable, which may promote their use in applications where biodegradability is desired.
- Individual engine manufacturers determine what implications, if any, the use of biodiesel fuel has on the manufacturers' commercial warranties.
- Although several factors affect the cost of biodiesel fuel, its average cost exceeds that of petroleum-based diesel fuel. The relative cost of converting an existing fleet to biodiesel blends, however, is much lower than the cost of converting to other alternative fuel.

In 1995, the National Biodiesel Board and the National Renewable Energy Laboratory together with the University of Missouri Agricultural Engineering Department collected real-world data for inclusion in the Alternative Fuels Data Center.

Qualitative and quantitative biodiesel fueling performance and operational data were collected from urban mass transit buses at the Bi-State Development Agency in St. Louis Missouri. A total of 10 vehicles were selected for fueling; 5 - 6V92 TA Detroit Diesel engines were fueled with a 20/80 biodiesel/diesel fuel blend and 5 - 6V92 TA Detroit Diesel control vehicles were fueled on petroleum based low-sulfur diesel fuel (LSD). The real-world impact of a biodiesel blend on maintenance, reliability, cost, fuel economy and safety compared to LSD was investigated for this project.

Vehicles were selected and fueling began April 14, 1994 and concluded September 15, 1995. The buses experienced small but observable differences in fuel economy and maintenance costs. Emergency road calls were few in number for both B20 and diesel fuel control buses. An analysis of the engine lubricating oil indicated that the wear metals normally found in the B20 fueled buses were quite similar to those in the diesel control buses. The unmodified DDC 6V92TA engines produced lower levels of CO, HC, and PM. Slightly higher levels of NOx were noted, however, the increase was not different from the emissions that were recorded for the diesel control buses.

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APPENDIX B: EMISSIONS CHARTS

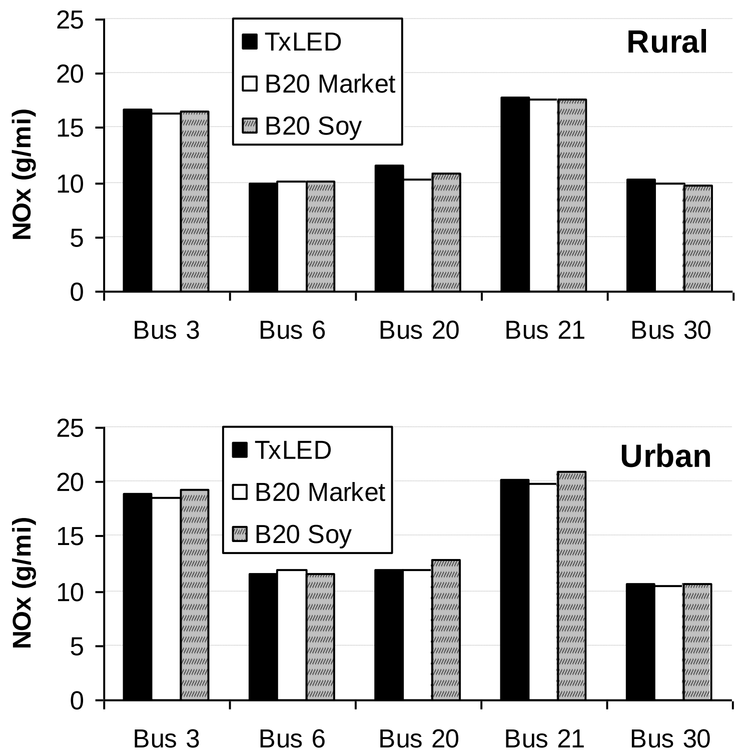

Figure B1. Average Individual Bus Mass NOx Emissions Rates.

