Oxidation Catalyst Effects on Natural Gas Transit Bus Ultrafine Particle Emissions

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* The statements and opinions expressed in this paper are solely the authors’ and do not represent the official position of the California Air Resources Board. The mention of trade names, products, and organizations does not constitute endorsement or recommendation for use.
The majority (69%) of the compressed natural gas (CNG) transit buses operating in the Los Angeles, CA metropolitan area currently operate without oxidation catalysts. A series of laboratory chassis dynamometer tests was conducted to compare ultrafine (< 100 nm) particle emissions emitted by a CNG transit bus with and without an oxidation catalyst. Particle number distributions were measured with a TSI model 3936 Scanning Mobility Particle Sizer (SMPS) with a long DMA and ultrafine CPC and samples were collected simultaneously under two dilution conditions – a one-stage mini-dilution of raw exhaust and an EPA-approved constant volume sampler (CVS). Average idle mode ultrafine total particle emissions from the CNG bus were 40 – 180 times lower than a baseline diesel bus operating on ultra-low sulfur fuel and agreed within a factor of 2 under both dilution conditions. In contrast, during 55 MPH steady-state driving, the CNG vehicle number emissions were 20 times higher when measured in the CVS tunnel compared to the mini-diluter. Surprisingly, this relationship was unchanged by addition of an oxidation catalyst to the CNG vehicle. While the results of this study suggest CNG vehicles may emit significantly higher nanoparticle concentrations than trap-equipped diesel buses, the source of these particles has not been fully identified. It is suspected that oil composition and consumption rate may play a role and further investigation of more vehicles is warranted both in the laboratory and on the road.
Overview

• **ARB’s Transit Bus Emissions Study 2001**
  – Preliminary findings published, accepted, or in draft
    • [http://www.arb.ca.gov/research/cng-diesel/cng-diesel.htm](http://www.arb.ca.gov/research/cng-diesel/cng-diesel.htm)
  – “snap-shot” of fleet: “toxicity” comparison
  – two late-model, similar-engine, in-use Los Angeles transit buses:
    • Diesel +/- DPF
    • CNG (no Oxidation Catalyst)
  – Steady-state and Transient cycles (CBD, NYB, UDDS)

• **CNG +/- Oxidation Catalyst May 2002**

• **SMPS Particle Size Distributions**
  – Idle and 55 mph Steady-State
LA Transit Bus Fleet (Nov. ’01)

2001 LAMTA Bus Fleet Mix

- 594 Diesel+Cat.
- 800 Diesel+DPF
- 1331* CNG (No Cat.)
- 20 CNG+Cat.

*Including 370 NG buses on order

Cat = oxidation catalyst
DPF = diesel particulate filter
### 2001 Test Vehicles

|                                | Natural Gas**
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>“CNG”</td>
</tr>
<tr>
<td>Fuel:</td>
<td>Compressed natural gas</td>
</tr>
<tr>
<td>Mileage at start:</td>
<td>19,629</td>
</tr>
<tr>
<td>MTA Bus#:</td>
<td>5300</td>
</tr>
<tr>
<td>Type &amp; Weight</td>
<td>New Flyer Transit</td>
</tr>
<tr>
<td>Model Year:</td>
<td>2000</td>
</tr>
<tr>
<td>Engine Manufacturer:</td>
<td>Detroit Diesel</td>
</tr>
<tr>
<td>Engine Model:</td>
<td>Series 50G</td>
</tr>
<tr>
<td>Displacement/Type:</td>
<td>8.5L/4 cyl/4 stroke</td>
</tr>
<tr>
<td>After-treatment</td>
<td>None</td>
</tr>
</tbody>
</table>

|                                | Baseline Diesel***
|                                | “diesel OEM”    |
| Fuel:                          | Ultra-low sulfur |
| Mileage at start:              | 15,169          |
| MTA Bus#:                      | 3007            |
| Type & Weight                  | New Flyer Transit |
| Model Year:                    | 1998            |
| Engine Manufacturer:           | Detroit Diesel  |
| Engine Model:                  | Series 50       |
| Displacement/Type:             | 8.5L/4 cyl/4 stroke |
| After-treatment                | Catalyzed muffler |

|                                | Trap Diesel***
|                                | “CRT”          |
| Fuel:                          | Ultra-low sulfur |
| Mileage at start:              | 15,569          |
| MTA Bus#:                      | 3007            |
| Type & Weight                  | New Flyer Transit |
| Model Year:                    | 1998            |
| Engine Manufacturer:           | Detroit Diesel  |
| Engine Model:                  | Series 50       |
| Displacement/Type:             | 8.5L/4 cyl/4 stroke |
| After-treatment                | Johnson-Matthey Continuously Regenerating Trap (CRT™) |

