Progress Report:
Toledo Area Regional Transit Authority (TARTA)
and the City of Toledo
Biodiesel Study

June 30, 2007

(This Progress Report is based on data collected in the first one-third of the project.)

Sponsor: Congresswoman Marcy Kaptur – her vision and support are vital to this project.

Partners: TARTA, the City of Toledo, the Intermodal Transportation Institute at The University of Toledo, H2 Engine Systems, Shrader Tire and Oil, Chevron, Biodiesel Partnership for Renewable Energy
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Executive Summary
Progress Report: Toledo Area Regional Transit Authority (TARTA) and the City of Toledo Biodiesel Study
June 30, 2007

(This Progress Report is based on data collected in the first one-third of the project.)

With the vision and leadership of Congresswoman Marcy Kaptur, the Toledo Area Regional Transit Authority (TARTA) and the Intermodal Transportation Institute (ITI) at the University of Toledo developed a long-term, large scale comprehensive research project to understand and assess the impacts of using a mixture of renewable biofuel and diesel fuel (B-20: 20% biofuel and 80% ultra-low sulfur diesel) compared to ultra-low sulfur diesel. The following factors make this study unique.

1. This is the first study that does on-road testing of ultra-low sulfur diesel and the first attempt to investigate the impact of using B-20 made with ultra-low sulfur diesel.
2. The testing is exhaustive including nearly 60 vehicles over a three year period and involves more than 5 million miles of operation.
3. With three years of data, it is possible to estimate and compare the life cycle costs of using ultra-low sulfur (ULS) diesel fuel versus B-20 made with ULS diesel.
4. In addition to tail pipe emission testing, this study examines in-bus air quality. Using these data, the study attempts to create a model to estimate the impact of in-bus air quality on health and wellness.
5. This is the first study that examines the use of hydrogen gas as an additive to B-20.

The purpose of the study is to investigate the impact of using ULS diesel and B-20 made with ULS diesel on engine emissions and air quality inside the bus as well as on operating costs including fuel economy and maintenance costs. In addition, the impact on engine wear is assessed by examining the metal content of the engine oil after each oil change. These cost factors are combined to estimate and compare the total life cycle costs of operating vehicles on ULS diesel fuel and B-20 made with ULS diesel. During the study, 48 buses from TARTA and 10 vehicles from the City of Toledo will be part of the research.

Assess the Use of B-20
For both TARTA and the City of Toledo, switching costs were minimal. The only precaution was to run the vehicles until the tanks, which contained diesel, were nearly empty before filling them with B-20 made with ULS diesel. During the changeover, no problems were experienced. For TARTA and the City of Toledo, there have been minimal problems with the use of B-20. As experienced in other studies, fuel filters became plugged as B-20 dissolved some of the sediment in the fuel system. This was easily addressed. The mechanics at the City of Toledo felt that there was an improvement in smell and engine noise when B-20 was used compared to ULS diesel. The mechanics and supervisors at TARTA indicated that there was no difference between ULS diesel and B-20 with respect to these items. Drivers at both TARTA and the City of Toledo felt that B-20 was an improvement over ULS diesel in engine operations, smell inside the bus, and engine noise.
Performance and Costs
For the City of Toledo, there was an improvement in miles per gallon (mpg) for B-20 over ULS diesel. The differences were large enough to offset the higher cost for B-20 compared to ULS diesel. (A positive percent indicates that B-20 has a higher value, either mpg or fuel costs, than ULS diesel and a negative percent indicates that B-20 has a lower value.) With respect to engine maintenance on the three City of Toledo vehicles currently in the study, two vehicles did not have any engine related maintenance during the study. The Crane LET-2 vehicle had a significant problem with the fuel injector pump and the fuel pump accumulator. After a significant amount of investigation, maintenance staff and management at the City of Toledo determined that this problem was not related to the use of B-20. In fact, four other Crane LET-2 vehicles that were not using B-20 had the same failure. It was judged that the maintenance costs for this vehicle is an outlier that does not support a cause and effect relationship between the fuel and engine maintenance. The City of Toledo data compares January 1, 2007 – April 26, 2007 for B-20 to January 1, 2006 – April 26, 2006 for ULS diesel.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>MPG</th>
<th>Fuel Costs ($/mi)</th>
<th>Engine ($/mi) Maintenance</th>
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<tbody>
<tr>
<td></td>
<td>B-20</td>
<td>ULS</td>
<td>Change</td>
</tr>
<tr>
<td>Ford F-250</td>
<td>12.38</td>
<td>11.15</td>
<td>11.0%</td>
</tr>
<tr>
<td>Crane LET-2</td>
<td>2.67</td>
<td>2.53</td>
<td>5.53%</td>
</tr>
<tr>
<td>Mack MR6885</td>
<td>2.46</td>
<td>2.29</td>
<td>7.42%</td>
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For TARTA, the fuel economy results were mixed. (A positive percent indicates that B-20 has a higher value, either mpg or fuel costs, than ULS diesel and a negative percent indicates that B-20 has a lower value.) For the Bluebird buses, mpg was higher for the buses using B-20 compared to buses using ULS. This is true regardless of route type (stop-and-go versus over the road). For the Thomas buses, the opposite is true. This seems to indicate that engine type/manufacturer makes the difference in mpg.

<table>
<thead>
<tr>
<th>Type of Trip</th>
<th>MPG</th>
<th>Fuel Costs ($/mi)</th>
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<tbody>
<tr>
<td></td>
<td>B-20</td>
<td>ULS</td>
</tr>
<tr>
<td>Stop-and-Go (Thomas)</td>
<td>4.36</td>
<td>4.65</td>
</tr>
<tr>
<td>Stop-and-Go (Bluebird)</td>
<td>4.58</td>
<td>4.45</td>
</tr>
<tr>
<td>Over the Road (Thomas)</td>
<td>5.21</td>
<td>5.60</td>
</tr>
<tr>
<td>Over the Road (Bluebird)</td>
<td>5.03</td>
<td>4.65</td>
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On the Thomas buses in the TARTA fleet, engine related maintenance was $0.0226/mile for the buses using B-20 and $0.0375/mile for buses using ULS diesel. This is based on 9.5 months of data and about 700,000 miles of operation. For the Bluebird buses, engine related maintenance was $0.0321/mile for buses using B-20 and $0.0142/mile for buses using ULS diesel.
With respect to engine wear for the TARTA fleet, oil test data were collected for fifteen B-20 and twelve ULS Thomas buses from October 1, 2006 to May 8, 2007. This was done when the engine oil was changed. Analysis of the engine oil was conducted by Staveley Services, an expert in fluid analysis. The results showed that in 11.9% of the cases, buses using B-20 had a reading that was greater than normal compared to 17.7% for the buses using ULS diesel.

Abnormal is defined as being above a standard determined by Staveley. For both B-20 and ULS diesel, the average for each of the metallic components in the oil is much lower than the standards. On the average, there is one statistically significant difference between the amounts of metal found in the engine oil. Lead is higher when B-20 is used than when ULS is used. However, both levels (B-20: 4.99 ppm and ULS diesel: 1.56 ppm) are substantially below the standard (50 ppm). The research team consulted with experts at Detroit Diesel, who manufacture diesel engines for buses and trucks, and they suggested that both of these values are well below the standard and do not give an indication of excessive wear. The research team will continue to investigate this important area.

There are insufficient data to develop life cycle costs. These estimates will be developed next year as more data becomes available.

Environmental Impact Assessment
The research examines the environmental impact of operating these vehicles including tail pipe emissions, in-bus air quality, and the impact of using different feedstock for biodiesel. At this point in the study, the last item has not been addressed.

A successful emission testing protocol was developed for characterizing emission characteristics from public transport buses. The protocol identifies the important influencing factors that affect vehicular emissions during real world operating conditions. Emission testing was performed in three stages: (1) a standard emission test protocol (CBD cycle performed on a chassis dynamometer), (2) engine idling, and (3) a sample daily operating run/route of TARTA buses. The procedure also presents a feasible comparison strategy to analyze the effect of alternative diesel fuels on vehicular emission. Emission comparison for TARTA buses showed that although B-20 biodiesel in comparison to ULS diesel fuel emitted higher concentrations of nitric oxide (NO) and nitrogen dioxide (NO₂) for 300 series (Bluebird), and lower carbon monoxide (CO) concentration for both 300 (Bluebird) and 500 (Thomas) series fleets, other factors such as the engine’s operating conditions, preventative maintenance history, vehicle operation in different engine loads and engine operating temperatures had a larger influence on emission behavior. Regular engine idling mode and higher engine temperatures were found to reduce vehicular emissions most significantly (up to 30-42%) while performing preventative maintenance reduced emission concentrations by 15-20%. Engine temperatures, exhaust temperature, accelerator pedal position, percent of engine load and engine rpm were the most important variables affecting the concentrations of the pollutants studied.

This study was also able to characterize the indoor air pollutant behavior inside public transport buses during daily operational runs. Comparison of indoor and outdoor
concentrations showed that outdoor concentrations strongly influenced the indoor concentrations and were consistently higher than the indoor concentrations during the runs. Analysis also showed that pollutant concentration at the rear end of the bus was two to seven times the front end concentration. Particulate matter analysis indicated that the indoor concentration of fine particulates in both the B-20 biodiesel and ultra-low sulfur diesel buses were identical, and the concentrations depend primarily on ambient particulate matter (PM) concentrations and not on the type of fuel used in the buses. The results also showed that the PM$_{1.0}$ mass was comprised of approximately 40% of the particles between 0.30-0.40 µm, 25% of the particles between 0.40-0.50 µm, and 35% of the particles between 0.50 and 1.0 µm in diameter.

The indoor pollutant concentrations were analyzed against important operating conditions such as traffic, passenger counts and activity, bus operation status (idling/running), door position (open/closed) and ambient meteorology to study the influence of each variable on the pollutants. Three hourly concentration models were developed for predicting indoor gaseous air pollutant concentrations using the most significant variables. Regression models developed for particulate matter using nine variables (total passenger counts, cars and bus/trucks ahead, bus status (idle/running), door status (open/closed), ambient PM$_{2.5}$ concentrations, visibility (as a measure of outdoor particulate highs), temperature, relative humidity and wind speed) explained approximately 86-89% of the hourly indoor mass concentrations of fine particulates.

**Hydrogen Enhancement Project**

The primary objective of the Hydrogen Enhancement Project is to identify and demonstrate novel techniques that can effectively and efficiently provide a vehicle fleet operator with a solution that reduces the annual fuel cost, reduces exhaust emissions and enables the better use of renewable energy products. The vehicle has been modified and is prepared as a sophisticated mobile test bed. To date, the limited test data acquired when driving around the Toledo area shows an improvement in fuel economy of at least 10%. The testing has been of limited duration but has included high speed operation around the I-75 and I-475 road system. The vehicle hydrogen enhancement system needs to be optimized and the hydrogen gas supplied to the engine derived from either electrolyzed water or fuel cracked syngas in order that a safe and economic system is created.

Projecting the benefits to a fleet of 173 buses, and using the 2006 TARTA annual records for average fuel economy of 4.08 mpg and average vehicle usage of 25,000 miles and fuel purchased at $2.20 per gallon, then the following is possible:

- The annual savings in fuel purchased with a 10% improvement in fuel economy will be $233,100 for the fleet.
- This represents an annual reduction of 1.17 thousand tons of carbon dioxide emissions for the fleet.

(The dollars saved are gross estimates and do not include the cost to retrofit the engines.)

The one further benefit from using hydrogen gas is the improved efficiency of engine operation which can be directed to producing greater power from a given engine. This characteristic enables the use of lower calorific (energy content) fuels such as B-50 and even
B-100 without degrading the performance of the vehicle in normal operation. This has the advantage that a vehicle fleet operator such as TARTA could eventually operate all its vehicles on fully renewable fuels.

**New Activities Planned For Year 2**

1. Resolve TARTA fuel data collection concerns and increase dramatically the amount of data available for analysis of fuel consumption and fuel costs.

2. Identify the type of bus routes to determine if there is a relationship between the route (stop-and-go or over the road) and fuel economy.

3. Investigate the differences in fuel economy between vehicles with different engines: Thomas buses versus the Bluebird buses, and TARTA buses and City of Toledo vehicles.

4. Conduct detailed analysis of maintenance costs to determine if there is a relationship between the type of fuel used and engine related maintenance.

5. Expand the number of City of Toledo vehicles in the program so side-by-side comparisons can be done.

6. Conduct in-vehicle testing of air quality for the City of Toledo vehicles.

7. Perform tailpipe testing for buses on specific routes.

8. Investigate different levels of biodiesel from B-5 up to B-100.


10. Investigate the possibility of using additives in ULS diesel and in B-20 to determine if there are differences in fuel economy and emissions.

11. For the hydrogen boost project, conduct additional testing on the rolling dynamometer, tail pipe emissions, and fuel economy.
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and the City of Toledo
Biodiesel Study

June 30, 2007
OVERVIEW AND BACKGROUND

With the vision and leadership of Congresswoman Marcy Kaptur, the Toledo Area Regional Transit Authority (TARTA) and the Intermodal Transportation Institute (ITI) at the University of Toledo developed a long-term, large-scale comprehensive research project to understand and assess the impacts of using a mixture of renewable biofuel and diesel fuel (B-20: 20% biofuel and 80% ultra low sulfur diesel) compared to ultra-low sulfur diesel.

There are several factors that combine to make this study unique.

