ARB’s Study of Emissions from Two “Late-model” Diesel and CNG Heavy-duty Transit Buses

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ABSTRACT

The Air Resources Board (ARB) led a research effort to collect emissions data from two late-model heavy-duty transit buses in three different configurations. The objectives of the study were 1) to assess driving cycle effects, 2) to evaluate toxicity between late-model heavy duty engine technologies in use in California, and 3) to investigate total PM and ultrafine particle emissions. Chassis dynamometer testing was conducted at ARB’s Heavy-duty Emissions Testing Laboratory (HDETL) in Los Angeles. The impetus behind this work was to compare the emissions from transit buses powered by similar engines and fueled by very low sulfur diesel and compressed natural gas (CNG). Three vehicle configurations were investigated: 1) a CNG bus equipped with a 2000 DDC Series 50G engine, 2) a diesel bus equipped with a 1998 DDC Series 50 engine and a catalyzed muffler, and 3) the same diesel vehicle retrofitted with a Johnson Matthey Continuously Regenerating Technology (CRT™) diesel particulate filter (DPF) in place of the muffler. The CNG engine was certified for operation without an oxidation catalyst. The catalyzed muffler was a Nelson Exhaust Systems’ unit. The CRT was installed new and de-greened prior to testing. The diesel vehicle was fueled by ARCO (a BP company) ECD-1. The duty cycles were, 1) idle operation, 2) a 55 mph steady-state (SS) cruise condition, 3) the Central Business District (CBD) cycle, 4) the Urban Dynamometer Driving Schedule (UDDS); and 5) the New York City Bus Cycle (NYBC). Collection of PM over multiple cycles was performed to ensure sufficient sample mass for subsequent chemical analyses. Information on regulated (NO\textsubscript{x}, HC’s, PM, and CO) and non-regulated (CO\textsubscript{2}, NO\textsubscript{2}, gas-phase toxic HC’s, carbonyl compounds, polycyclic aromatic hydrocarbons (PAH), elements, and elemental and organic carbon) emissions was collected. Size-resolved PM mass and number emission measurements were conducted and extracts from all total PM samples were tested in the Ames mutagenicity bioassay analysis.

This paper introduces the project and provides an overview of some results.
Project Scope

- Five cycles: Idle, SS, CBD, NYBC, UDDS
- Chassis dynamometer testing at ARB’s HDVEL
- Criteria Pollutants ($\text{NO}_x$, total PM, CO, Total HC’s)
- Other Gases of Interest (NMHC, $\text{CO}_2$ and $\text{NO}_2$)
- Panel of Toxics:
  - 13 Carbonyl Compounds (Formaldehyde to Hexanal)
  - VOC’s (1,3-Butadiene, BTEX)
  - 24 PAH’s (Phase distribution from Benzo(g,h,i)perylene to Naphthalene)
- Elemental and EC/OC
- Mutagenicity via Modified Ames Assay
- Size-segregated Ultrafine Mass and Number Emissions
Chassis Dynamometer Laboratory
**Test Vehicles**

<table>
<thead>
<tr>
<th></th>
<th>Natural Gas** “CNG”</th>
<th>Baseline Diesel*** “diesel OEM”</th>
<th>Trap Diesel*** “CRT”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel:</strong></td>
<td>Compressed natural gas</td>
<td>Ultra-low sulfur BP/ARCO ECD-1</td>
<td>Ultra-low sulfur BP/ARCO ECD-1</td>
</tr>
<tr>
<td><strong>Mileage at start:</strong></td>
<td>19,629</td>
<td>15,169</td>
<td>15,569</td>
</tr>
<tr>
<td><strong>MTA Bus#:</strong></td>
<td>5300</td>
<td>3007</td>
<td>3007</td>
</tr>
<tr>
<td><strong>Type &amp; Weight:</strong></td>
<td>New Flyer Transit 33,150 lbs</td>
<td>New Flyer Transit 30,510 lbs</td>
<td>New Flyer Transit 30,510 lbs</td>
</tr>
<tr>
<td><strong>Model Year:</strong></td>
<td>2000</td>
<td>1998</td>
<td>1998</td>
</tr>
<tr>
<td><strong>Engine Manufacturer:</strong></td>
<td>Detroit Diesel</td>
<td>Detroit Diesel</td>
<td>Detroit Diesel</td>
</tr>
<tr>
<td><strong>Engine Model:</strong></td>
<td>Series 50G</td>
<td>Series 50</td>
<td>Series 50</td>
</tr>
<tr>
<td><strong>Displacement/Type:</strong></td>
<td>8.5L/4 cyl/4 stroke</td>
<td>8.5L/4 cyl/4 stroke</td>
<td>8.5L/4 cyl/4 stroke</td>
</tr>
<tr>
<td><strong>After-treatment</strong></td>
<td>None</td>
<td>Catalyzed muffler</td>
<td>Johnson-Matthey Continuously Regenerating Trap (CRT™)</td>
</tr>
</tbody>
</table>

