Emissions of Toxic Pollutants from Compressed Natural Gas and Ultra-low Sulfur Diesel - Fueled Transit Buses

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Overall Objective

Investigate the regulated and toxic pollutant emissions from heavy-duty vehicles with and without control technologies.
Project Aims

- Investigate toxic emissions for CNG and ULSD-fueled heavy duty diesel vehicles
- Investigate the effect of after-treatment control technologies on emissions
- Investigate the effect of test cycles on emission rates
- Investigate ultrafine PM emissions
Study is a “snap-shot” of the fleet and not a fleet average
Research Team

- Dept. Environmental Toxicology, UC Davis; Dept. Environmental Engineering, UC Davis.

Contributing:
- South Coast AQMD, UCLA
Experimental Design

Emissions

Gaseous

PM - Toxics

VP - Toxics

Chemical

Chemical

Bioassay

Chemical

Bioassay
# Vehicle Configurations

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Diesel w/ OC</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Diesel w/ DPF</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>CNG no OC</td>
<td>✔</td>
<td></td>
</tr>
<tr>
<td>CNG w/ OC</td>
<td></td>
<td>✔</td>
</tr>
</tbody>
</table>
# Vehicles and After-Treatments

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Model Yr</th>
<th>Engine Make</th>
<th>After-Treatment (Study)</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>1998</td>
<td>DDC-S50</td>
<td>DOC (1a)</td>
<td>ULSD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OC-DPF (1a)</td>
<td></td>
</tr>
<tr>
<td>CNG 00</td>
<td>2000</td>
<td>DDC-S50G</td>
<td>None (1a &amp; 1b)</td>
<td>CNG</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>OC (1b)</td>
<td></td>
</tr>
<tr>
<td>CNG 01</td>
<td>2001</td>
<td>Cummins-Westport C-Gas Plus</td>
<td>OC (1b)</td>
<td>CNG</td>
</tr>
</tbody>
</table>
Catalyzed Diesel Paticulate Filter (DPF) for DDC 50 Diesel (Johnson-Matthey, Inc)
Oxidative Catalyst for CNG DDC S50G Engine
Fuels

- Ultra-Low Sulfur Diesel (ULSD)
  - < 15 ppm sulfur
- Compressed Natural Gas (CNG)
  - Methane (mole %): > 88%
Measurements
Phases 1a & 1b

- Regulated pollutants (TPM, THC/NMHC, NOx, NO₂, CO, CO₂)
- On-site, VOC-GC analyses c matching off-site analyses
- Elemental/Organic Carbon
- Elements
- PM size-segregated mass (1a only), PM number & size
Toxic Pollutant Measurements

- Polycyclic Aromatic Hydrocarbons (PAHs)
- Carbonyls, BTEX, 1,3 Butadiene
- Bioassay - mutagenicity
Sampling
Central Business District (CBD) Cycle

![Graph showing Central Business District (CBD) Cycle]

- Time (seconds)
- Speed (mph)

The graph illustrates the speed variation over time, with the y-axis representing speed in miles per hour (mph) and the x-axis representing time in seconds.
PM Emissions – CBD

PM Emissions

Vehicle Configuration

<table>
<thead>
<tr>
<th>Emissions (mg/mile)</th>
<th>Diesel (OC)</th>
<th>Diesel (DPF)</th>
<th>CNG.00</th>
<th>CNG.00 (OC)</th>
<th>CNG.01 (OC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>119 +/- 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CO Emissions - CBD

CO Emissions

Vehicle Configuration

Diesel (OC)  Diesel (DPF)  CNG.00  CNG.00 (OC)  CNG.01 (OC)

Emissions (mg/mile)

0  4  8  12
Polycyclic Aromatic Hydrocarbons

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
- Benz[a]Anthracene

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

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

Expected PAH phase distribution in ambient and exhaust samples
Polycyclic Aromatic Hydrocarbons

PM-PAHs - CBD

Vehicle Configuration

Emissions (ug/mi)

Diesel (OC)  Diesel (DPF)  CNG.00a  CNG.00b  CNG.00 (OC)  CNG.01 (OC)