1. This is the first study that does on-road testing of ultra-low sulfur diesel, which is the required fuel for all diesel vehicles manufactured in 2007 and beyond. It is also the first attempt to investigate the impact of using B-20 made with ultra-low sulfur diesel.
2. The testing is exhaustive. It includes nearly 60 vehicles over a three year period and involves more than five million miles of operation.
3. With three years of data collected over the life of the study, it is possible to estimate and compare the life cycle costs of using ultra low sulfur (ULS) diesel fuel versus B-20 made with ULS diesel.
4. In addition to tail pipe emission testing, this study examines in-bus air quality. Using these data, the study attempts to create a model to estimate the impact of in-bus air quality on health and wellness.
5. This is the first study that examines the use of hydrogen gas as an additive to B-20. This portion of the study is done with a single vehicle because significant modifications are needed so the vehicle can accept hydrogen through the air intake system.

Vehicular pollution has increased in the past years as the number of vehicles on the road has increased. The emissions from vehicles contribute to serious particulate and ozone pollution that pose a severe global air pollution problem. Various emissions from vehicles such as nitrogen oxides (NOx), sulfur dioxides (SO2) and hydrocarbons (HC) are identified threats to the human health and environment in addition to being precursors to ozone and secondary particulate formation.

Diesel emissions are also very high in primary particulate matter (PM) emissions that need to be controlled. Several EPA emission regulations and control strategies have been implemented to reduce vehicular emissions over the past years, the most recent one being implemented on January 1, 2007. The current regulation requires a 97 percent reduction in the sulfur content of highway diesel fuel.

Since June 1st 2006, the EPA has required all refineries in the United States to produce a minimum of 80% of their fuel as ULS diesel which has a maximum sulfur content of 15 parts per million (ppm). This fuel, in comparison to low sulfur diesel which has a maximum of 500 ppm of sulfur, is a big step forward to reduce the pollution generated by diesel operated engines. ULS diesel, which is the only fuel specified to be used with advanced sulfur-sensitive emission control equipment introduced in 2007, plus newer diesel vehicles, together...
can reduce the solid particle emissions by up to 99% and more than 90% of semi-volatile hydrocarbons.

Purpose

The purpose of the study is to investigate the impact of using ULS diesel and B-20 made with ULS diesel on engine emissions and air quality inside the bus as well as on operating costs, including fuel economy and maintenance costs. In addition, the impact on engine wear is assessed by examining the metal content of the engine oil after each oil change. These cost factors are combined to estimate and compare the total life cycle costs of operating vehicles on ULS diesel fuel and B-20 made with ULS diesel. This study involves 48 buses from TARTA and 10 vehicles from the City of Toledo. The TARTA buses are divided into two groups with one group using ULS diesel and another using B-20 made with ULS diesel.

During the study, the following factors will be measured, evaluated, and discussed.

1. Use of B-20:
   • Start-up problems: What, if any, were encountered in switching from diesel to biodiesel?
   • On-going problems: Were any encountered in using biodiesel?
   • Vehicle service: How did the mechanics and their supervisors react to servicing vehicles that burned biodiesel?
   • Driver reaction: What was the driver’s reaction to the use of biodiesel, especially power and performance?

2. Performance and Costs:
   • Methods used to gather data and to ensure accuracy – an overview.
   • Miles per gallon and fuel cost per mile for TARTA and the City of Toledo.
   • Maintenance costs for TARTA and the City of Toledo.
   • Engine wear for TARTA.
   • Life cycle costs.

3. Environmental Impacts:
   • Methods used to gather data and to ensure accuracy – an overview.
   • In-bus air quality.
   • Tail pipe emissions.
   • Impact of using different feedstock for biodiesel.

4. Hydrogen Enhancement Project:
   • Technology and anticipated outcomes - brief and simplified statement
   • Modifications made to the bus – an overview.
   • Methods used to gather data and to ensure accuracy – an overview.
   • Impact of the addition of hydrogen on fuel economy.
   • Impact of the addition of hydrogen on emissions.
Implementation And Preparation

Efforts to initiate the study began in the late summer of 2005. These efforts can be grouped into three areas: infrastructure, information gathering and instrumentation, and team development. To enable TARTA to store adequate quantities of ULS diesel and B-20 made with ULS diesel, as well as standard diesel, it was necessary to rework its fuel storage system and to create a mechanism to dispense B-20. This was pivotal to the project because all of the vehicles, both the City of Toledo vehicles as well as the TARTA buses, would fuel at this new island.

To ensure that the large amount of data needed by the study design could be accurately and efficiently collected, computerized electronic systems were installed on the buses. It was essential to verify that TARTA’s information systems received, stored, and provided accurate data; initial tests were done to verify results. The instrumentation used to assess in-bus air quality was calibrated, tested, and recalibrated to ensure that the data collected by these instruments were accurate.

In addition to the technology, it was essential to bring together a team to carry out the work. World Energy was selected as the supplier of the B-20. Shrader Tire and Oil joined with Chevron to donate all of the engine oil testing. Conversations with engine suppliers were held to ensure that using B-20 would not impact warranties. These tasks were completed by March 1, 2006, when the first bus was fueled with B-20.

USING BIODIESEL

At this time, the City of Toledo has three vehicles operating on B-20 made with ULS diesel: a 2003 Ford F-250 pickup truck with a 6.0 liter power stroke diesel, a 2003 Mack MR6885 refuse packer with a 12.0 liter Mack Diesel, and a 2001 Crane LET – 2 recycle truck with an 8.3 liter Cummins Diesel. TARTA is using 38 Thomas buses with 2003 Detroit Diesel MBE 900 engines and 10 Bluebird buses with 2006 Cummins ISB 5.9 liter engines. Half of each type are using ULS diesel and the other half are using B-20 made with ULS diesel.

Change-Over Problems
For the City of Toledo, switching costs were minimal. In all three cases, levels in the diesel fuel tanks were allowed to reach the lowest level possible and the next fueling was done with B-20. During the change over, no problems were noticed in any of the cases.

For TARTA, switching costs were also minimal. Fuel levels were allowed to drop to very low levels in the buses that would use B-20 before they were filled with B-20. During the changeover, no problems were noticed.

On-Going Problems

For the City of Toledo, there have been no on-going problems with the use of biodiesel, no engine or fuel system related maintenance costs, and no cold weather gelling problems with
the 2003 Ford F-250 or with the 2003 Mack MR6885 refuse packer. The 2001 Crane LET-2 recycle truck experienced no cold weather gelling problems, but there have been some fuel related problems. After nearly three months of operation, the fuel filter became plugged causing a loss in power. This happened for the second time about two and a half months later. This problem appears to be caused by the B-20 acting as a solvent to clean out deposits that have built up over time in the fuel system. This problem has been noted in other studies. This was the oldest vehicle (2001) that was switched from straight diesel fuel to B-20 which may explain the reason for this isolated problem. About five months after the changeover, there also was a problem with the fuel injection pump and the fuel pump accumulator on this vehicle. They were replaced and no new problems have been observed after three months of operation. The pump accumulator has failed on three similar vehicles that had not been switched to B-20, therefore, the mechanics at the City of Toledo do not attribute this failure to the change from diesel to B-20.

For TARTA, there have been minimal problems with the use of B-20 made with ULS diesel. After a short period of time, the fuel filters became plugged. This was corrected by altering the Preventive Maintenance Interval (PMI) so the fuel filters are changed every three months. TARTA reported no problems associated with gelling during winter months, even at zero degrees Fahrenheit and below. It should be noted that the TARTA vehicles are kept in a heated garage overnight.

Mechanics’ Perspective on B-20

For TARTA, a preliminary survey questionnaire was developed and administered to two mechanics and their supervisors. Based on the feedback from them, the questionnaire was modified. Questionnaires were sent to all the mechanics at TARTA (eleven in total) regarding their perspectives on B-20 compared to ULS diesel; everyone responded. Overall, from the mechanics’ point of view, there is no difference between B-20 and ULSD. For each of the following conditions, the mechanics saw no difference.

1. Smell of B-20 during maintenance
2. Smell of engine oil during scheduled maintenance
3. Frequency of engine oil topping
4. Frequency of engine oil change
5. Engine oil cleanliness
6. Engine noise with B-20
7. Frequency of unscheduled maintenance
8. Severity of unscheduled maintenance
9. Eye comfort during maintenance
10. Comfort of hands during maintenance

Because a smaller number of vehicles are using B-20 at the City of Toledo, inputs were directly gathered from the mechanics working on those vehicles. They felt the vehicles running on B-20 ran smoother and quieter and that the odor was less offensive than similar vehicles using ULS diesel. (It should be noted that the response of the mechanics at the City
of Toledo are more typical of observations made by mechanics in other studies using biodiesel.)

Drivers’ Perspective on B-20

For TARTA, the preliminary questionnaire for the drivers was given to their supervisor to gain feedback and was modified based on the response. Next, the questionnaires were placed in the drivers’ mailboxes and then collected by the supervisor. They were asked to compare B-20 to ULS diesel. The response rate was poor at 3.3%. (The survey will be repeated during the second year to improve the response rate.) The average results of this survey are shown below:

1. Engine start-ability  No difference between B-20 and ULSD
2. Engine feels smooth  B-20 is slightly better than ULSD
3. Smell inside the bus  B-20 is slightly better than ULSD
4. Engine noises  B-20 is slightly better than ULSD
5. Frequency of breakdown  No difference between B-20 and ULSD
6. Severity of breakdown  B-20 is slightly better than ULSD
7. Engine power  B-20 is slightly better than ULSD
8. Fuel consumption (mpg)  B-20 is slightly better than ULSD

Overall, the drivers’ perspective is that B-20 is slightly better than ULSD.

Drivers at the City of Toledo felt the engines ran smoother and quieter on B-20 than on ULS diesel. They noticed no loss of power with B-20 compared to ULS diesel. They also felt that the exhaust smell was less offensive.

PERFORMANCE AND COSTS

The overall study was designed to investigate the impact of a mixture of renewable biofuel and diesel fuel on operating costs, as well as engine performance and expected life, in a subset of the TARTA bus fleet and City of Toledo vehicles.

Design of the Study

Fuels
Two fuels were evaluated: (1) ULS diesel fuel and (2) B-20, a mix of ULS diesel fuel (80%) and biofuel (20%).

Vehicles
The fuels are being used in 48 buses at TARTA (38 Thomas buses and 10 Blue Bird buses). The vehicles are divided into two groups of equal size, one using ULS fuel and the other using B-20. In addition, three vehicles (one Ford F-250 truck, one Mack MR688S refuse packer, and one Crane LET-2 recycle truck) from the City of Toledo are included in the study.
Data Collection

The following data on performance and costs were collected during the period covered in this report ending June 30, 2007. Data collection will continue into year two of the study.

Fuel Data (Collected each time a vehicle is fueled.)
- Type of fuel
- Amount of fuel
- Odometer reading

Oil Added Data (Collected each time oil is added.)
- Make, type and viscosity of oil
- Amount of oil
- Odometer reading

Oil Changed Data (Collected each time oil is changed.)
- Make, type and viscosity of oil
- Amount of oil
- Odometer reading
- Oil sample analysis data

Cost Data
The following elements were identified by TARTA personnel and the study team as items that could have an impact on the operation, repair, and maintenance of the vehicles.

1. Cost per gallon for each type of fuel
2. Repair costs: air intake system, cooling system, radiator, fan, water pump, thermostats, coolant pre-heater engine, fan clutch, fan drive, exhaust system, emission controls, fuel system, tank and pump.
3. Maintenance costs.
   a. TARTA does regular preventive maintenance on their vehicles at the recommended periods (3 months) or mileage intervals. There are three levels of service: A, B, and C. Service A is typically lubrication, oil, and filter change. Additional services like brake service etc., are done under B and C. Usually B and C are performed along with A. Typically, every three months A-B or A-C maintenance is performed. An analysis of the costs, spring 2004 through winter 2005 by quarter, showed that the maintenance costs accounted for nearly two thirds (64.1%) with B service the most frequent service followed by A and C.
   b. On the City of Toledo vehicles, preventive maintenance is performed every 4,500 miles.

Problems with Data Collection

The collection of repair and maintenance cost data did not present many problems. There were some initial problems in accessing the TARTA data base, but they have been resolved.
Base line data for the repair and maintenance costs on the vehicles were established before the use of biofuels was started.

Regarding the mileage and fuel usage data, in the beginning it appeared the data collection would be simple as the required data on fuel (type, amount, and odometer reading) should be available from the data base maintained by TARTA. Remote access to these data has proven only partially successful because part of the data base can be observed but not digitally transferred. Second, there were data reporting problems and missing data on mileage and fuel usage. To verify the accuracy of the database on fuel usage and mileage, data have been collected manually for this report. Efforts are underway to fix this data problem. The data from the City of Toledo has been reliable.

**Fuel Cost History**

The following table and graph show TARTA’s costs for ULS diesel and B-20 made with ULS diesel. The spread between the two fuels has been between 4.2 and 19.2 cents per gallon. The average spread over the eight month period is 11.3 cents per gallon. This represents only a 5.7% increase in the cost of B-20 compared to ULS diesel.