* Buses from Los Angeles County Metropolitan Transit Authority fleet.
** The CNG bus was re-tested after 2 months (~2000mi) of fleet use (“CNG retest”).
*** Baseline diesel and trap diesel were the same vehicle.
Criteria Emissions

CBD Average Results

* PM uncorrected for background

** CRT near detection limit

NOx History for MTA #5300 CNG Bus over CBD

*Tested by WVU for BP’s ECD Demonstration Program

**CNG Fuel Methane No.=77
CRT Effect on Diesel Bus NO\textsubscript{X} Emissions

- Modeling results suggest that a modest increase in the diesel NO\textsubscript{2}/NO\textsubscript{X} fraction (20-25%) results in more benefits than disbenefits.

**Source:**
1) DaMassa, J., “Air Quality Effects of Trap-Related Emissions,” ARB’s International Diesel Retrofit Advisory Committee Meeting, Feb. 6, 2002.
2) Croes, B., J. DaMassa, D. Dabdub, A. Ayala, A. Servin, and D. Drechsler, “Impact of NO2/NO Split in NO\textsubscript{X} Emissions from Diesel Sources Equipped with PM Traps,” In preparation.
Normalized g/mi Emissions of VOC’s

- 1,3-Butadiene
- Benzene
- Toluene
- Ethylbenzene
- o-xylene
- m,p-xylene
- Styrene

• Measurable levels of 1,3-Butadiene in CNG only

Source: Kado, N.Y., R.A. Okamoto, A. Ayala, P.A. Kuzmicky, R. Kobayashi, M. Gebel, L. Zafonte, and P. Rieger, “Chemical and Bioassay Analyses of Toxic Emissions from Compressed Natural Gas (CNG) and Environmentally Clean Diesel (ECD1™) with Oxidation Catalyst and with Particle Trap (CRT™),” In preparation.
Normalized g/mi Emissions of Carbonyls

Normalized Total Carbonyls over CBD
(CRT = 1)

- Formaldehyde
- Acetaldehyde
- Acetone
- Acrolein
- Propionaldehyde
- Crotonaldehyde
- Methacrolein
- Hexanal
- Butyraldehyde
- Benzaldehyde
- Valeraldehyde
- m-tolualdehyde
- Methyl ethyl ketone
Polycyclic Aromatic Hydrocarbons

CBD PAH Emissions*

* All results uncorrected for background
** Excluding Naphthalene

* All results uncorrected for background
** Excluding Naphthalene
EC/OC Split

Variation of Average Fractions for Diesel Baseline

0% 20% 40% 60% 80% 100%
TB NYBC IDLE

EC/TPM OC/TPM Elements/TPM

Variation of Average Fractions for CRT

0% 20% 40% 60% 80% 100%
TB NYBC IDLE

EC/TPM OC/TPM Elements/TPM

Variation in Average Fractions for CNG

0% 20% 40% 60% 80% 100%
TB NYBC IDLE

EC/TPM OC/TPM Elements/TPM

Elemental Composition

- Detectable levels of oil components: Ca, Cl, P, Zn, S
- Wear metal Fe
- Tunnel Blank << Sample

Tunnel Blank (CBD & SS)

- March 2001
  - School bus w/DPF
  - CRC lab inter-comparison: HD Class 8 truck

- June 2001
  - School bus w/DPF

CNG

- Si
- Ca
- Cu
- Fe
- Al

Diesel Baseline

- Al
- Si
- Zn
- Fe

CRT

- Si

CNG retest

- S
Modified Ames Assay Results
Normalized Potency (Rev./µg) for TA98 w/o S9 - CBD

Note: Tunnel Blank << Sample
MOUDI Impactor and CVS PM Measurement Comparison

![Diagram showing MOUDI and TPM measurement comparisons for Diesel Baseline, CRT, and CNG Retest in CBD mg/mile.](image-url)
Particle Size Distributions - Steady State Tests

Note: Diluted exhaust temp. ranged approx. from 80 to 90 F

**Source:**

Caveats and Future Work

• Some data still needs peer review
• Resolution of CVS approach for “low-emission” vehicles needs further study
• Two buses ≠ fleet average
• Assay activity ≠ cancer risk

• **Testing of two CNG buses w/ Oxi Cat underway**

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