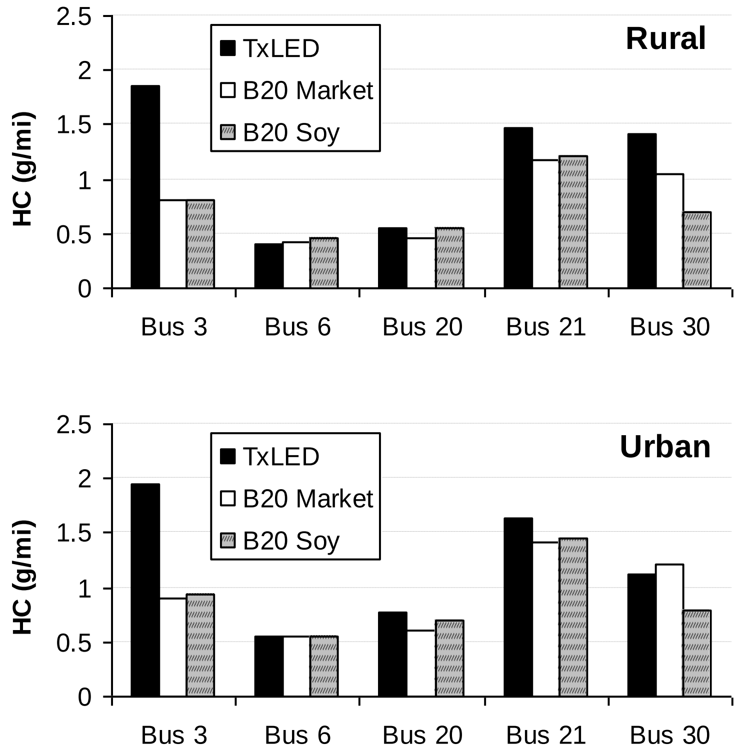

Figure B2. Average Individual Bus Mass HC Emissions Rates.

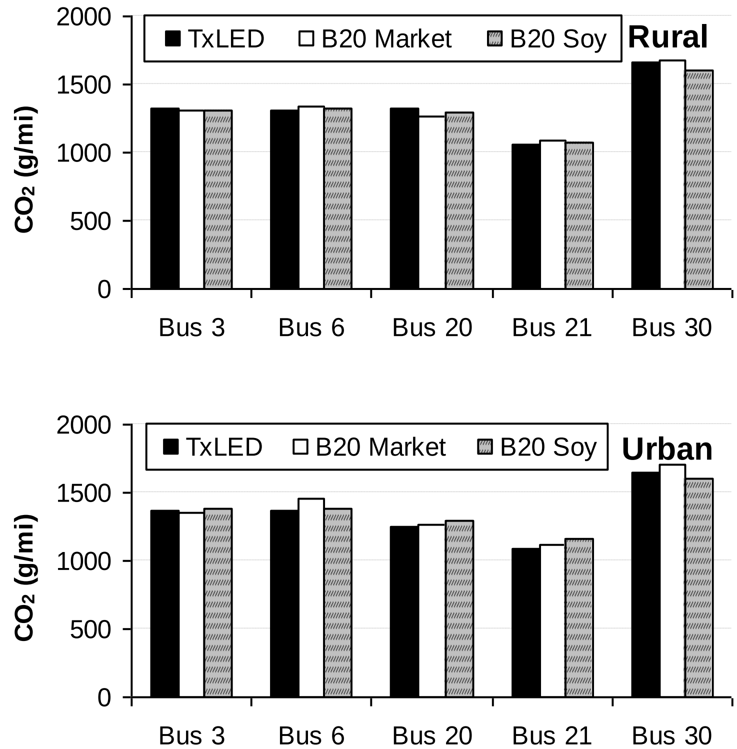

Figure B3. Average Individual Bus Mass CO_2 Emissions Rates.

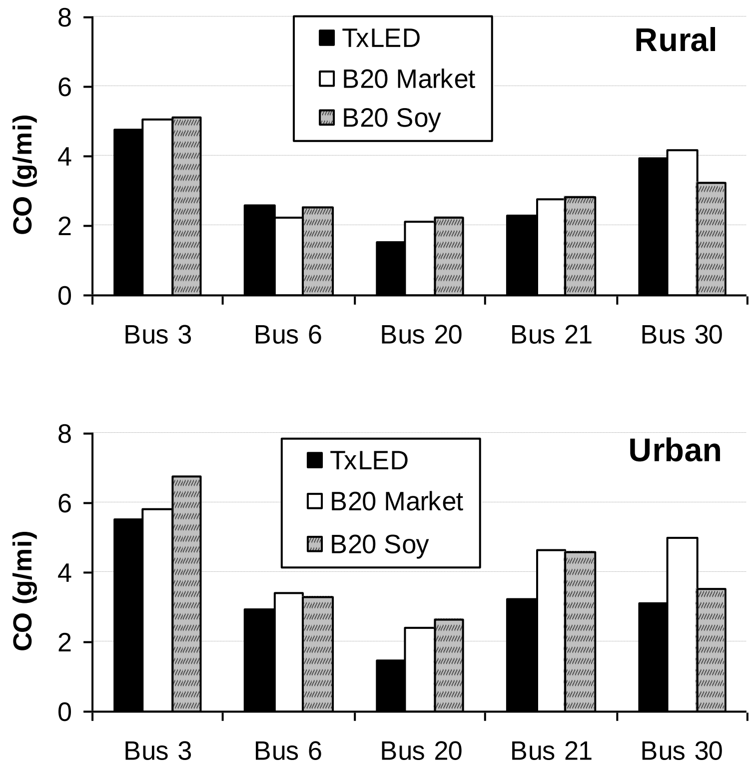

Figure B4. Average Individual Bus Mass CO Emissions Rates.