**Comparative Cost of B-20 to USL Diesel**

*(in $’s)*

<table>
<thead>
<tr>
<th>Month</th>
<th>B-20</th>
<th>ULS</th>
<th>Difference (B-20 - ULS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oct-06</td>
<td>2.039</td>
<td>1.859</td>
<td>0.180</td>
</tr>
<tr>
<td>Nov-06</td>
<td>2.081</td>
<td>2.002</td>
<td>0.079</td>
</tr>
<tr>
<td>Dec-06</td>
<td>2.039</td>
<td>1.906</td>
<td>0.133</td>
</tr>
<tr>
<td>Jan-07</td>
<td>1.759</td>
<td>1.717</td>
<td>0.042</td>
</tr>
<tr>
<td>Feb-07</td>
<td>1.961</td>
<td>1.837</td>
<td>0.125</td>
</tr>
<tr>
<td>Mar-07</td>
<td>2.239</td>
<td>2.047</td>
<td>0.191</td>
</tr>
<tr>
<td>Apr-07</td>
<td>2.260</td>
<td>2.209</td>
<td>0.050</td>
</tr>
<tr>
<td>May-07</td>
<td>2.325</td>
<td>2.222</td>
<td>0.103</td>
</tr>
<tr>
<td>Average</td>
<td>2.088</td>
<td>1.975</td>
<td>0.113</td>
</tr>
</tbody>
</table>
MPG and Fuel Cost per Mile for TARTA Buses

Comparison of Average MPG (Thomas Buses – Stop-and-Go)
Data were collected for 15 buses using B-20 and 13 using ULS. The mpg for each bus group was calculated. Fuel cost/mile is based on the prices provided by TARTA: B-20 = $2.088/gallon, ULS diesel = $1.975/gallon. (These are the average costs from October 2006 to May 2007 as shown in the table above.)

- For the Thomas buses, the average mpg for the buses using B-20 is 6.24% lower than the mpg for buses using ULS.
- For the Thomas buses, the average fuel cost/mile for the buses using B-20 is 12.7% higher than the cost per mile for buses using ULS

### MPG for Thomas Buses (Stop-and-Go): April 10, 2007

<table>
<thead>
<tr>
<th>B-20 Buses</th>
<th>ULS Buses</th>
<th>Difference*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Buses</td>
<td>MPG</td>
<td>Number of Buses</td>
</tr>
<tr>
<td>15</td>
<td>4.36</td>
<td>13</td>
</tr>
</tbody>
</table>

* MPG Difference = (MPG of B-20 bus minus MPG of ULS bus) / MPG of ULS bus x 100

### Fuel Cost for Thomas Buses (Stop-and-Go): April 10, 2007

<table>
<thead>
<tr>
<th>B-20 Buses</th>
<th>ULS Buses</th>
<th>Difference**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Buses</td>
<td>Fuel Cost/Mile</td>
<td>Number of Buses</td>
</tr>
<tr>
<td>15</td>
<td>$0.479</td>
<td>13</td>
</tr>
</tbody>
</table>

** Fuel Cost/Mile Difference = (Fuel Cost/Mile of B-20 bus minus Fuel Cost/Mile of ULS bus) / Fuel Cost/Mile of ULS bus x 100
Comparison of Average MPG (Blue Bird buses – Stop-and-Go)

Fuel cost/mile is based on a price provided by TARTA: B-20 = $2.088/gallon, ULS diesel = $1.975/gallon. (These are the average costs from October 2006 to May 2007 as shown in the table previously).

- For the Bluebird buses, the average mpg for buses using B-20 is 2.92% higher than the mpg of buses using ULS.
- For the Bluebird buses, the average fuel cost/mile of buses using B-20 is 2.70% higher than the fuel cost/mile for buses using ULS.

### MPG of Bluebird Buses (Stop-and-Go): June 2007

<table>
<thead>
<tr>
<th></th>
<th>B-20 Buses</th>
<th>ULS Buses</th>
<th>Difference*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buses</td>
<td>Number of</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Buses</td>
<td>MPG</td>
<td>MPG</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>4.58</td>
<td>4.45</td>
</tr>
</tbody>
</table>

* MPG Difference = (MPG of B-20 bus minus MPG of ULS bus) / MPG of ULS bus x 100

### Fuel Cost of Bluebird Buses (Stop-and-Go): June 2007

<table>
<thead>
<tr>
<th></th>
<th>B-20 Buses</th>
<th>ULS Buses</th>
<th>Difference**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of</td>
<td>Number of</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Buses</td>
<td>Buses</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fuel Cost/Mile</td>
<td>Fuel Cost/Mile</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>$ 0.456</td>
<td>$ 0.444</td>
</tr>
</tbody>
</table>

** Fuel Cost/Mile Difference = (Fuel Cost/Mile of B-20 bus - Fuel Cost/Mile of ULS bus) / Fuel Cost/Mile of ULS bus x 100

Comparison of Average MPG (Thomas Buses – Over the Road)

To examine the impact of long-distance travel, a route that involved highway and expressway driving and had few stops was examined. Data were collected for Thomas buses running on this route. Fuel cost/mile is based on a price provided by TARTA: B-20 = $2.088/gallon, ULS diesel = $1.975/gallon. (These are the average costs from October 2006 to May 2007.)

- For the Bluebird buses, the average mpg for buses using B-20 is 8.17% higher than the mpg for buses using ULS.
- For Bluebird buses, the average fuel cost/mile for buses using B-20 is 13.9% higher than fuel cost/mile for buses using ULS.

### MPG of Thomas Buses (Over the Road): June 2007

<table>
<thead>
<tr>
<th></th>
<th>B-20 Buses</th>
<th>ULS Buses</th>
<th>Difference*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of</td>
<td>Number of</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Days</td>
<td>Days</td>
<td></td>
</tr>
<tr>
<td></td>
<td>MPG</td>
<td>MPG</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>5.21</td>
<td>1</td>
</tr>
</tbody>
</table>

* MPG Difference = (MPG of B-20 bus minus MPG of ULS bus) / MPG of ULS bus x 100
Comparison of Average MPG (Bluebird Buses – Over the Road)

To examine the impact of long-distance travel, a route that involved highway and expressway driving and had few stops was examined. Data were collected for Bluebird buses running on this route. Fuel cost/mile is based on a price provided by TARTA: B-20 = $2.088/gallon, ULS diesel = $1.975/gallon. (These are the average costs from October 2006 to May 2007.)

- For the Bluebird buses, the average mpg for buses using B-20 is 8.17% higher than the mpg for buses using ULS.
- For Bluebird buses, the average fuel cost/mile for buses using B-20 is 2.35% lower than fuel cost/mile for buses using ULS.

It is interesting to note the rather large differences in mpg between different bus types, Thomas versus Bluebird, and between types of applications, stop-and-go versus over the road. These items should be investigated during future project work.
Maintenance Cost for TARTA Buses

Data were collected for the maintenance and repair costs for 15 B-20 and 12 ULS diesel Thomas buses from October 1, 2006 to June 12, 2007. This represents about 700,000 miles of operation. The average maintenance and repair costs for the buses were determined. Engine related costs were $0.0375/mile for ULS and $0.0226/mile for B-20 buses. The total repair and maintenance costs were $0.229/mile for ULS buses compared to $0.191/mile for B-20 buses. The stop-and-go fuel costs were used for the Thomas buses because they represent typical bus fleet operations.

- For the Thomas buses using B-20, the engine related repair cost is 39.7% lower than the ULS buses.
- For the Thomas buses using B-20, the fuel and engine related repair cost is 8.42% higher than the ULS buses.
- For the Thomas buses using B-20, the total maintenance and repair cost is 16.6% lower than the ULS buses. However, it is difficult to assign the maintenance and repair costs for the non-engine/fuel related cost to the use of B-20.
- For the Thomas buses, the total maintenance and repair costs plus the fuel cost are virtually the same for buses using B-20 compared to buses using ULS diesel. It is not likely that the choice of fuel has an impact on non-engine related repair costs.

### Maintenance Cost for Thomas Buses: October 1, 2006 – June 12, 2007

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS</td>
<td>$0.425</td>
<td>$0.0375</td>
<td>$0.463</td>
<td>$0.229</td>
<td>$0.692</td>
</tr>
<tr>
<td>B-20</td>
<td>$0.479</td>
<td>$0.0226</td>
<td>$0.502</td>
<td>$0.191</td>
<td>$0.693</td>
</tr>
<tr>
<td>Difference*</td>
<td>12.7%</td>
<td>-39.7%</td>
<td>8.42%</td>
<td>-16.6%</td>
<td>0.001%</td>
</tr>
</tbody>
</table>

*Cost/Mile Difference = (Cost/Mile B-20 bus - Cost/Mile ULS bus) / Cost/Mile ULS bus x 100

Data were collected for maintenance and repair for four B-20 and four ULS diesel Bluebird buses from October 1, 2006 to June 12, 2007. This represents about 200,000 miles of operation. The average maintenance and repair costs for the buses were determined. Engine related costs were $0.0142/mile for ULS and $0.0321/mile for B-20 buses. The total repair and maintenance costs were $0.215/mile for ULS buses compared to $0.289/mile for B-20 buses. The stop-and-go fuel costs were used for the Bluebird buses because they represent typical bus fleet operations.

- For the Bluebird buses using B-20, the engine related repair cost is 126% higher than the ULS buses.
- For the Bluebird buses using B-20, the fuel and engine related repair cost is 6.55% higher than the ULS buses.
- For the Bluebird buses using B-20, the total maintenance and repair cost is 34.45% higher than the ULS buses.
higher than the ULS buses. However, it is difficult to assign the maintenance and repair costs for the non-engine/fuel related cost to the use of B-20.

- For the Bluebird buses using B-20, the total maintenance and repair cost plus fuel cost is 15.5% higher than the ULS buses. It is not likely that the choice of fuel has an impact on non-engine related repair costs.

### Maintenance Cost for Bluebird Buses: October 1, 2006 – June 12, 2007

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>A* (Fuel Cost ($/mile))</th>
<th>B (Engine-Related Repair Costs ($/mile))</th>
<th>C (A+B) (Fuel Cost &amp; Engine-Related Repair Costs ($/mile))</th>
<th>D (Non-Engine-Related Repair Costs &amp; Maintenance ($/mile))</th>
<th>E (A+B+D) Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS (4 buses)</td>
<td>$0.444</td>
<td>$0.0142</td>
<td>$0.458</td>
<td>$0.215</td>
<td>$0.673</td>
</tr>
<tr>
<td>B-20 (4 buses)</td>
<td>$0.456</td>
<td>$0.0321</td>
<td>$0.488</td>
<td>$0.289</td>
<td>$0.777</td>
</tr>
<tr>
<td>Difference**</td>
<td>2.70%</td>
<td>126%</td>
<td>6.55%</td>
<td>34.45%</td>
<td>15.5%</td>
</tr>
</tbody>
</table>

*Fuel cost data are based on experiment results collected in May 2007

** (B-20 - ULS) / ULS x 100%

### Details of Engine-Related Costs

Maintenance data for the Thomas and Bluebird buses were collected from October 1, 2006 through June 12, 2007. As the details of the engine related costs are examined for the Thomas buses, the largest difference occurs in electric engine controls. For the Bluebird buses it is in engine repairs. Further investigation may indicate whether there is a causal link between these cost differences and the use of fuel.

### Engine Related Cost Details -Thomas Buses

<table>
<thead>
<tr>
<th>Engine Related</th>
<th>B-20 ($/mile)</th>
<th>ULS ($/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cooling System</strong></td>
<td>0.007470</td>
<td>0.007248</td>
</tr>
<tr>
<td><strong>Engine</strong></td>
<td>0.004077</td>
<td>0.005058</td>
</tr>
<tr>
<td><strong>Coolant Preheater</strong></td>
<td>0.002446</td>
<td>0.001927</td>
</tr>
<tr>
<td><strong>Exhaust System</strong></td>
<td>0.002320</td>
<td>0.000992</td>
</tr>
<tr>
<td><strong>Electric Engine Control</strong></td>
<td>0.002175</td>
<td>0.013116</td>
</tr>
<tr>
<td><strong>Fuel System</strong></td>
<td>0.001871</td>
<td>0.004953</td>
</tr>
<tr>
<td><strong>Fuel Pump</strong></td>
<td>0.000743</td>
<td>0.000000</td>
</tr>
<tr>
<td><strong>Fan</strong></td>
<td>0.000591</td>
<td>0.000099</td>
</tr>
<tr>
<td><strong>Water Pump</strong></td>
<td>0.000472</td>
<td>0.000000</td>
</tr>
<tr>
<td><strong>Fuel Tank</strong></td>
<td>0.000269</td>
<td>0.001905</td>
</tr>
<tr>
<td><strong>Air Intake System</strong></td>
<td>0.000201</td>
<td>0.001940</td>
</tr>
<tr>
<td><strong>Fan Drive</strong></td>
<td>0.000000</td>
<td>0.000255</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>0.022636</td>
<td>0.037492</td>
</tr>
</tbody>
</table>
### Engine Related Cost Details - Bluebird Buses

<table>
<thead>
<tr>
<th>Engine-related Task</th>
<th>B-20($/mile)</th>
<th>ULS($/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>0.01514</td>
<td>0.00547</td>
</tr>
<tr>
<td>Electric Engine Control</td>
<td>0.00755</td>
<td>0.00666</td>
</tr>
<tr>
<td>Cooling System</td>
<td>0.00479</td>
<td>0.00085</td>
</tr>
<tr>
<td>Coolant Preheater</td>
<td>0.00344</td>
<td>0.00006</td>
</tr>
<tr>
<td>Fuel System</td>
<td>0.00116</td>
<td>0.00066</td>
</tr>
<tr>
<td>Fuel Pump</td>
<td>0.00000</td>
<td>0.00052</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>0.03209</strong></td>
<td><strong>0.01422</strong></td>
</tr>
</tbody>
</table>

(Bluebird Buses, 10-1-2006 to 6-12-2007)
Engine Wear for TARTA Buses

Oil test data were collected for 15 B-20 and 12 ULS diesel Thomas buses from October 1, 2006 to May 8, 2007. Analysis of the engine oil tests conducted by an outside agency showed an oil abnormal rate for B-20 of 11.9% compared to 17.7% for ULS. For both B-20 and ULS diesel, the average of the metallic components in the oil is within the standards.

