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

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National Renewable Energy Laboratory (NREL)

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Agenda

• Project objectives and approach
• Mileage accumulation, fuel economy
• Road Calls and Maintenance
• Fuel, fuel filter analysis
• Oil analysis
• Chassis dynamometer emission results
• Conclusions
B20 Fleet Evaluation – Objectives

• Compare vehicles operating in the field on B20 and conventional diesel over 24 months:
  – Engine performance
  – Fuel economy
  – Vehicle maintenance cost
  – Fuel-induced variations in operation and maintenance
  – Lube oil performance
  – Emissions

• Exhibit high degree of experimental control in vehicle selection and duty cycle
• Aid engine OEMs in exploring affects of B20 on engine durability
• Aid potential B20 users in understanding costs, benefits, and differences in operation
B20 Fleet Evaluation – Approach

- 9 mechanically identical Denver RTD transit buses:
  - 2000 Orion V; Cummins ISM
  - 5 operated on B20, 4 on diesel
- Dedicated to Skip Route in Boulder – identical duty cycle
- RTD submitted data electronically from their internal database
  - Fuel, Labor, Parts
- In-use fuel economy and maintenance costs analyzed by NREL
- Fuel delivery and vehicle tank sample analysis
- Periodic oil sampling at drain interval and analysis
- Two study buses emissions tested on chassis dyno at NREL’s ReFUEL facility
Mileage Accumulation

Running Average Monthly Miles Per Bus

- 4,200 miles per month per bus
On-road Fuel Economy

- 4.41 mpg Diesel, 4.41 mpg B20
• 24-month average maintenance costs:
  – $0.54/mile Diesel, $0.51/mile B20
  – Diesel transmission repairs drive difference
Maintenance Costs – Engine, Fuel System

- 24-month average engine and fuel system maintenance costs:
  - $0.05/mile Diesel, $0.07/mile B20

Running Engine, Fuel System Maintenance Cost per Mile

- May 06: Failed injector, all 6 replaced
- June 06: Scheduled cylinder head change, all 6 injectors replaced (again)
Maintenance Costs – Engine, Fuel System

<table>
<thead>
<tr>
<th></th>
<th>Diesel</th>
<th>B20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel pump</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Fuel injector</td>
<td>1</td>
<td>13</td>
</tr>
</tbody>
</table>

- Injector discrepancy driven by replacement of full set, then cylinder head replacement
- No reason to suspect B20 fuel currently
  - Further investigation planned
Road Calls

Running Miles Between Road Calls (MBRC)

- Average MBRCs are comparable
  - 3,197 Diesel, 3,632 B20
Fuel Analysis

- Biodiesel content of delivery samples scattered
  - Changes to fuel blending & sampling implemented May ‘05
- Vehicle samples taken are near B20
- **Knowledge of sampling point is important**
Fuel Analysis

• March 2006 vehicle fuel sample analysis
  – Acid value, peroxides, aldehydes (alkanals) determined by Safest™
  – Acid value and peroxides consistently low as compared to NREL B20 fuel quality survey
  – Alkanals indicate some oxidative degradation, but are not high

<table>
<thead>
<tr>
<th>Vehicle Number</th>
<th>B100 Content Volume %</th>
<th>Acid Value mgKOH/g</th>
<th>Peroxide Safest™ ppm</th>
<th>Aldehyde Safest™ mmol/mL</th>
</tr>
</thead>
<tbody>
<tr>
<td>2207</td>
<td>20.3</td>
<td>&lt;0.1</td>
<td></td>
<td>58.212</td>
</tr>
<tr>
<td>2208</td>
<td>18.4</td>
<td>&lt;0.1</td>
<td>13.22</td>
<td>57.902</td>
</tr>
<tr>
<td>2209</td>
<td>17.4</td>
<td>&lt;0.1</td>
<td>11.59</td>
<td>55.696</td>
</tr>
<tr>
<td>2210</td>
<td>18.7</td>
<td>&lt;0.1</td>
<td>16.75</td>
<td>73.35</td>
</tr>
<tr>
<td>2211</td>
<td>19.7</td>
<td>&lt;0.1</td>
<td>11.42</td>
<td>61.546</td>
</tr>
</tbody>
</table>
Fuel Analysis

- Composite March 2006 vehicle fuel samples had more detailed analysis
  - Higher cetane number
  - Lower sulfur content
  - 2.4% lower B20 energy content