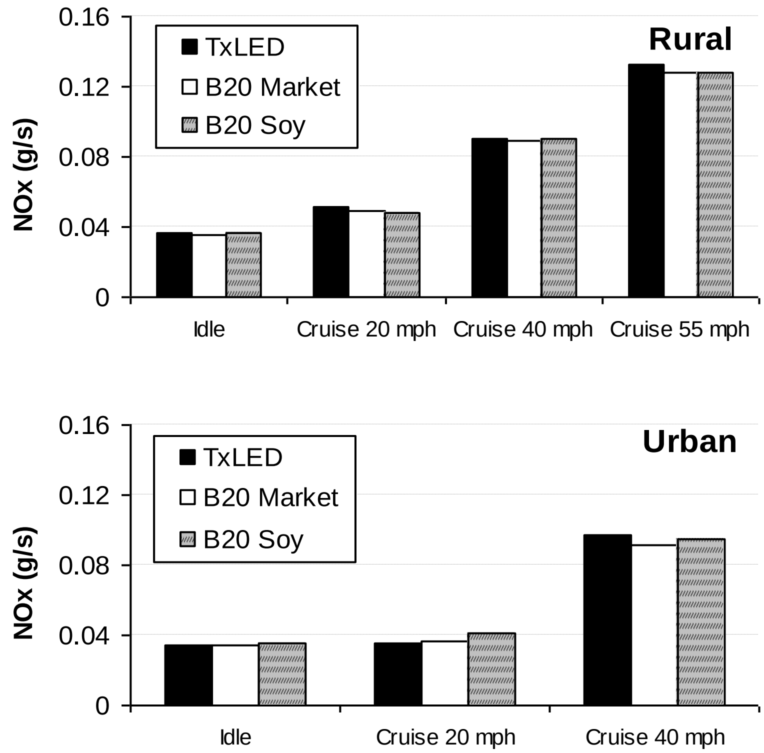

Figure B5. Average Texas Fleet NOx Emissions Rates for Different Stable Speeds.

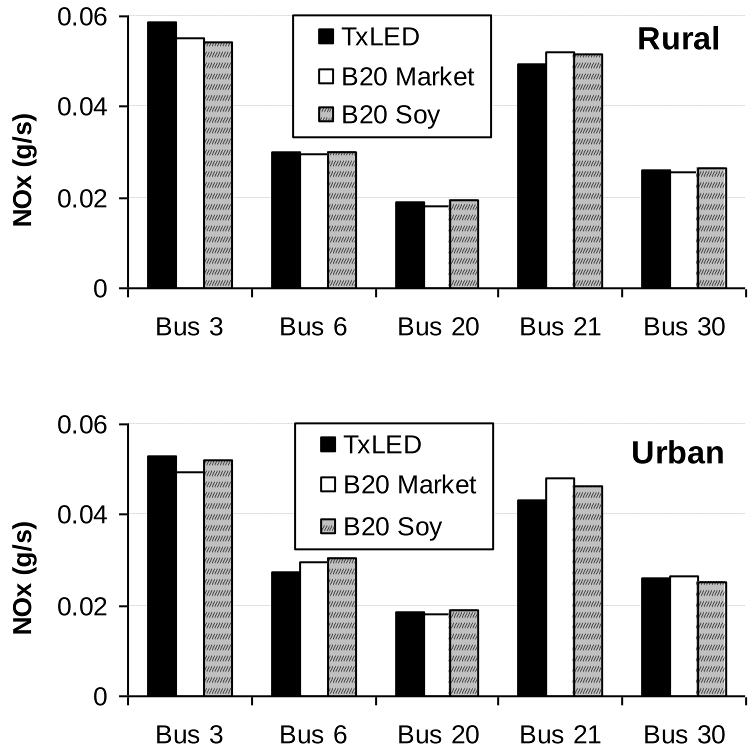

Figure B6. Individual Bus Average NOx Idling Emissions Rates.