- The rate of abnormal observations in the oil tested from B-20 buses was 32.8% LOWER than that of ULS.
- The average content of lead in the engine oil at the time of an oil change showed significant differences between B-20 and ULS. Lead is higher in B-20 than ULS.
- In all cases, the averages are within the specifications.

### Number of Abnormal Observations

<table>
<thead>
<tr>
<th></th>
<th>Abnormal</th>
<th>Normal</th>
<th>Total</th>
<th>Abnormal rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-20</td>
<td>8</td>
<td>59</td>
<td>67</td>
<td>11.9%</td>
</tr>
<tr>
<td>ULS Diesel</td>
<td>11</td>
<td>51</td>
<td>62</td>
<td>17.7%</td>
</tr>
</tbody>
</table>

### Average ppm for Trace Metal in the Oil

<table>
<thead>
<tr>
<th></th>
<th>Iron</th>
<th>Chromium</th>
<th>Lead</th>
<th>Copper</th>
<th>Tin</th>
<th>Alumini -num</th>
<th>Nickel</th>
<th>Silver</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-20</td>
<td>33.64</td>
<td>2.06</td>
<td>4.99</td>
<td>5.48</td>
<td>0.00</td>
<td>8.13</td>
<td>0.00</td>
<td>0.34</td>
<td>6.33</td>
</tr>
<tr>
<td>ULS Diesel</td>
<td>33.15</td>
<td>2.16</td>
<td>1.56</td>
<td>5.53</td>
<td>0.03</td>
<td>8.82</td>
<td>0.00</td>
<td>0.35</td>
<td>6.82</td>
</tr>
</tbody>
</table>

### Specification

<table>
<thead>
<tr>
<th></th>
<th>Iron</th>
<th>Chromium</th>
<th>Lead</th>
<th>Copper</th>
<th>Tin</th>
<th>Alumini -num</th>
<th>Nickel</th>
<th>Silver</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specification</td>
<td>150</td>
<td>25</td>
<td>50</td>
<td>0</td>
<td>25</td>
<td>30</td>
<td>10</td>
<td>5</td>
<td>50</td>
</tr>
</tbody>
</table>

### Average ppm for Trace Metals in Oil for B-20 and ULS

![Graph showing average ppm for trace metals in oil for B-20 and ULS]
The only metal that is significantly different statistically is lead, which is higher for buses using B-20 than for buses using ULS diesel.

### MPG and Fuel Cost per Mile for City of Toledo Vehicles

As shown in the following tables, for the City of Toledo vehicles in the study, mpg using B-20 is higher than mpg when using ULS diesel. In this case, data were also available for low sulfur diesel (LSD). The tables below list the results for the Ford F-250, the Crane LET-2, and the Mack MR6885. The F-250 shows the largest improvement in mpg (11.0% for the period of January 1 to April 26, 2007 for B-20 compared to January 1 to April 26, 2006 for ULS diesel). The percent increases in mpg for the Crane LET-2 and the Mack MR6885 for B-20 over ULS diesel are 5.53% and 7.42%, respectively. The smaller improvements for these two vehicles may be caused by the type of driving. The refuse packer and the recycle truck make frequent stops when compared to the F-250.

#### Truck #2344 (2003 Ford F250)

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Time Period</th>
<th>Average MPG*</th>
<th>Fuel Cost ($/gallon)*</th>
<th>Fuel Cost ($/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSD</td>
<td>1/1/2005 - 7/13/2005</td>
<td>12.16</td>
<td>$1.79</td>
<td>$0.147</td>
</tr>
<tr>
<td>ULS</td>
<td>1/1/2006 - 7/13/2006</td>
<td>11.31</td>
<td>$2.33</td>
<td>$0.206</td>
</tr>
<tr>
<td>B-20</td>
<td>7/13/2006- 4/26/2007</td>
<td>12.27</td>
<td>$2.15</td>
<td>$0.175</td>
</tr>
<tr>
<td>ULS</td>
<td>1/1/2006 - 4/26/2006</td>
<td>11.15</td>
<td>$2.00**</td>
<td>$0.179</td>
</tr>
<tr>
<td>B-20</td>
<td>1/1/2007 - 4/26/2007</td>
<td>12.38</td>
<td>$2.10</td>
<td>$0.170</td>
</tr>
</tbody>
</table>

* Based on data from the City of Toledo.

** The average price for ULS diesel for 1/1/2007 – 4/26/2007 was used to compare the fuel cost per mile between ULS diesel and B-20 over this time period.
Truck #2667 (2001 Crane LET-2)

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Time Period</th>
<th>Average MPG*</th>
<th>Fuel Cost ($/gallon)*</th>
<th>Fuel Cost ($/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSD</td>
<td>1/1/2005 - 9/19/2005</td>
<td>2.63</td>
<td>$1.85</td>
<td>$0.703</td>
</tr>
<tr>
<td>LSD/ULS</td>
<td>9/19/2005 - 4/26/2006</td>
<td>2.30</td>
<td>$2.31</td>
<td>$1.004</td>
</tr>
<tr>
<td>ULS</td>
<td>1/1/2006 - 9/19/2006</td>
<td>2.51</td>
<td>$2.36</td>
<td>$0.940</td>
</tr>
<tr>
<td>B20</td>
<td>9/19/2006 - 4/26/2007</td>
<td>2.55</td>
<td>$2.13</td>
<td>$0.835</td>
</tr>
<tr>
<td>ULS</td>
<td>1/1/2006 - 4/26/2006</td>
<td>2.53</td>
<td>$2.00**</td>
<td>$0.791</td>
</tr>
<tr>
<td>B-20</td>
<td>1/1/2007 - 4/26/2007</td>
<td>2.67</td>
<td>$2.10</td>
<td>$0.787</td>
</tr>
</tbody>
</table>

* Based on data from the City of Toledo.

** The average price for ULS diesel for 1/1/2007 – 4/26/2007 was used to compare the fuel cost per mile between ULS diesel and B-20 over this time period.

Truck #2681 (2003 Mack MR6885)

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Time Period</th>
<th>Average MPG*</th>
<th>Fuel Cost ($/gallon)*</th>
<th>Fuel Cost ($/mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSD</td>
<td>1/1/2005 - 9/25/2005</td>
<td>2.41</td>
<td>$1.87</td>
<td>$0.776</td>
</tr>
<tr>
<td>ULS</td>
<td>1/1/2006 - 9/25/2006</td>
<td>2.27</td>
<td>$2.42</td>
<td>$1.066</td>
</tr>
<tr>
<td>B20</td>
<td>9/25/2006 - 4/26/2007</td>
<td>2.38</td>
<td>$2.14</td>
<td>$0.899</td>
</tr>
<tr>
<td>ULS</td>
<td>1/1/2006 - 4/26/2006</td>
<td>2.29</td>
<td>$2.00**</td>
<td>$0.873</td>
</tr>
<tr>
<td>B-20</td>
<td>1/1/2007 - 4/26/2007</td>
<td>2.46</td>
<td>$2.10</td>
<td>$0.854</td>
</tr>
</tbody>
</table>

* Based on data from the City of Toledo.

** The average price for ULS diesel for 1/1/2007 – 4/26/2007 was used to compare the fuel cost per mile between ULS diesel and B-20 over this time period.

MPG Comparisons
(January – April of 2006 and 2007)

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Time Period</th>
<th>MPG of Truck #2344 (2003 Ford F250)</th>
<th>MPG of Truck #2667 (2001 Crane LET-2)</th>
<th>MPG of Truck #2681 (2003 Mack MR6885)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS</td>
<td>1/1/2006 - 4/26/2006</td>
<td>11.15</td>
<td>2.53</td>
<td>2.29</td>
</tr>
<tr>
<td>B-20</td>
<td>1/1/2007 - 4/26/2007</td>
<td>12.38</td>
<td>2.67</td>
<td>2.46</td>
</tr>
<tr>
<td>Difference*</td>
<td></td>
<td>11.0%</td>
<td>5.53%</td>
<td>7.42%</td>
</tr>
</tbody>
</table>

*Difference = (B-20 - ULS) / ULS x 100%

Maintenance Cost for City of Toledo Vehicles

As shown in the following tables for the City of Toledo, the F-250 and the Mack MR6885 showed no engine related maintenance during the study. The engine related maintenance for the Crane LET-2 is significantly higher for B-20 use than ULS diesel use. However, in evaluating the cause of this difference, the mechanics and management at the City of Toledo
do not believe that it was the result of using B-20. Other Crane LET-2 used by the City of Toledo that are not involved in the study experienced the same maintenance pattern as the Crane LET-2 using B-20. For maintenance and non-engine related costs, the results are $0.372, $0.576, and $1.337 per mile for the Ford F-250, the Crane LET-2, and the Mack MR6885 trucks when they used ULS diesel and $0.143, $1.042, and $0.912 per mile when using B-20. These data are for 1/1/2006 to 4/26/2006 for ULS diesel and 1/1/2007 to 4/26/2007 for B-20. Non-engine related maintenance may not be impacted by the type of fuel used.

### Maintenance and Non-Engine Related Costs

<table>
<thead>
<tr>
<th></th>
<th>Ford F-250</th>
<th>Crane Let-2</th>
<th>Mack MR6885</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS*</td>
<td>$0.0372</td>
<td>$0.576</td>
<td>$1.337</td>
</tr>
<tr>
<td>B-20**</td>
<td>$0.143</td>
<td>$1.42</td>
<td>$0.912</td>
</tr>
</tbody>
</table>

* ULS data is from January 1 to April 26, 2006
** B-20 data is from January 1 to April 26, 2007

### Truck #2344 (2003 Ford F250)

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Time Period</th>
<th>Engine Related Costs</th>
<th>Maintenance and Non-engine Related Cost</th>
<th>Miles Traveled</th>
<th>Engine-related (Costs/Mile)</th>
<th>Maintenance and Non-engine Related (Cost/Mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS</td>
<td>1/1/2006 - 7/13/2006</td>
<td>$0</td>
<td>$2,124.86</td>
<td>8,898</td>
<td>$0</td>
<td>$0.239</td>
</tr>
<tr>
<td>B-20</td>
<td>7/13/2006- 4/26/2007</td>
<td>$0</td>
<td>$4,455.53</td>
<td>20,357</td>
<td>$0</td>
<td>$0.219</td>
</tr>
<tr>
<td>ULS</td>
<td>1/1/2006 - 4/26/2006</td>
<td>$0</td>
<td>$1,918.73</td>
<td>5,152</td>
<td>$0</td>
<td>$0.372</td>
</tr>
<tr>
<td>B-20</td>
<td>1/1/2007 - 4/26/2007</td>
<td>$0</td>
<td>$1,275.15</td>
<td>8,887</td>
<td>$0</td>
<td>$0.143</td>
</tr>
<tr>
<td>Difference*</td>
<td>B-20 Jan - April 2007</td>
<td>ULS Jan- April 2006</td>
<td></td>
<td></td>
<td></td>
<td>-61.5%</td>
</tr>
</tbody>
</table>

*Difference = (B-20 - ULS) / ULS x 100%

The results show that for the Ford F-250 truck, the maintenance and non-engine related cost per mile was 61.5% lower for B-20 compared to ULS.

### Truck #2667 (2001 Crane LET-2)

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Time Period</th>
<th>Engine Related Costs</th>
<th>Maintenance and Non-engine Related Cost</th>
<th>Miles Traveled</th>
<th>Engine-related (Costs/Mile)</th>
<th>Maintenance and Non-engine Related (Cost/Mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS</td>
<td>1/1/2006 -9/19/2006</td>
<td>$2,029</td>
<td>$22,892</td>
<td>4,571</td>
<td>$0.44</td>
<td>$5.01</td>
</tr>
<tr>
<td>B-20</td>
<td>9/19/2006- 4/26/2007</td>
<td>$8,144</td>
<td>$5,647</td>
<td>4,661</td>
<td>$1.75</td>
<td>$0.81</td>
</tr>
<tr>
<td>ULS</td>
<td>1/1/2006 - 4/26/2006</td>
<td>$0</td>
<td>$1,626</td>
<td>2,821</td>
<td>$0.00</td>
<td>$0.576</td>
</tr>
<tr>
<td>B-20</td>
<td>1/1/2007- 4/26/2007</td>
<td>$7,937</td>
<td>$3,095</td>
<td>2,971</td>
<td>$2.672</td>
<td>$1.042</td>
</tr>
<tr>
<td>Difference*</td>
<td>B-20 Jan - April 2007</td>
<td>ULS Jan- April 2006</td>
<td></td>
<td></td>
<td></td>
<td>80.9%</td>
</tr>
</tbody>
</table>

*Difference = (B-20 - ULS) / ULSD x 100%

The results show that for the Crane LET-2 truck, the maintenance and non-engine related cost per mile was 80.9% higher with B-20 than with ULS.
The results show that for the Mack MR6885 truck, the maintenance and non-engine related cost per mile was 31.8% lower with B-20 compared with ULS.

