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

Presentation to South Coast Air Quality Management District

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Project Scope

- Dynamometer Testing at ARB’s Heavy-duty Vehicle Emissions Laboratory (HDVEL) in Los Angeles
- Five driving schedules and corresponding tunnel blanks: 1) Idle, 2) Steady State (55mph, ~60% rated power), 3) CBD, 4) UDDS, 5) NYCB
- Pollutants: TPM, THC/NMHC, NOx, CO, NO2, and CO2
- On-site Analysis for Speciation of VOC’s
- Carbonyl Compounds
- Phase distribution of PAH’s
- PM extractions for Ames Bioassay
- Elemental Carbon/Organic Carbon Split
- Elements Analysis
- Size-segregated mass emissions (MOUDI)
- Particle number and size distribution (SMPS and ELPI)
- Fuel and lube oil analysis
## Test Fleet

<table>
<thead>
<tr>
<th></th>
<th>&quot;CNG&quot;</th>
<th>&quot;Diesel (OEM)&quot;</th>
<th>&quot;CRT&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
<td>2000 DDC Series 50G</td>
<td>1998 DDC Series 50</td>
<td>1998 DDC Series 50</td>
</tr>
<tr>
<td><strong>Aftertreatment</strong></td>
<td>None</td>
<td>OEM Catalyzed Muffler</td>
<td>CRT™</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>CNG</td>
<td>ECD-1</td>
<td>ECD-1</td>
</tr>
<tr>
<td><strong>Odometer</strong></td>
<td>19,629</td>
<td>15,169</td>
<td>15,569</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>33,150 lbs</td>
<td>30,510</td>
<td>30,510</td>
</tr>
</tbody>
</table>

- Los Angeles County Metropolitan Transit Authority fleet
- 8.5 liter, 4-stroke, turbocharged, 4-cylinder, New Flyer Low 40 passenger transit buses
Experimental Setup
Regulated Emissions

Total PM Uncorrected for TB - CBD

NOx - CBD

THC/NMHC - CBD

CO - CBD

Total PM Uncorrected for TB - SS

NOx - SS loaded cruise

THC/NMHC - SS loaded cruise

CO - SS loaded cruise
Bioassay Analysis

**Procedure**

- Collection of PM on Filter
- Collection of vapor-phase on PUF
- Solvent Extraction
- Salmonella/Microsuspension procedure
- TA98 and TA 100 Tester Strains with and w/o +S9 Metabolic Enzymes
Mutagenicity Results

CBD Emissions

- Mutagen Emissions
- Vehicle Type: CNG.1, Diesel (OEM), CRT, CNG retest
- Mutagen Emissions (+S9) and (-S9)

Steady State Emissions

- Mutagen Emissions
- Vehicle Type: CNG, Diesel (OEM), CRT
- Mutagen Emissions (+S9) and (-S9)

CBD Specific Activity (-S9)

- Specific Mutagenic Activity (Rev/ug)
- Vehicle Type: CNG.1, Diesel (OEM), CRT, CNG retest
- Sample and TBblank

Steady State Specific Activity (-S9)

- Specific Mutagenic Activity (Rev/ug)
- Vehicle Type: CNG, Diesel (OEM), CRT
- Sample and TBblank
Toxic Gas-Phase HC’s - Sampling Methodology

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

Tedlar Bag Collection

On-site GC-FID’s
Carbonyl Compounds

Sampling Methodology and Analysis

- Collection on DNPH cartridges
- High-precision Liquid Chromatography Analysis

Target Analytes

- Formaldehyde
- Acetone
- Propionaldehyde
- Methyl ethyl ketone
- Butyaldehyde
- Valeraldehyde
- Hexanal

- Acetaldehyde
- Acrolein
- Crotonaldehyde
- Methacrolein
- Benzaldehyde
- M-tolualdehyde
Carbonyl Emission for CBD Cycle
(range of values for multiple tests denoted)

- Formaldehyde
- Acetaldehyde
- Total Carbonyls
Carbonyl LOD ~ 0.9

Vehicle Emission (mg/mile)

<table>
<thead>
<tr>
<th>CNG vehicle</th>
<th>Diesel w/CRT</th>
<th>CNG re-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formaldehyde</td>
<td>Acetaldehyde</td>
<td>Total Carbonyls</td>
</tr>
</tbody>
</table>