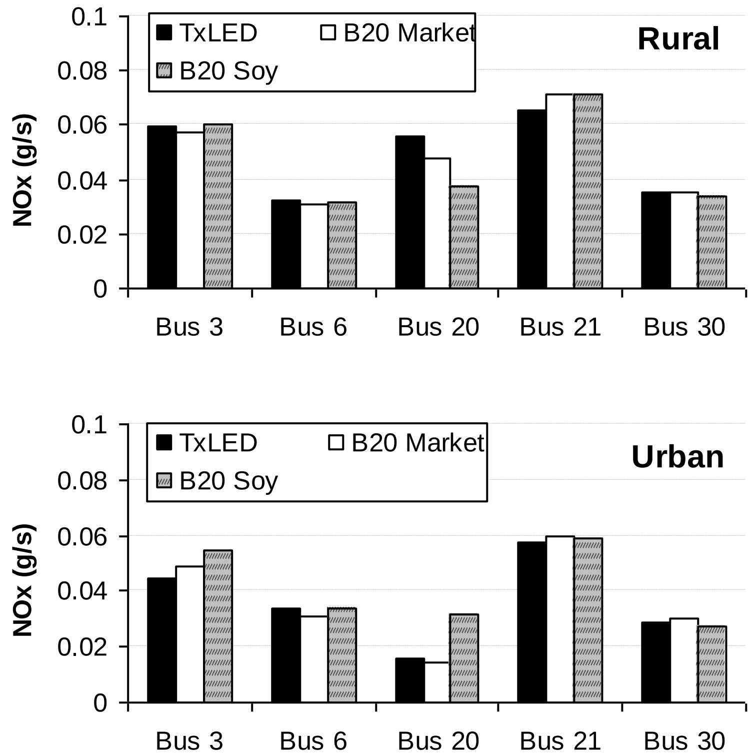

Figure B7. Individual Bus Average NOx Emissions Rates for Cruising at 20 mph.

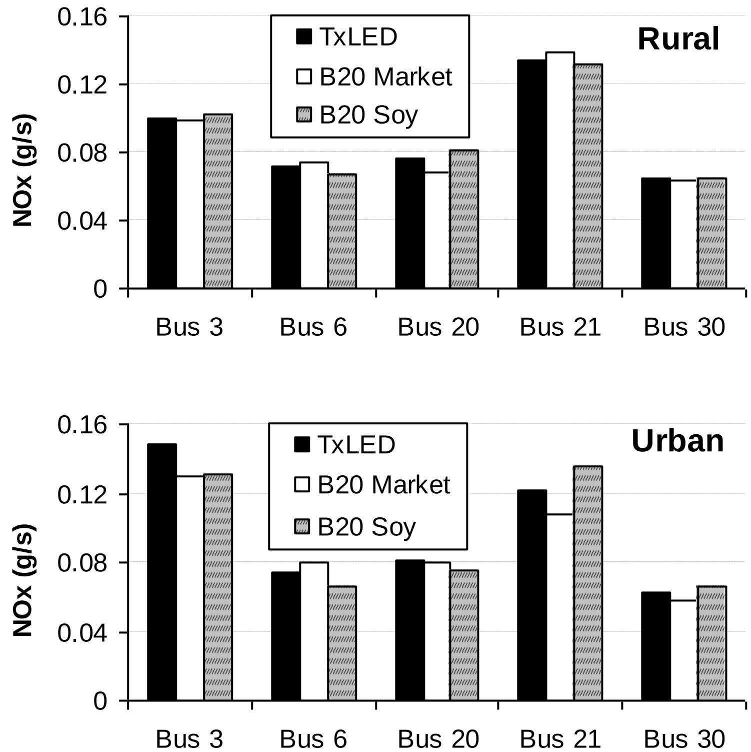

Figure B8. Individual Bus Average NOx Emissions Rates for Cruising at 40 mph.

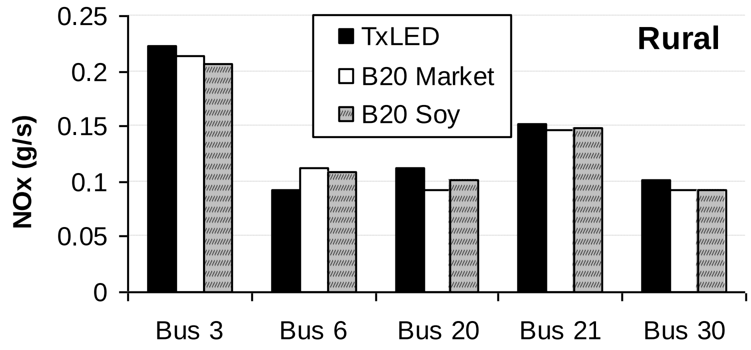

Figure B9. Individual Bus Average NOx Emissions Rates for Cruising at 55 mph.