**Total Cost Per Mile for the City of Toledo Vehicles**

As shown in the following tables, fuel costs per mile are cheaper for all of the City of Toledo vehicles when B-20 is used compared to ULS diesel. The overall fuel and maintenance costs are lower for the Ford F-250 and the Mack MR6885 trucks when B-20 is used compared to ULS diesel. The opposite is true for the Crane LET-2 truck.

### Truck #2681 (2003 Mack MR6885)

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Time Period</th>
<th>Engine Related Costs</th>
<th>Maintenance and Non-engine Related Cost</th>
<th>Miles Traveled</th>
<th>Engine-related (Costs/Mile)</th>
<th>Maintenance and Non-engine Related (Cost/Mile)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS</td>
<td>1/1/2006 - 9/25/2006</td>
<td>$0</td>
<td>$5,923</td>
<td>7,003</td>
<td>$0</td>
<td>$0.846</td>
</tr>
<tr>
<td>B-20</td>
<td>9/25/2006 - 4/26/2007</td>
<td>$0</td>
<td>$6,592</td>
<td>5,876</td>
<td>$0</td>
<td>$1.120</td>
</tr>
<tr>
<td>ULS</td>
<td>1/1/2006 - 4/26/2006</td>
<td>$0</td>
<td>$2,380</td>
<td>3,182</td>
<td>$0</td>
<td>$1.337</td>
</tr>
<tr>
<td>B-20</td>
<td>1/1/2007 - 4/26/2007</td>
<td>$0</td>
<td>$4,148</td>
<td>3,783</td>
<td>$0</td>
<td>$0.912</td>
</tr>
</tbody>
</table>

**Difference**

<table>
<thead>
<tr>
<th>B-20 Jan - April 2007</th>
<th>ULS Jan - April 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0</td>
<td>$0</td>
</tr>
</tbody>
</table>

*Difference = (B-20 - ULS) / ULS x 100%

### Truck #2344 (2003 Ford F250)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS</td>
<td>1/1/2006 - 4/26/2006</td>
<td>$0.179</td>
<td>$0.000</td>
<td>$0.179</td>
<td>$0.372</td>
<td>$0.551</td>
</tr>
</tbody>
</table>

**Difference**

<table>
<thead>
<tr>
<th>B-20 - ULS</th>
<th>ULS</th>
</tr>
</thead>
<tbody>
<tr>
<td>-5.03%</td>
<td>-61.6%</td>
</tr>
</tbody>
</table>

*Difference = (B-20 - ULS) / ULS x 100%

### Truck #2667 (2001 Crane LET-2)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS</td>
<td>1/1/2006 - 4/26/2006</td>
<td>$0.791</td>
<td>$0.000</td>
<td>$0.791</td>
<td>$0.576</td>
<td>$1.367</td>
</tr>
</tbody>
</table>

**Difference**

<table>
<thead>
<tr>
<th>B-20 - ULS</th>
<th>ULS</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.0505%</td>
<td>337%</td>
</tr>
</tbody>
</table>

*Difference* = (B-20 - ULS) / ULS x 100%
### Truck #2681 (2003 Mack MR6885)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS</td>
<td>1/1/2006-4/26/2006</td>
<td>$0.873</td>
<td>$0.00</td>
<td>$0.873</td>
<td>$1.34</td>
<td>$2.213</td>
</tr>
<tr>
<td>B-20</td>
<td>1/1/2007-4/26/2007</td>
<td>$0.854</td>
<td>$0.00</td>
<td>$0.854</td>
<td>$0.912</td>
<td>$1.766</td>
</tr>
<tr>
<td>Difference*</td>
<td></td>
<td>-2.18%</td>
<td>-2.18%</td>
<td>-32.1%</td>
<td>-20.2%</td>
<td></td>
</tr>
</tbody>
</table>

*Difference* = (B-20 - ULS) / ULS x 100%

### Life Cycle Costs

Life-cycle costs (LCCs) are all the anticipated costs associated with a project throughout its life. LCC analysis is employed to evaluate alternative design configurations, alternative manufacturing methods, alternative support schemes, etc. Thus, life-cycle costs include costs from pre-operations through operations or to the end of the alternative.

#### Life Cycle for a Biodiesel Fleet

The total life cycle cost is the sum of infrastructure, bus alteration, refueling, and maintenance expenses of a transit fleet over an assumed estimated 30 year life cycle. This cost is usually converted to a present value.

\[
\text{LCC for Fleet} = \text{Total cost over the life of the fleet} \\
\text{(over 30 years discounted to the present value)}
\]

The economic performance of alternative fuels for buses can be measured by estimating and comparing the expected total cost of running a bus fleet during its anticipated operating life using different fuels. The comparison of total costs is enhanced by considering the present value of total fleet costs over the fleet’s life cycle.

\[
\text{Total Cost} = \text{Infrastructure Cost} + \text{Refueling Cost} + \text{Maintenance Cost}
\]

Total costs of running a bus are infrastructure, refueling and maintenance costs.

*Infrastructure costs* represent building and tankage installation expenditures. Changing fuel storage and delivery systems, as well as bus engines and fuel systems, to use biodiesel may require additional expenditures.

*Refueling costs* include actual fuel expenditures and refueling labor charges.
*Maintenance expenses* include repair, rebuild, and insurance costs, and costs associated with the loss of ridership and good will due to unexpected breakdowns. Major maintenance costs involve engine rebuilds and general bus maintenance and repair. These are the expenses attributable to the use of biodiesel fuels.

The life cycle cost calculations will begin in the next year once all of the data from year one are in place and verified.
ENVIRONMENTAL IMPACTS ASSESSMENT

The purpose of this research is to study the effects of using alternative diesel fuel on vehicular emissions and indoor air quality of public transport buses in the City of Toledo, Ohio and vehicles used by the City of Toledo for public works. The study also aims to analyze the different parameters that affect vehicular emissions and indoor air quality inside the bus compartment and to characterize the behavior of pollutants under various operating conditions. This section focuses on the following aspects of environmental assessment:

- Overview of the methods used to gather data and to ensure accuracy
- Tail pipe emissions
- In-bus air quality
- Impact of using different feedstock for biodiesel

Overview of Experimental Procedures

The experiments are divided into two groups: exhaust emissions and in-bus air quality. The experimental design and the instrumentation used are discussed in this section.

Emission Profiling

Instrumentation

Exhaust emissions were measured using a standard Testo 350 XL unit with six gas sensors: oxygen (O₂), carbon dioxide (CO₂), carbon monoxide (CO), nitric oxide (NO) and nitrogen dioxide (NO₂) with calculated total oxides of nitrogen (NOₓ), sulfur dioxide (SO₂) and a temperature sensor. During the test procedures, an On-Board Diagnostics (OBD) unit (connected to the engine diagnostic software) was connected to the computer control in the buses to download the engine performance data including rpm, speed, and engine power. The OBD also gives details regarding total vehicle and engine mileage, total operation time of the vehicle, total time at idling, and fuel and engine temperature for use in data analysis.

Study Design

The emission data was collected for three types of test protocols:

1. **Idle testing**: Idle tests of the buses involves setting up the OBD connection with the computer and connecting it to the Engine Diagnostic Software. A list of important engine parameters to be monitored is generated and prepared for data-logging. Emission monitoring instrumentation is connected to the sampling probes and is set up at the exhaust. Both sets of instruments are started simultaneously in order to maintain easy comparison. The bus is then started in the desired idling mode (fast or normal idle) and the engine and emission characteristics are monitored for 15 to 20 minutes.

2. **Dynamometer testing**: A sample set of buses from every fleet were subjected to the Central Business District (CBD) Cycle (driving in the city, not suburban) to simulate operating conditions. Emissions testing was carried out during load simulation to obtain real time emission behavior of the buses during operation.

3. **UT-TARTA Test Cycle**: A new test protocol was developed for standardizing the testing procedure for all TARTA buses. This run simulates an actual operational run
of TARTA buses and gives specific details about the emission behavior of buses in the City of Toledo. All buses were tested after midnight on a weekend to ensure there was no traffic to disrupt the standard run. The buses ran on TARTA Route #20 which runs between the TARTA garage and Meijer’s on Central Avenue; it has a distance of approximately nine miles each way. The bus was scheduled to make five stops in each direction which lasted ten seconds each to simulate passenger pickup/drop off. During stage 1 (TARTA garage to Meijer’s), the buses were generally started in cold-start, and during stage 2 (Meijer to TARTA garage), the engines were warmed up and demonstrate hot-start characteristics. The total run time for each test stage was always between 20 minutes and 15 seconds to 21 minutes.

In-Bus Air Quality

Instrumentation

Indoor air quality data are being monitored continuously for two selected buses operating on ULS diesel and B-20 made with ULS diesel fuels from the 500 series (Thomas buses). Each bus has a complete set of IAQ monitoring instruments consisting of one Yes ‘Plus’ IAQ monitor with seven gas sensors (CO2, CO, NO, NO2, SO2, Volatile Organic Compounds [VOC] and formaldehyde [HCHO]), with temperature and relative humidity sensors) and one Grimm Dustmonitor 1.108 for 15 grades of particulate matter mass and number concentration measurement. The vehicle’s operation (factors like door open/closed status, bus idling) and traffic conditions (passenger numbers; buses and cars on the road) are also monitored every minute.

Study Design

The experimental setup included bus and route selection. For the purpose of this study, all the data was collected from the same vehicle and the bus was run on the same route throughout the test period. Inside the bus there were five cameras (Figure 1): one facing the road, two facing the doors and two facing indoors. The road facing camera was used to count buses, trucks and cars. The indoor facing cameras were used for counting passengers. The door facing cameras along with the road facing camera were used for checking the vehicle idling and door opening status. All the camera recordings were checked every minute to get the traffic, passenger and bus status information, which was then tabulated.
A summary of results is given below:

**Emissions vs. Temperature Analysis**

Emission testing for Bus #515 (B-20) was carried out in hot-start (HS) and cold-start (CS) phases in the CBD cycle. The observations from the tests are discussed here.

1. **CO Concentrations:** Initial spike in CO concentrations for cold-start (CS) engine (430 ppm) is twice as high as the hot-start engine (HS) (225 ppm) during startup. After the startup stage, the concentration for the cold-start engine drops significantly (one forth of the concentration observed during startup) and the concentration falls below the emissions from the hotter engine.

2. **NO Concentrations:** NO concentrations are higher for cold-start engines throughout the run period. In the cold-start, as the engine temperature increases, the NO concentrations decrease and after 15 minutes, the emission characteristics are similar to a hot-start engine.

3. **NO2 Concentrations:** NO2 concentrations are higher for cold-start engines throughout the run. An initial spike during startup is much more prominent for cold-start engines.

4. **CO2 Concentrations:** CO2 concentrations are higher for cold-start engines throughout the run period.
Idling Test - Series 300 (Bluebird Buses): Fuel Comparison

The idling test for the series 300 (Bluebird buses) was done in fast-idle condition. In the 300 series buses, the engine runs on regular-idle for the first five minutes during which the fast-idle is delayed and the engine speed is at 750 rpm. After five minutes, the engine shifts to ramp mode and the fast-idle mode is triggered. This stage continues for 15 seconds. Thereafter, the fast-idle mode is activated and the engine speed increases to 1200 rpm. The observations from the testing are discussed below:

1. **CO Concentrations**: CO emissions are higher for buses using B-20 (buses #300 - #304) than buses using ULS diesel (buses #305 - #309). Also, during normal-idling stage, concentrations are higher as compared to fast-idling and there is a marked decrease in concentration as the fast-idle is triggered.

2. **NO Concentrations**: NO emissions are lower for buses using B-20 (buses #300 - #304) than buses using ULS diesel (buses #305 - #309). During normal-idling stage, concentrations are lower as compared to fast-idling and there is a marked increase in concentration as the fast-idle is triggered.

3. **NO\textsubscript{2} Concentrations**: NO\textsubscript{2} emissions are higher for buses using B-20 (buses #300 - #304) than buses using ULS diesel (buses #305 - #309). During normal-idling stage, concentrations are higher as compared to fast-idling. There is a marked decrease in concentration as the fast-idle is triggered.

4. **CO\textsubscript{2} Concentrations**: CO\textsubscript{2} emissions are lower for buses using B-20 (buses #300 - #304) than buses using ULS diesel (buses #305 - #309). During normal-idling stage, concentrations are higher as compared to fast-idling. There is a marked increase in concentration when the fast-idle is triggered (ramp stage), but the concentrations again increase when fast-idle is achieved.

The test for all the buses except #304 were done on a warmer day which resulted in the ambient and engine temperatures for #304 to be well below the temperatures for all the other buses. This caused #304 to demonstrate unusual emission behavior as compared to the other buses. For this reason, the emissions from bus #304 were not included for averaging the concentrations. These average results showed that by using B-20 in series 300 buses (Bluebird buses) for idling conditions, there was a 55% increase in CO concentrations and 25% increase in NO\textsubscript{2} concentrations but a 14% decrease in NO concentrations and 3% decrease in CO\textsubscript{2} concentrations.