Carbonyl Emission for SS tests
(range of values for multiple tests denoted)

- Formaldehyde
- Acetaldehyde
- Total Carbonyls
Carbonyl LOD ~ 0.1

Vehicle Emission (mg/mile)

<table>
<thead>
<tr>
<th>CNG vehicle</th>
<th>Diesel w/CRT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formaldehyde</td>
<td>Total Carbonyls</td>
</tr>
</tbody>
</table>

Additional Carbonyls for CBD Cycle

Vehicle Emission (mg/mile)

- Acrolein
- Acetone
- Propionaldehyde
- Butyraldehyde
- Methyl Ethyl Ketone
- Methacrolein
- Benzoaldehyde
- Crotonaldehyde
- Valeraldehyde
- m-Tolualdehyde
- Hexanal

CNG vehicle
Diesel w/CRT
CNG re-test
Carbonyl LOD ~ 0.1
Polycyclic Aromatic Hydrocarbons

TARGET PAHS

Particle Associated PAHs
- Benzo[ghi]perylene
- Dibenz[ah]anthracene
- Indeno[1,2,3-cd]pyrene
- Perylene
- Benzo[a]pyrene
- Benzo[e]pyrene
- Benzo[k]fluoranthene
- Benzo[b]fluoranthene
- Chrysene
- Benzo[a]Anthracene

Semi-Volatile PAHs
- Pyrene
- Fluoranthene
- Methyl Phenanthrene
- Anthracene
- Phenanthrene
- Fluorene

Volatile PAHs
- Dimethyl naphthalene
- Acenaphthene
- Acenaphthylene
- Dimethyl naphthalene
- Biphenyl
- 1-methyl naphthalene
- 2-methyl naphthalene
- Naphthalene

Particle Associated PAH's | OEHHA Unit risk for cancer by inhalation per million (ug/m3)E-1
--- | ---
Benz[a]anthracene | 1100
Chrysene | 11
Benzo[b]fluoranthene | 110
Benzo[k]fluoranthene | 110
Benzo[a]pyrene | 1200
Dibenz[ah]anthracene | 1200

Expected PAH phase distribution in ambient and CARB diesel exhaust samples
*All results not corrected for tunnel blanks and XAD values corrected for background contamination
• **CBD and SS Results PAHs in PM**  
  --Diesel (OEM)-Most PAHs Detected  
  --CNG CBD - Most PAHs m.w. 252 Not Detected except for BaP  
  --CNG SS- All PAHs m.w. 252 Not Detected  
  --CRT- CBD and SS Only Benz[a]anthracene and Chrysene Detected  

• **CBD and SS Semi-volatile PAHs**  
  --Diesel (OEM) Generally the Highest Levels  
  --CNG Similar Levels to Diesel OEM  
  --CRT Lowest Levels  

• **CBD and SS Volatile PAHs**  
  --At Similar Levels  

• **Fluoranthene and Pyrene Phase Distribution**  
  --CBD Diesel(OEM)-Primarily in Filter  
  --SS Distributed more evenly between the Filter and PUF  
  --CRT and CNG-Primarily in PUF
EC/OC and Elemental Analysis

**EC/OC Procedure**
- Quartz-Filter Collection of PM
- DRI/IMPROVE Optical/Thermal Analysis

**Elemental Analysis**
- Teflon-Filter Collection of PM
- X-ray Fluorescence

Primary Dilution Tunnel
Sampling Probes
Average Composition of PM

- OC dominates CNG PM composition across all cycles
- Similar tunnel blank composition
- EC/OC fraction in Diesel (OEM) PM shows strong cycle dependence
- OC dominates CRT PM composition across all cycles

**NOTE:** TPM = Total PM = EC + OC + Elements
Elemental Analysis Results

- Ca, Cl, P, Zn, S are oil components
- Fe from engine wear
- Si source unknown
- Si emissions: Diesel (OEM) >> CNG ~ CRT
- In general, TB << SS and CBD