Diesel (OC) 45
Polycyclic Aromatic Hydrocarbons

SV-PAHs - CBD

Vehicle Configuration

Emissions (ug/mi)

Diesel (OC)  Diesel (DPF)  CNG.00a  CNG.00b  CNG.00 (OC)  CNG.01 (OC)

265
Polycyclic Aromatic Hydrocarbons

V-PAHs - CBD

Vehicle Configuration

Diesel (OC)  Diesel (DPF)  CNG.00a  CNG.00b  CNG.00 (OC)  CNG.01(OC)

Emissions (ug/mi)

405  196
Mutagenic Potency

Specific Activity (Potency) - CBD

Vehicle Configuration

Specific Mutagenic Activity (Rev/ug)

0 10 20 30

Diesel (OC) Diesel (DPF) CNG.00a CNG.00b CNG.00 (OC) CNG.01(OC)
Mutagen Emissions - CBD

Mutagen Emissions

Vehicle Configuration

Emissions (rev/mi x 10^5)

Diesel (OC)  Diesel (DPF)  CNG.00a  CNG.00b  CNG.00 (OC)  CNG.01(OC)

PM  SV
HYDROCARBON ANALYSIS

- Tedlar Bag Sampling
- Onsite GC to limit hold time
- SOP # MLD 102/103
  GC/FID Analysis w/cryo-trapping
  Speciation of C2-C12+
- Report:
  Benzene, Toluene, Ethyl Benzene, Xylenes (BTEX)
  and
  1,3 Butadiene
- GC/MS Confirmation of BTEX
Mid Range Chromatogram (T03013; 04/20/01)
Diesel fueled bus no trap, CBD cycle

C2 Hydrocarbons
< 15% of NMHC

Propane/Propene
< 5% of NMHC

n-Alkanes (C9+)

Benzene

Toluene
Mid Range Chromatogram (T03130; 06/07/01)
CNG fueled bus, CBD cycle

C2 Hydrocarbons
~ 70% of NMHC

Propane/Propene
~ 20% of NMHC

n-Butane Isopentane Benzene Toluene
Partial Light End Chromatogram - (04/20/01)
CNG fueled bus; CBD cycle

Isopentane

Pentane

1,3 Butadiene
Total BTEX and Benzene Emission (CBD Cycle)
(Error bars represent 1 std dev of replicate measurements)
(Tunnel blank value = average of mass emissions/miles per cycle)
1,3 Butadiene Average Emission (CBD Cycle)
(Error bars represent 1 std dev of replicate measurements)
(Tunnel blank value = average of mass emissions/miles per cycle)

1,3 Butadiene was not detected for any vehicle configuration or tunnel blank except CNG.00 Without OxiCat
Carbonyl Analysis

- Heated line Sampling
- DNPH Coated Silica Cartridges
- SOP # MLD 104
  Extraction with Acetonitrile
  HPLC analysis w/ UV Detection
  13 Target Compounds
Average Carbonyl Emissions (CBD Driving Cycle)
(Error bars for carbonyl sum derived from 1 std dev of replicate runs)
(Tunnel blank value = average of mass emissions/miles per cycle)

Both OxiCat and DPF usage show large reduction in formaldehyde
Summary

- DPF reduces PM, CO, HC, NMHC, EC, OC, elements
- DPF also reduces carbonyls, VOCs, PM-bound and semivolatile PAHs, and PM-bound and semivolatile mutagen emissions
- CNG catalyst reduces PM, OC, CO, HC, NMHC, CH$_4$
- CNG catalyst also reduces carbonyls, VOCs, semivolatile PAHs, and PM-bound and semivolatile mutagen emissions
Summary

• NO\textsubscript{X} from CNG engines approximately 50% lower than NO\textsubscript{X} from diesel engine

• DPF-equipped bus has NO\textsubscript{X} emissions that contain 50% NO\textsubscript{2}

• Although not shown, test cycle differences are seen

• After-treatment durability and deterioration and vehicle maintenance were not evaluated
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