### Idling Test: Average Exhaust Emissions from Different Fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>O\textsubscript{2} (%)</th>
<th>CO (ppm)</th>
<th>NO (ppm)</th>
<th>NO\textsubscript{2} (ppm)</th>
<th>CO\textsubscript{2} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodiesel (B-20)</td>
<td>16.21</td>
<td>235.82</td>
<td>258.08</td>
<td>48.81</td>
<td>3.61</td>
</tr>
<tr>
<td>ULS Diesel</td>
<td>15.97</td>
<td>152.02</td>
<td>301.49</td>
<td>38.96</td>
<td>3.72</td>
</tr>
<tr>
<td>% Decrease by using B-20</td>
<td>-1.49%</td>
<td>-55.12%</td>
<td>14.40%</td>
<td>-25.28%</td>
<td>2.97%</td>
</tr>
</tbody>
</table>
Christopher and Kangwook (2006) reported that the average fuel use and CO₂ emissions rates were approximately the same for the biodiesel and petroleum diesel fuels but the average emissions rates of NO decreased by 10%, CO by 11%, hydrocarbons by 22%, and particulate matter (PM) by 10% for B-20 compared with those for petroleum diesel fuel. The decrease in NO emissions observed was different from the results reported by others, based on engine dynamometer testing.

**Idling Test - Series 500 (Thomas Buses): Fuel Comparison**

Idling emissions were monitored for the first 15 minutes for all 37 buses (19 B-20 + 18 ULS diesel) from the 500 series (Thomas buses). Comparisons of idling emission concentrations provided in Figure 2 show that, on an average, B-20 emitted a lower concentration of all the monitored pollutants except for CO₂, which showed a 2.6% increase as compared to ULS diesel fueled buses. NO concentrations were almost similar in both cases with B-20 fuel emitting 1.17% less than ULS diesel buses. CO concentration showed a marked 15% reduction for B-20 fuel as compared to ULS diesel fuel. SO₂ and NO₂ for B-20 fuel showed nearly 5% and 6% reductions respectively. There was less than 1% difference between the average exhaust gas temperatures for the two fueled buses, therefore, the datasets were comparable.

![Figure 2: Idling Emission Concentration Comparison for Series 500 Buses](image-url)
Idling Test - Series 500 (Thomas Buses): Effect of Engine Starting Temperature (Hot Start vs. Cold Start)

A comparison of exhaust emissions during cold-start and hot-start is given in the table below. The results show that the emissions during cold-start are higher than during hot-start. This is obvious because of better combustion during hot-start due to higher temperatures.

<table>
<thead>
<tr>
<th>Bus Number</th>
<th>Mode</th>
<th>Starting Engine Temperature (°F)</th>
<th>CO (ppm)</th>
<th>NO (ppm)</th>
<th>SO2 (ppm)</th>
<th>NO2 (ppm)</th>
<th>CO2 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>Cold</td>
<td>78</td>
<td>196</td>
<td>423</td>
<td>77</td>
<td>55</td>
<td>3.20</td>
</tr>
<tr>
<td></td>
<td>Hot</td>
<td>154</td>
<td>195</td>
<td>289</td>
<td>57</td>
<td>46</td>
<td>2.58</td>
</tr>
<tr>
<td>503</td>
<td>Cold</td>
<td>97</td>
<td>214</td>
<td>393</td>
<td>73</td>
<td>55</td>
<td>3.19</td>
</tr>
<tr>
<td></td>
<td>Hot</td>
<td>159</td>
<td>212</td>
<td>328</td>
<td>64</td>
<td>52</td>
<td>3.04</td>
</tr>
</tbody>
</table>

Concentration Comparison Between Hot And Cold Starts
(Data collected for 15 minute intervals on the same day.)

Emissions Modeling for Idling: Series 500 (Thomas Buses)

Simultaneous monitoring of vehicular exhaust emission and engine performance variables (OBD) for 15 buses of the 500 series was conducted. The average emissions from each bus were then statistically analyzed using Best Subset Regression. The variables used in the analysis were coolant temperature (in °F, representative of engine temperature), engine oil temperature (°F), fuel temperature (°F), ambient temperature (°F), exhaust temperature (Tf, in °F), air filter use (days), fuel filter use (days), fuel grade (1 = B-20, 0 = ULS diesel) and engine mileage. The best models for each pollutant were selected based on their model statistics.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Model</th>
<th>Model Statistics</th>
</tr>
</thead>
</table>
| NO (ppm)  | 1395 - 11.0 Coolant Temp + 3.12 Tf oF - 0.538 Air Filter Use | S = 116.261  
R-Sq = 91.1%  
R-Sq(adj) = 87.7% |
| NO2 (ppm) | 91.1 - 1.01 Coolant Temp + 0.341 Tf oF + 0.000379 Mileage - 9.81 Fuel Grade | S = 12.0665  
R-Sq = 89.6%  
R-Sq(adj) = 83.7% |
| CO (ppm)  | - 481 + 0.00165 Mileage + 2.43 Coolant Temp - 10.6 Eng Oil Temp + 9.65 Fuel Temp + 2.76 Tf + 0.567 Air Filter Use - 0.266 Fuel Filter Use | S = 27.6448  
R-Sq = 91.0%  
R-Sq(adj) = 75.3% |
| CO2 (%)   | 4.66 - 0.000004 Mileage - 0.0249 Coolant Temp + 0.0122 Tf oF - 0.00291 Air Filter Use | S = 0.179925  
R-Sq = 96.2%  
R-Sq(adj) = 94.1% |
It can be observed that engine temperature and exhaust temperature were the most important variables affecting the concentrations of all the pollutants. The age of the air filter was also a very important variable affecting the concentrations.

**Effects of Fuel Chemistry on Tailpipe Emissions for Toledo Garbage Trucks**

Tailpipe emission testing for the City of Toledo garbage disposal trucks yielded results that are different from the TARTA bus emissions (Figure 3). The same instrumentation was used for emission testing and 15 minute emission monitoring which was conducted for one truck each with B-20 and ULS diesel fuels for two different fleets. Trucks running on B-20 produced higher CO concentrations but lower NO, SO₂, and CO₂ concentrations as compared to ULS diesel fueled trucks. NO₂ concentrations were fairly similar for both fuels. Additional testing is planned for both idling and on-the-run conditions to characterize the emission behavior of the different trucks during varied operating conditions.

**Figure 3: Comparison of Tailpipe Emissions for B-20 and ULS Diesel Fueled Trucks from the City of Toledo Garbage Disposal Fleet**

**In-Bus Air Quality**

*Concentration Comparison for Different Days of the Week*

Figure 4 represents a sample time series plot showing the variation of CO₂ with time (5:00 am – midnight) for a test week. The concentrations show an exponential increase during the first three hours which can be attributed to the office/school going passengers and heavy traffic on the route. After 10:00 am, the concentrations decrease until around 1:00 pm when the passengers and traffic subside. After 1:00 pm, there is a steady increase in CO₂ concentrations until 6:00 pm, very similar to the trend seen in passenger and traffic activity. After 6:00 pm, the concentrations steadily decreased until midnight barring a spike at 9:00 pm when there is a momentary increase in passenger traffic.
Figure 4: CO₂ Concentration Trend: Weekly

Figure 5 represents a sample time series plot showing the variation of CO with time (5:00 am – midnight) for a test week. The concentrations show an exponential increase during the first three hours which can be attributed to the office/school going traffic on the route. After the 10:00 am rush, the concentrations decrease until evening and as the evening traffic builds up, the CO concentrations increase as well. On Wednesday and Thursday evening, there was a marked increase in the traffic, especially for trucks and heavy vehicles, which can be seen directly in the CO concentrations.
Sulfur dioxide concentrations also showed a marked correlation with the heavy truck traffic on the road (Figure 6). The concentrations increased during the 9:00-10:00 am traffic and remained high throughout the day. The SO$_2$ concentration was highly variable as compared to the other pollutants and maintained a seesaw trend.

![Time Series Plot of SO$_2$ (PPM)](image)

**Figure 6: SO$_2$ Concentration Trend: Weekly**

Nitric oxide concentrations (Figure 7) start increasing at 8:00 am and show high concentrations until noon. The concentrations again show an increase during the evening hours between 4:00 pm and 8:00 pm. These phases also correlate well with high traffic periods during the day.

![Time Series Plot of NO (PPM)](image)

**Figure 7: NO Concentration Trend: Weekly**
Indoor Particulate Matter (PM) Profile

The average variation of particulate matter (PM$_{1.0}$) with the time of day shows that the concentration of PM$_{1.0}$ is highest during the morning pullout from the garage (6:00 - 7:00 am). As the bus moves out of the garage, the concentration constantly decreases until 7:30 am. The concentration increases at 7:30 am and remains high until noon. This 4.5 hour period corresponds to the highest number of commuters during the day both for children going to school and vehicular traffic. The concentration drops from noon to 1:30 pm when there is negligible ridership on the bus. There is a slight increase between 1:30-2:30 pm, and the concentration again drops continuously until 8:30 pm. Following a sudden increase at 8:30 pm, the concentration again decreases until 11:20 pm when the bus run ends (refer to Figures 8 and 9).

Figure 8: Average Variation of PM$_{1.0}$ Components (Mass Concentration) with Time of Day

Figure 9: Average Variation of PM$_{1.0}$ Components (Number Concentration) with Time of Day
From Figures 8 and 9, it can also be concluded that all components of PM$_{1.0}$ contribute to any peak in PM$_{1.0}$ mass concentration. The plots also show that PM$_{1.0}$ mass comprised of about 40% of particles between 0.30-0.40 µm, but these particles contribute close to 65-70% of the total particle count. Particles with an aerodynamic diameter between 0.40-0.50 µm contribute approximately 25% to PM$_{1.0}$ mass and count concentration. Particles between 0.50 and 1.0 µm in diameter collectively contribute only 6-10% of the total number of particles, but their contribution to mass is almost 35%.

**Comparison of Indoor vs. Just-Outside PM Concentrations**

For comparing the PM concentration behavior inside and just-outside the test bus cabin, and to analyze their relationship, two TSI Dust Trak 8520 monitors were used with 1 µm nozzles. One unit drew air from inside the cabin and one unit was connected to a two foot long pipe which drew air from outside the cabin.

It was observed that indoor concentration trends were similar to the concentration trends just outside the bus and were found to be affected by the just-outside concentrations (similar to Wargo, et al.), but are generally lower than just-outside concentrations (similar to Rodes, et al.) by a margin of 30-70% during test runs (refer to Figure 10). It was also noted that even though outdoor concentrations were affecting the fine particulate concentrations inside the bus, any peak in concentration inside the bus was a result of passenger activity and not the ambient concentrations. This resulted in a much higher increase (up to four times) in the concentrations inside than in the outdoor air. It was also observed that the concentration was highest (sometimes ten times higher) when the test bus was inside the garage with all buses idling (before the morning pullout).

![Comparison between PM 1.0 Concentrations Inside and Just-Outside the Bus](image)

**Figure 10: PM$_{1.0}$ Concentration Comparison: Inside vs. Outside the Bus**
Concentration Comparison for Different Locations: Front of the Bus vs. Back of the Bus

The Dust Trak set was also used for comparing the pollutant concentrations at the front and back of the bus. It can be seen that there is a marked difference in the concentration buildup during the operational run and when the bus is parked in the garage (Figure 11). After the operational runs when the bus is parked in the garage, the indoor and outdoor concentrations were almost similar throughout the three days of observations. During the runs, the concentration at the back of the bus was consistently higher by two to seven times the front end concentration, which is similar to that observed by Solomon, et. al. (2001).

Comparison of Indoor PM Concentrations in B-20 and ULS Diesel Buses

Comparison of indoor fine particulate concentrations inside B-20 and ULS diesel buses was conducted using an 11 day hourly dataset between December 21 and December 31, 2006. Barring some episodes of high levels, the concentration of PM remained identical in both B-20 and ULS diesel buses. In order to analyze the difference in the fine particulate data statistically, a Paired T-Test was performed. The test showed that in both cases, the fine particulate concentrations inside B-20 and ULS diesel fueled buses are statistically similar (Figure 12). This showed that the indoor concentrations in both sets of buses were affected by a single source of pollutants like the ambient concentrations. Additional analysis was conducted using weekly data sets for the two buses operating on the same route (Figure 13). Although the PM$_{1.0}$ concentration peaks were higher for B-20 buses during most morning pullouts, the ULS diesel bus concentration peaks were higher during most of the afternoon operation. This shows that the indoor PM$_{1.0}$ concentration was affected more by traffic and passenger related activities that are different for the two buses. These activities vary with the operating time periods rather than with the type of fuel used in the bus.
Figure 12: Comparison of Indoor Fine PM with Fuel: ULSD vs. B-20
Paired T-Test: T-Test of mean difference = 0 (vs not = 0):

T-Value = -1.18, P-Value = 0.241

Time Series Plot of 0.80-1.0 um Sized Particles inside TARTA Buses

T-Value = 0.37, P-Value = 0.714
Effect of Influencing Variables on Indoor PM Concentrations

Main effects plots (ANOVA) were drawn for particles using Minitab 15 to qualitatively understand the influence of the various operational and traffic conditions on particulate concentrations. The software plots the influencing factors against the mean concentration obtained at each interval of the variable for the desired dataset. It can be seen that concentrations of ultra-fine particles are clearly affected by the bus operation status and door status (similar to Wargo, et. al.). Higher concentrations are observed both when the bus was idling, and the door was open. The presence of a diesel operating bus/truck ahead of the vehicle also increased the fine particulate concentration and had a linear trend with the number of buses. Total passengers and the presence of gasoline operated cars did not show a clear correlation with the particulate concentration. (See Figure 14.) It can also be seen that the influence of the bus operating status (idling/running) and door position status (open/close) is much more significant for smaller particles (diameter between 0.30 and 0.40 µm) whereas the presence of a diesel operated bus/truck ahead of the test bus influenced the larger particles (diameter between 0.80 and 1.0 µm) more significantly.
Figure 14: Effects of Various Factors on Particulate Number Concentration for Fine Particles between 0.30 and 0.40 µm in Diameter