**NOTE:** Cumulative results per test sequence, not per cycle
CRT Effect on Diesel Bus NO$_x$ Emissions

Ave NO/NO$_2$ Split from "Baseline" Diesel Bus

<table>
<thead>
<tr>
<th></th>
<th>NO g/mi</th>
<th>NO$_2$ g/mi</th>
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</thead>
<tbody>
<tr>
<td>CBD</td>
<td>29.28</td>
<td>0.92</td>
</tr>
<tr>
<td>SS</td>
<td>22.49</td>
<td>2.14</td>
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</tbody>
</table>

Ave NO/NO$_2$ Split in CRT-equipped Diesel Bus

<table>
<thead>
<tr>
<th></th>
<th>NO g/mi</th>
<th>NO$_2$ g/mi</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBD</td>
<td>17.7</td>
<td>16.7</td>
</tr>
<tr>
<td>SS</td>
<td>13.8</td>
<td>12.7</td>
</tr>
<tr>
<td>NYBC</td>
<td>28.3</td>
<td>23.8</td>
</tr>
<tr>
<td>UDDS</td>
<td>14.1</td>
<td>9.0</td>
</tr>
</tbody>
</table>

Ave % NO$_2$ in CRT Exhaust

<table>
<thead>
<tr>
<th></th>
<th>Ave % NO$_2$ in Total NOx</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBD</td>
<td>45</td>
</tr>
<tr>
<td>SS</td>
<td>45</td>
</tr>
<tr>
<td>NYBC</td>
<td>45</td>
</tr>
<tr>
<td>UDDS</td>
<td>45</td>
</tr>
</tbody>
</table>
Average of Individual Scans - Mini-diluter- SS Tests
SIZE-SCAN MODE

Note: CNG retest#1 = 55mph, 0% gradient, CNG retest#2=55mph,0.6% gradient
Final Remarks

Regulated and NO₂ Emissions

• CRT showed reductions in CO (87%), THC (100%), and uncorrected PM (88%) relative to Diesel (OEM)

• CRT and Diesel OEM NOₓ not significantly different

• Significantly different NO₂/NOₓ ratios in CRT (50%) and Diesel OEM (3%)

• CNG NOₓ exhibited high variability. CNG re-test NOₓ was 75% of Diesel (OEM) NOₓ

Ultrafine Number Emissions

• CRT showed reduction in size distribution across entire size range compared to Diesel OEM

• Only accumulation mode was evident in diesel

• For SS, modes in CNG size distributions were not distinct, but nanoparticle (<50nm) concentrations were higher than for CRT

• For SS, total particle numbers were always lower for CNG and CRT compared to Diesel OEM
Final Remarks (cont’d)

Toxic Hydrocarbons and Carbonyl Compounds

- Butadiene was only detected in CNG vehicle exhaust (with 1 exception: Diesel without trap idle test).

- Generally, BTEX concentrations in CVS exhaust samples were close to ambient levels

- Generally, BTEX emission follows the order: CNG > Diesel (OEM) > CRT

- Carbonyl emissions from CNG vehicle were much higher than from CRT-equipped vehicle

- Total carbonyl emissions (by mass) from CNG vehicles are two orders of magnitude higher than BTEX and 1,3 Butadiene emissions

- CNG vehicle carbonyl emissions are dominated (>80%) by formaldehyde
Composition of PM

- OC dominates CNG PM composition across all cycles.
- Similar tunnel blank composition.
- EC/OC fraction in Diesel (EOM) PM shows strong cycle dependence.
- OC dominates CRT PM composition across all cycles.
- Ca, Cl, P, Zn, S are oil components.
- Fe from engine wear.
- Si source unknown. Emissions: Diesel (OEM) >> CNG ~ CRT.

PAH’s and Bioassay

- Emission rates (ug/mi) for most PAH’s were higher in the CBD than SS.
- Emission rates for CNG retest were generally higher than CNG.
- Differences were observed in the properties of PM from CNG, Diesel (OEM), and CRT.
- CRT PAH levels are similar levels to TB’s.
- Generally, CNG and Diesel (OEM) are higher than TB’s.
- Emissions of mutagenic compounds showed cycle dependence.
- For CBD, bioassay follows: CNG > Diesel (OEM) > CRT.
- For SS, bioassay follows: CNG > CRT > Diesel (OEM).