<table>
<thead>
<tr>
<th>Analysis</th>
<th>ASTM Method</th>
<th>B20 Composite</th>
<th>Diesel Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water &amp; Sediment vol %</td>
<td>D2709</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Cloud Point ºC</td>
<td>D2500</td>
<td>-13</td>
<td>-14</td>
</tr>
<tr>
<td>Sulfur ppm</td>
<td>D5453</td>
<td></td>
<td>324</td>
</tr>
<tr>
<td>Sulfur ppm</td>
<td>D2622</td>
<td>272</td>
<td></td>
</tr>
<tr>
<td>Aromatics vol %</td>
<td>D1319</td>
<td>25.6</td>
<td></td>
</tr>
<tr>
<td>Olefins vol %</td>
<td></td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Saturates vol %</td>
<td></td>
<td></td>
<td>73.1</td>
</tr>
<tr>
<td>C mass%</td>
<td>D5291</td>
<td>84.7</td>
<td>86.6</td>
</tr>
<tr>
<td>H mass%</td>
<td></td>
<td>12.9</td>
<td>13.2</td>
</tr>
<tr>
<td>Derived Cetane Number</td>
<td>D6890</td>
<td>51</td>
<td>48</td>
</tr>
<tr>
<td>LHV BTU/lb</td>
<td>D240</td>
<td>17,860</td>
<td>18,307</td>
</tr>
</tbody>
</table>
B20 Fuel Filter Plugging

Three filter plugging events:
1. April 2005 – 2 buses
   - Brown slime
   - Unknown cause
   - Biocide applied to next fuel delivery

<table>
<thead>
<tr>
<th>Bus</th>
<th>% Biodiesel</th>
<th>CFPP °C</th>
<th>Water (ppm)</th>
<th>Bug Alert™</th>
</tr>
</thead>
<tbody>
<tr>
<td>2207</td>
<td>18.4</td>
<td>-24</td>
<td>72</td>
<td>139 (med)</td>
</tr>
<tr>
<td>2208</td>
<td>16.9</td>
<td>-25</td>
<td>77</td>
<td>27 (low)</td>
</tr>
<tr>
<td>2209</td>
<td>19.2</td>
<td>-25</td>
<td>88</td>
<td>57 (low)</td>
</tr>
<tr>
<td>2210</td>
<td>20.3</td>
<td>-25</td>
<td>97</td>
<td>1 (very low)</td>
</tr>
<tr>
<td>2211</td>
<td>15</td>
<td>-30</td>
<td>78</td>
<td>93 (low-med)</td>
</tr>
</tbody>
</table>

2. June 2005 – 1 bus
   - B20 storage tank low in both cases
3. July 2006 – 2 buses
   - Sediment plugged dispenser and fuel filters
Lube Oil Analysis

- One set of oil drain samples (March, April 2006) analyzed by Cummins
- Exponential decay of ZDDP and TBN consistent with previous Cummins testing
- No difference in ZDDP decay between diesel and B20 samples
- TBN decay may be occurring more slowly in B20 samples
## Lube Oil Analysis (cont’d)

<table>
<thead>
<tr>
<th></th>
<th>Diesel</th>
<th>B20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Dilution</td>
<td>Low</td>
<td>Lower</td>
</tr>
<tr>
<td>Metals (evaporative)</td>
<td>No difference</td>
<td></td>
</tr>
<tr>
<td>Metals (engine wear)</td>
<td>Low</td>
<td>Lower @ high mileage</td>
</tr>
<tr>
<td>Soot</td>
<td>Low</td>
<td>50% lower</td>
</tr>
<tr>
<td>Viscosity, viscosity index</td>
<td>No difference</td>
<td></td>
</tr>
</tbody>
</table>
Bus Chassis Dynamometer Testing

- 2 In-Use Buses tested
- Cummins ISM 2000 Engine – No EGR
- In-Use B20 vs. Conventional Diesel Fuel

<table>
<thead>
<tr>
<th></th>
<th>Skip Bus Route</th>
<th>CSHVC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg Speed</td>
<td>15.6 mph</td>
<td>14.2 mph</td>
</tr>
<tr>
<td>Max Speed</td>
<td>40 mph</td>
<td>44 mph</td>
</tr>
<tr>
<td>Stops/mile</td>
<td>0.78</td>
<td>0.75</td>
</tr>
</tbody>
</table>

![Bus Chassis Dynamometer Testing Image]
Bus Chassis Dynamometer Test Results

- NOx (g/mi): ≈ - 4.5%
- THC X 10 (g/mi): ≈ - 29.0%
- CO (g/mi): ≈ - 24.0%
- PM X 10 (g/mi): ≈ - 18.5%
- Fuel Economy (mpg): ≈ - 2%

Error bars show 95% confidence interval of the mean.
Conclusions

• Usage – average mileage comparable
• On-road fuel economy – no significant difference
• Road calls – similar for both groups
• Total maintenance costs – similar
• Fuel System and Engine maintenance costs – no significant difference
• Early B20 splash-blending issues, generally B20 in-tank
• Limited lube oil data suggests no harm with B20 use, some potential benefits
• Significant emissions reductions including NOx
Special Thanks

- US DOE – Stephen Goguen
- NREL – Ken Proc, Bob McCormick, Bob Hayes
- RTD – Lou Ha
- Cummins – Howard Fang
- Blue Sun Biodiesel – Sean and Ryan Lafferty
- Power Service Products – David Forrester