Main Effects Plot for PM 0.30-0.40 um
Data Means

Note: Y axis – The number concentration of the particulate
X axis – Number of passengers in the bus, cars ahead, bus/trucks ahead, idling or running condition, and closed or open doors

Pollutant Concentration Modeling
The pollutant concentrations obtained from the instruments were presented in one minute intervals. For the purpose of modeling, both the concentrations and traffic (and operational) data were processed to obtain one hour averages. The data were then analyzed using best subset regression technique using Minitab 15 which identifies the best two models for every number set of variables. The best model variables were selected and multiple regression was used for obtaining the regression models (see table below).
Regression Models for Analyzing/Predicting the Hourly Indoor Concentrations

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Hourly Concentration Models</th>
<th>Model Statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂(PPM)</td>
<td>443 + 16.7 Total Passengers + 170 High Traffic</td>
<td>S = 53.6283</td>
</tr>
<tr>
<td></td>
<td></td>
<td>R-Sq = 81.9%</td>
</tr>
<tr>
<td>SO₂(PPM)</td>
<td>0.639 + 0.00928 Total Passengers + 0.0470 Number of Bus/Trucks</td>
<td>S = 0.0318803</td>
</tr>
<tr>
<td></td>
<td>- 0.0509 Idling - 0.00151 Indoor Temp (F) - 0.0153 Indoor RH(%)</td>
<td>R-Sq = 80.1%</td>
</tr>
<tr>
<td></td>
<td>+ 0.00950 Ambient Dry Bulb Temp (F) + 0.00243 Ambient RH (%)</td>
<td>R-Sq(adj) = 77.0%</td>
</tr>
<tr>
<td></td>
<td>+ 0.0991 Mon + 0.0542 Tue + 0.0356 Wed + 0.0713 Thu</td>
<td>S = 0.0318803</td>
</tr>
<tr>
<td>CO(PPM)</td>
<td>- 52.4 + 0.146 Time - 0.235 Total Passengers + 6.09 Number of Bus/Trucks</td>
<td>S = 3.21293</td>
</tr>
<tr>
<td></td>
<td>- 2.82 Idling + 2.85 Door Open + 6.33 High Traffic</td>
<td>R-Sq = 75.4%</td>
</tr>
<tr>
<td></td>
<td>+ 0.804 Indoor Temp (F) + 1.51 Indoor RH(%) - 0.997 Dry Bulb Temp (F)</td>
<td>R-Sq(adj) = 71.2%</td>
</tr>
<tr>
<td></td>
<td>- 12.8 Mon - 5.49 Tue + 1.24 Wed - 3.38 Thu</td>
<td>S = 3.21293</td>
</tr>
</tbody>
</table>

The CO₂ model shows a high adjusted R² value (81.5%) and requires only total passenger numbers and a high traffic indicator (1 [yes] or 0 [no]) as influencing variables. These features agree strongly with the properties of an ideal model of adequacy and parsimony. The SO₂ model utilizes passenger count, traffic numbers and indicator values, idling status, indoor and ambient meteorological data and the day of the week (1 for applicable variable, e.g., for Monday, Mon = 1; all other day variables are 0; for Friday, all day variables are 0) for predicting concentrations. Mondays have the highest concentration which agrees with the graphical output. The model also has a reasonably high adjusted R² value of 77%. CO concentrations show dependence on traffic numbers and indicator values, bus engine idling (Yes=1, No=0) and door status (Open=1, Closed=0), ambient and indoor meteorological data and the day of the week. Wednesdays and Fridays have the highest concentrations in the output which agrees with the graphical output.

**Indoor PM₁₀ Model**

Stepwise regression modeling with backward elimination was conducted for PM₁₀ mass concentration inside the bus with an hourly data set for January using nine influencing variables including passenger count, number of cars and buses/trucks ahead, test bus operation status (idling [0] / running [1]), door position status (open [0] / closed [1]), ambient PM₂.₅ concentrations (μg/m³) and ambient meteorological data for visibility (0-10), temperature (°F), relative humidity (%) and wind speed (miles per hour).

The analysis produced five models with an adjusted R² value ranging between 86-89%. The best regression model for the PM₁₀ mass concentration consisted of seven influencing variables – passenger count, bus operation status, visibility, ambient temperature, humidity,
wind speed and ambient PM$_{2.5}$ concentration. The best model (see table below) shows that approximately 89% of the hourly indoor concentration could be explained by the chosen combination of the variables. All the variables in the best model, except visibility, showed a positive correlation to the indoor PM$_{1.0}$ mass concentration showing that as the visibility improved, the indoor PM concentration decreased. Also, with an increase in passenger count, ambient temperature, relative humidity, wind speed and ambient PM$_{2.5}$ concentration, there was a subsequent increase in the concentration of indoor PM$_{1.0}$ concentration.

**Best Regression Model for Predicting/Analyzing PM$_{1.0}$ Behavior**

\[
\text{PM } 1.0 \, (\mu g/m^3) = -53.71 + 0.54 \text{ Dry Bulb Temperature} + 0.340 \text{ Relative Humidity} + 0.435 \text{ Wind Speed} + 0.66 \text{ Ambient PM } 2.5 \, (\mu g/m^3)
\]

**Effects of Using Different Grades of Biodiesel on Vehicular Emissions**

Additional analysis is being planned for testing the effects of using different grades of biodiesel (B-5, B-10, B-15, B-100, etc.) on the tailpipe emissions of different fleets of TARTA buses. Future study plans include the use of one bus from each fleet for the analysis which will be tested on a stage-wise basis. The fuel will be drained out of the elected buses and the fuel tanks will be replaced before beginning the testing procedure. In the first stage, the bus will be fueled with B-5 grade and allowed to run on a selected route for one whole day. After the run, the bus will be tested for idling emissions in hot-start mode the same day and in cold-start mode the following morning. The same test will be repeated the next day with the next higher grade of biodiesel: B-10, B-15 and higher in order.

**Conclusion**

A successful emission testing protocol was developed for characterizing emission characteristics from public transport buses. The protocol identifies the important influencing factors that affect vehicular emissions during real-world operating conditions. Emission testing was performed in three stages: (i) a standard emission test protocol (CBD cycle performed on a chassis dynamometer), (ii) engine idling, and (iii) a sample daily operating run/route of TARTA buses. The procedure also presents a feasible comparison strategy to analyze the effect of alternative diesel fuels on vehicular emission. Emission comparison showed that B-20 grade biodiesel and ULSD fuels did not exhibit significantly different emission behavior from each other but the factors having higher statistical influence on emission behavior were the operating conditions of the engine, preventative maintenance history, vehicle operation in different engine loads and engine operating temperatures. Lower engine idling rpm and higher temperatures were found to reduce vehicular emissions most significantly, up to 30 - 42%.

This study was also able to characterize the indoor air pollutant behavior inside public transport buses during daily operational runs. Comparison of indoor and outdoor concentrations showed that outdoor concentrations strongly influenced the indoor
concentrations and were consistently higher than the indoor concentrations during the runs. Analysis also showed that pollutant concentration at the rear end of the bus was up to two to seven times the front end concentration. Particulate matter analysis indicated that the indoor concentration of fine particulates in both the B-20 biodiesel and ultra-low sulfur diesel buses were identical, and the concentrations depended primarily on ambient PM concentrations and not on the type of fuel used in the buses. The results also showed that the PM$_{1.0}$ mass comprised of around 40% particles between 0.30-0.40 µm, 25% particles between 0.40-0.50 µm and 35% particles between 0.50 and 1.0 µm in diameter.

The indoor pollutant concentrations were analyzed against important operating conditions such as traffic, passenger counts and activity, bus operation status (idling/running), door position (open/closed), and ambient meteorology to study the influence of each variable on the pollutants. Three hourly concentration models were developed for predicting indoor gaseous air pollutant concentrations using the most significant variables. Regression models developed for particulate matter using nine variables (total passenger counts, cars and bus/trucks ahead, bus status [idle/running], door status [open/closed], ambient PM$_{2.5}$ concentrations, visibility [as a measure of outdoor particulate highs], temperature, relative humidity and wind speed) explained approximately 86-89% of the hourly indoor mass concentrations of fine particulates.
HYDROGEN ENHANCEMENT PROJECT

Introduction

The primary objective of the Hydrogen Enhancement Project is to identify and demonstrate novel techniques that can effectively and efficiently provide a vehicle fleet operator with a solution that reduces the annual fuel cost, reduces exhaust emissions and enables the better use of renewable energy products. The Toledo based bus company, TARTA, operates over 170 full sized vehicles and in 2006 purchased over one million gallons of fuel to operate its fleet.

H₂ Engine Systems is providing an addition to the TARTA/City of Toledo Biodiesel Study by undertaking the development of hydrogen enhancement and providing demonstration of its proprietary techniques on a TARPS type Ford based Goshen bus. There have been demonstration programs showing the benefits of enhancing the burn characteristics of internal combustion engines using hydrogen as the enhancement medium. The majority of programs have dealt with gasoline or natural gas powered spark ignition engines. Very little has been undertaken with compression ignition engines and what has been done was always using mineral based diesel fuel.

The majority of vehicle related programs that have been researched employ onboard electrolysis equipment that produces hydrogen and oxygen gases. All the systems investigated appear to be unsophisticated in their execution in that there is no optimized control of the amounts of gas generated and the gases are drawn into the engine using the vacuum created by the engine induction system. In the case of a turbocharged diesel engine, the hydrogen and oxygen are drawn into the hot compressor before being distributed to the cylinders.

H₂ Engine Systems is applying a professional and more sophisticated approach to hydrogen fuel enhancement when compared to any prior art and is focused on the optimization of enhancing the burn characteristics of biodiesel fuels.

The vehicle that is dedicated to the biodiesel hydrogen enhancement project is named BH-1 and is a Goshen bus body on a Ford 350 series with a distinctive vehicle wrap.
BH-1 Bus Modifications

The initial objective of the project was to create and install a sophisticated system that could control the application of the modifier gas and monitor all key engine parameters. These parameters are monitored with sensors and are:

- Engine speed
- Tailshaft speed
- Diesel injector ON timing for cylinder No. 8
- Diesel injector OFF timing for cylinder No. 8
- Engine intake air temperature
- Engine coolant water temperature
- Outside air temperature
- Exhaust manifold gas temperature
- Injected modifier gas temperature
- Injected modifier gas pressure
- Engine intake air manifold pressure
- Exhaust gas constituent gases:
  - Carbon dioxide
  - Carbon monoxide
  - Oxygen
  - Nitric oxide
  - Nitrogen dioxide
  - Carbon particulates of varying sizes

The baseline system uses hydrogen gas as the modifying medium which is provided from high pressure storage tanks fixed beneath the chassis of the vehicle. This hydrogen supply incorporates further sensors that monitor:

- Hydrogen Fuel Tank Pressure (fuel gauge)
- Engine Bay Hydrogen Feed Pressure

Two manually variable pressure regulators are included in the hydrogen tank system supply together with an electrically operated solenoid valve that is the master switch for the supply to the engine bay.

Although the pressurized hydrogen tank system is required for the baseline testing only and will be replaced with a hydrogen-on-demand technology for the long term testing, safety is of paramount importance and hydrogen leak detectors are fitted at the high point of the tank surround in order to sense any leak of gas. A Halon fire suppression system can be activated to replace any oxygen present and prevent escaping gas from any possibility of igniting.

The hydrogen is fueled from a small tank farm that has been located at the TARTA facility. Three tanks are located in a purpose built frame under the bus chassis; they have a total capacity of 240 cubic feet of gas at 3,000 psi. The refueling operation takes approximately 20 to 30 seconds and the volume of gas is sufficient to mix with many complete refills of B-20 biodiesel fuel.

Hydrogen gas is transferred to the BH-1 bus using a tandem hose proving pressurized gas and a spill return vent. The bus is fitted with a dedicated fuel flap and a 3,500 psi stainless
steel fueling nozzle. The nozzle has a non return valve located immediately behind the nozzle bracket assembly.

The hydrogen gas is stored in three 80 cubic feet composite cylinders located in-line beneath the bus floor and inside the chassis rails. Each cylinder is fitted with a master ball valve and a pressure relief valve that vents to the rear axle area. The cylinders are coupled into a supply manifold which is fitted with a high pressure sensor that provides a signal that is used as the system fuel gauge. The high pressure manifold feeds a water cooled pressure regulator that is manually set to provide hydrogen gas to the engine compartment at around 170 psi. An intermediate pressure gauge senses this pressure and an electrically operated solenoid valve is fitted to the tank system to control the supply of hydrogen gas to the engine.

The tanks are located using compliant mounts and are secured in a steel frame that is bolted to the vehicle chassis. The right hand side, the bottom and front of the frame are covered with perforated aluminum sheet that forms a protection against small rocks and other debris thrown back from the vehicle tires. The vehicle left hand chassis rail forms a solid barrier to the tank frame on the left side.
The engine and engine compartment have minimum modifications made to them. It was an original objective not to integrate any of the Ford management system with the project electronics, but to provide key data from proprietary designed ancillary sensors.

The hydrogen fuel supply is provided into the engine compartment via a high pressure flexible line. A second pressure regulator is located in the engine compartment and this is manually set to provide a pressure between 40 psi and 50 psi to the hydrogen injectors. The engine air intake pipe connecting the output of the turbocharger compressor to the intercooler is modified with the injector housing block welded to the steel pipe. Two hydrogen injectors are located in this housing and are held between the housing block and a hydrogen supply block with threaded studs.

A pressure sensor is fitted to the injector hydrogen supply rail and a thermocouple measures the injected hydrogen temperature. Hydrogen is added to the engine intake air stream under pressure and it is assumed that a homogeneous mixture is achieved as the gasses pass through the intercooler matrix.

The engine intake manifold elbow is modified to accommodate a pressure sensor and thermocouple so that the intake air/hydrogen mixture parameters can be monitored.

The left hand exhaust manifold is modified to accept a thermocouple in order that exhaust gas temperature can be directly monitored.

The Ford wiring to the diesel injector on No. 8 cylinder has two current transformer modules attached to the switch ON and switch OFF electrical circuits. This enables the H₂ Engine Systems electronics modules to monitor the diesel injector actuation pulses and hence the injector operating period can be calculated.

The tail shaft from the gearbox is fitted with a magnetic pickup to enable vehicle speed to be monitored.
Electronic Supervisory Control and Data Acquisition (SCADA)

The vehicle sensing and control circuits are grouped into two locations and a dedicated microprocessor controls all functions from a 19” rack box fitted into a third shelf that has been added to the “radio cabinet” located in the bus behind the driver’s seat.

The proprietary microprocessor controller fitted to the top shelf in the “radio cabinet”

The majority of the dedicated project wiring terminates at or emanates from the signal box fixed beneath the vehicle floor and located close to the hydrogen filler bracket. This box contains three distinct layers of electronics:

- Thermocouple signal conditioning and cold junction emulation
- Hydrogen injector power amplifiers and associated electronics
- Analogue circuit amplifiers, digital signal conditioning, DC-DC power supply and emergency shut off relay.

The under floor mounted signal box with three layers of electronics
The microprocessor box takes analogue and digital signal information from the various sensors into the I/O of the computer. Output controls to operate the hydrogen injectors and a safety status signal to the fire suppressant system also use the computer I/O.

The connections to the control laptop computer and the driver’s touch screen monitor derive their connection with the computer using a high speed Ethernet.

The driver’s position is provided with a touch screen display that has several selectable drop-down screens and is able to provide duplicate information to that available on the controlling laptop computer regarding the data from the vehicle system sensors. It also provides an interactive input such that key functions in the control algorithms can be changed using the keypad input on the screen.

An emergency switch that disables the hydrogen supply to the vehicle is fitted above the driver’s head and within easy reach for immediate activation if a crisis situation arises and is a backup to the shut off procedures in the computer software. The switch also activates the fire suppression system if certain conditions exist.
The SCADA system incorporated into the microprocessor controller provides several screens of data to a laptop computer. The basic information screen gives a schematic overview of the hydrogen supply system and provides gauges that display key parameters in real time. Calculated values of engine speed, vehicle speed, period of diesel injector pulse and period of hydrogen injector pulse are also displayed.

![Basic SCADA screen](image)

A computer screen enables changes to the software algorithms to be made for storage in flash memory on the microprocessor board.

The microprocessor operates using a compiled software program that scans all input channels in a 200 millisecond period and calculates the pulse period of the signal to be applied to the hydrogen injectors. Data is arranged for display on the two separate screens and a file of all input data and calculations is created and updated every 200 milliseconds on the laptop hard drive.

**Software Control**

The fundamental control concept is to provide hydrogen to the engine using two injectors operating alternately and synchronized to engine speed.

The pulse duration of each injector is calculated from:

- Percentage of hydrogen to diesel fuel required (selectable from 1% to 4%, typically)
- Torque provided by the diesel engine (diesel injector period)
- Pressure differential across the injectors (hydrogen injector pressure minus engine intake air pressure)

There are more complex calculations incorporated in the software algorithms and certain limits are set when hydrogen will not be injected.

It is assumed that, until proven to be grossly inaccurate, the relationship of hydrogen volume supplied is directly proportional to the injector ON period. Similarly, the relationship of hydrogen volume supplied is indirectly proportional to the pressure differential encountered across the injector.
Results

There has been limited testing of the hydrogen injection system to date. Most of the vehicle driving around Toledo has been directed toward shake down of the hardware problems and debugging of the software.

A limited number of vehicle runs have been completed, sufficient to identify that there is a noticeable reduction in the diesel injection period when hydrogen is introduced as an enabling gas. Since the driver is part of the open loop feedback and the throttle level is directly related to the increased or reduced demand for diesel to maintain a required speed, it is possible to stop and start the hydrogen supply and analyze the diesel injection period changes in post processing.

The testing to date simply indicates a benefit from using hydrogen as a modifying gas. There is insufficient energy value in the hydrogen gas to account for the reduction in diesel demand. This is only a qualitative analysis at this time. Full rolling road dynamometer testing will provide an accurate and repeatable set of quantitative results.

The graph indicates the type of information achieved with the computer system on a first run of the vehicle when fully instrumented. There was no hydrogen used in this 40+ minute test.

Conclusions

The BH1 vehicle has been modified and is prepared as a sophisticated mobile test bed. Once the extensive tests have been completed using a rolling road dynamometer, it is intended to have this vehicle placed into normal everyday service in and around the Toledo Metro area.
To date, the limited test data acquired when driving around the Toledo area shows an improvement in fuel economy of at least 10%. The testing has been of limited duration but has included high speed operation around the I-75 and I-475 road system.

The vehicle hydrogen enhancement system needs to be optimized and the hydrogen gas supplied to the engine derived from either electrolyzed water or fuel cracked syngas in order that a safe and economical system is created. It must be expected that an overall improvement of fuel economy will be around 10% and may be as high as 15%.

Projecting the benefits to a fleet of 173 buses, and using the 2006 TARTA annual records for average fuel economy of 4.08 mpg and average vehicle usage of 25,000 miles then the following is possible (the dollars saved are gross estimates and do not include the cost to retrofit the engines):

- The annual savings of fuel purchased at $2.20 per gallon with a 10% improvement in fuel economy will be $233,100 for the fleet.
- This represents an annual reduction of 1.17 thousand tons of carbon dioxide emissions for the fleet.

It is proposed that the benefits of fitting the standard 40 ft urban bus with a safe and reliable hydrogen fuel enhancement system will reap major benefits in the fuel cost savings and the reduction in greenhouse gas emissions.

The one further benefit from using hydrogen gas is the improved efficiency of engine operation which can be directed to producing greater power from a given engine. This characteristic enables the use of lower calorific (energy content) fuels such as B-50 and even B-100 without degrading the performance of the vehicle in normal operation. This has the advantage that a vehicle fleet operator such as TARTA could eventually operate all its vehicles on fully renewable fuels.
NEW ACTIVITIES PLANNED FOR YEAR 2

1. Resolve TARTA fuel data collection concerns and increase dramatically the amount of data available for analysis of fuel consumption and fuel costs.

2. Identify the type of bus routes to determine if there is a relationship between the route (stop-and-go or over the road) and fuel economy.

3. Investigate the differences in fuel economy between vehicles with different engines: Thomas buses versus the Bluebird buses, and TARTA buses and City of Toledo vehicles.

4. Conduct detailed analysis of maintenance costs to determine if there is a relationship between the type of fuel used and engine related maintenance.

5. Expand the number of City of Toledo vehicles in the program so side-by-side comparisons can be done.

6. Conduct in-vehicle testing of air quality for the City of Toledo vehicles.

7. Perform tailpipe testing for buses on specific routes.

8. Investigate different levels of biodiesel from B-5 up to B-100.


10. Investigate the possibility of using additives in ULS diesel and in B-20 to determine if there are differences in fuel economy and emissions.

11. For the hydrogen boost project, conduct additional testing on the rolling dynamometer, tail pipe emissions, and fuel economy.
Addendum to Progress Report:

Toledo Area Regional Transit Authority (TARTA) and the City of Toledo Bio-Diesel Study

Talking Points
Addendum to Progress Report:
Toledo Area Regional Transit Authority (TARTA) and the City of Toledo
Bio-Diesel Study
Talking Points

With the vision and leadership of Congresswoman Marcy Kaptur, the Toledo Area Regional Transit Authority (TARTA) and the Intermodal Transportation Institute (ITI) at the University of Toledo developed a long-term, large-scale comprehensive research project to understand and assess the impacts of using a mixture of renewable biodiesel (B-20: 20% biofuel and 80% ultra low sulfur diesel) compared to ultra low sulfur diesel. The following make this study unique.

1. The first study that does on-road testing of ultra-low sulfur diesel and first attempt to investigate the impact of using B-20 made with ultra-low sulfur diesel.
2. The testing is exhaustive including nearly 60 vehicles over a three year period and involves more than 5 million miles of operation.
3. With three years of data, it is possible to estimate and compare the life cycle costs of using ultra-low sulfur (ULS) diesel fuel versus B-20 made with ULS diesel.
4. In addition to tail pipe emission testing, this study examines in-bus air quality.
5. The first study that examines the use of hydrogen gas as an additive to B-20.

**Use of B-20**
1. Switching costs from diesel to B-20 for TARTA and the City of Toledo were minimal.
2. There were no unexpected problems in the continuing use of B-20. Initially, both the City of Toledo and TARTA experienced the need to change fuel filters more frequently as B-20 helped to clean the fuel tank and lines.
3. Drivers at TARTA and the City of Toledo felt that the engines ran smoother and quieter, that there was less exhaust smell, and that there was no loss of power with B-20 compared to ULS diesel. They perceived no down side to the use of B-20.
4. Mechanics at TARTA saw no difference in the performance of B-20 compared to ULS diesel. Mechanics at the City of Toledo felt that the vehicles using B-20 ran smoother and quieter and had less odor than similar vehicles using ULS diesel.

**Performance and Costs**
1. The City of Toledo experienced an increase in miles per gallon (MPG) when using B-20 compared to ULS diesel, between 5.5% and 11.0%.
2. TARTA experienced mixed results. For the Bluebird buses, MPG was higher for the buses using B-20 compared to buses using ULS. This is true for stop-and-go as well as over the road routes. For the Thomas buses, the opposite is true. This seems to indicate that engine type/manufacturer makes a difference in MPG.
3. The City of Toledo experienced no significant difference in engine-related maintenance costs while TARTA had mixed results with much lower engine-related maintenance costs in the Thomas buses that used B-20. The opposite was true for the Bluebird buses.
4. There was no difference in engine wear between the B-20 and ULS diesel vehicles.

**Environmental Impact**
1. Overall, there are no significant differences in tailpipe emissions between B-20 and ULS diesel. However, there are significant improvements for both B-20 and ULS diesel compared to low sulfur diesel.
2. There is no difference in indoor air pollution when B-20 is compared to ULS diesel.
3. To reduce emissions, lower idling revolutions/minute and increase engine temperature.

**Hydrogen Enhancement**
1. Projecting a ten percent fuel savings to a fleet of 173 buses, and using the 2006 TARTA usage patterns, the annual savings of fuel purchased at $2.20 per gallon will be $233,100 and represents an annual reduction of 1.17 thousand tons of carbon dioxide. (The dollars saved are gross estimates and do not include the cost to retrofit the engines.)

**Perspectives**
1. TARTA and the City of Toledo are encouraged by the potential fuel savings from B-20
2. TARTA is pleased by the positive impact of B-20 use on emissions. (Emission and air quality testing on the City of Toledo vehicles begins in the second year.)
3. TARTA is purchasing 35 new Bluebird buses and is planning to use biodiesel in all.
4. The City of Toledo is expanding the use of biodiesel in its fleet.

**New Activities Planned For Year 2**
1. Identify the type of bus routes to determine if there is a relationship between the route (stop-and-go or over the road) and fuel economy.
2. Investigate the differences in fuel economy between vehicles with different engines: Thomas buses versus the Bluebird buses, and TARTA buses and City of Toledo vehicles.
3. Conduct detailed analysis of maintenance costs to determine if there is a relationship between the type of fuel used and engine related maintenance.
4. Expand the number of City of Toledo vehicles in the program so side-by-side comparisons can be done.
5. Conduct in-vehicle testing of air quality for the City of Toledo vehicles.
6. Perform tailpipe testing for buses on specific routes.
7. Investigate different levels of biodiesel from B-5 up to B-100.
8. Assess particulates in the exhaust stream.
9. Investigate the possibility of using additives in ULS diesel and in B-20 to determine if there are differences in fuel economy and emissions.
10. For the hydrogen boost project, conduct additional testing on the rolling dynamometer, tailpipe emissions, and fuel economy.

**Policy Consideration for Discussion**
1. The results from the first year could support a policy to require the use of a small amount of biofuel in all diesel fuel (2 to 5%), depending on availability and achieving consistent high quality fuel. Minnesota has a similar requirement that could be investigated.
2. Widespread use of biodiesel requires standards and testing to achieve a consistent, high quality. If Northwest Ohio is to become a center for this activity, it is essential that research and facilities to support this testing be created in our region.
3. With tight budgets in both public and private sector organizations, it is necessary to find ways to offset the extra cost for biodiesel. Alternatives should be examined.
4. It may be reasonable to argue that these incentives will be more than offset by the economic impact of using and paying for fuel grown by farmers in this country rather than shipping our dollars abroad for imported oil. Economic impacts can be assessed.