* Buses from Los Angeles County Metropolitan Transit Authority fleet

** The CNG bus was re-tested after an additional two months (~1500 miles) of fleet use (“CNG retest”).

*** Baseline diesel and trap diesel were the same vehicle.
J-M Continuously Regenerating Technology (CRT®)

• Passive aftertreatment
• Requirements:
  • Ultra low S fuel <15 ppm
  • exhaust T 275 ºC (40-50% of time)
  • NOx/PM ratio 8 (20 better)
  • Engine should be well-maintained
• One of 2 DPF’s verified by ARB in California
  • > 85% PM emission reduction (Level 3)
• Retrofit for >1994 model years
Dual Dilution Setup

Ambient Air

CVS intake air filters

Raw exhaust inlet into CVS (into page)

CVS Primary Dilution Tunnel 18” diameter

Compressed Air

Dilution Air

Mini-diluter

SMPS

ELPI

Mini-Diluter

CVS SMPS

SS probe box

△P Magnehelic

△P Thermocouple
ARB’s Dynamometer Lab
Mini-Diluter at CVS Exhaust Inlet

CVS tunnel

Probe in CVS inlet pipe
Mini- Diluter

Raw exhaust inlet into CVS (into page)

Compressed Air

Silica gel

Activated charcoal

ELPI

Dilution Ratios

~ 65 & 18 in 2001
~ 25 in 2002

Mini-diluter SMPS

30 Lpm

1.5 Lpm

30 Lpm

1.5 Lpm

Excess

HEPA

ΔP

Magnehelic

Thermocouple

ΔP

ΔP

ΔP

ΔP

ΔP

ΔP

ΔP

ΔP
CVS Sampling Station

Dilution Ratios ~ 8 to 25 (cycle & bus dependent)
Scanning Mobility Particle Sizer

- TSI 3080 Classifier, 3025A CPC
- 1.45 Lpm aerosol flow rate (14.5 Lpm sheath)
- 2-min up-scans & 30-sec retrace
- 6 – 225 nm
- dN/dlogDp (AIM ver4.3)
- TB and DR-corrected
2001 IDLE TESTS

2001 STEADY-STATE 55 MPH

CNG vs Diesel OEM
2001 Data Summary

- Both CNG & CRT configurations reduced number concentration by 10–100x compared to Diesel Baseline.
- Cycle effects: SS55 and NYB highest Total N.
- CRT had lowest Total N on all cycles except UDDS.
- CVS dilution artifacts hinder interpretation of real-world ultrafine distributions.
- CNG bus high NP mode may reflect higher nucleation of semi-volatile gas species due to lack of oxidation catalyst.
- Need to test CNG with oxidation catalyst…
**2002 Test Vehicles**

<table>
<thead>
<tr>
<th>Data label</th>
<th>Cummins</th>
<th>DDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>Cummins w/Oxi Cat #134</td>
<td>DDC CNG-3 #5300</td>
</tr>
<tr>
<td>Fleet</td>
<td>Omnitran New Flyer</td>
<td>Los Angeles MTA New Flyer</td>
</tr>
<tr>
<td>Chassis</td>
<td>New Flyer</td>
<td>CNG</td>
</tr>
<tr>
<td>Capacity</td>
<td>40 passenger</td>
<td>40 passenger</td>
</tr>
<tr>
<td>Fuel</td>
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<td>CNG</td>
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<tr>
<td>Engine</td>
<td>C 8.3 G-plus</td>
<td>Series 50 G</td>
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<tr>
<td>Model year</td>
<td>2001</td>
<td>2000</td>
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<tr>
<td>Mileage at start:</td>
<td>18,700</td>
<td>56,600</td>
</tr>
<tr>
<td>After-treatment</td>
<td>Oxidation Catalyst (OC) 18,700</td>
<td>OEM* and OC** 4,300</td>
</tr>
<tr>
<td>Total miles on OC</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**DDC is same bus as 2001**

**OEM configuration is with no controls**

**1st DDC 50G w/Oxi Cat on New Flyer chassis**
## CNG buses: Fuel and Lube Oil

<table>
<thead>
<tr>
<th></th>
<th>Cummins</th>
<th>DDC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel (3 samples)</strong></td>
<td>Methane No. &gt; 100</td>
<td>Methane No. &gt; 100</td>
</tr>
<tr>
<td><strong>Oil:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additives</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Wear Metals</td>
<td>Normal</td>
<td>Normal</td>
</tr>
<tr>
<td>Chlorine</td>
<td>25 ppm</td>
<td>12 – 22 ppm</td>
</tr>
<tr>
<td>Copper</td>
<td>73 ppm</td>
<td>Normal</td>
</tr>
</tbody>
</table>
CNG buses: Idle

**Mini-diluter**

- Cummins w/Oxi Cat
- DDC CNG-3 w/Oxi Cat
- DDC CNG-3

**CVS diluter**

- Cummins w/Oxi Cat
- DDC CNG-3 w/Oxi Cat
- DDC CNG-3
CNG buses: Steady-State 55 MPH

Mini-diluter

- Cummins w/Oxi Cat
- DDC CNG-3 w/Oxi Cat
- DDC CNG-3

\[ \frac{dN}{d\log D_p} \text{ (cm}^{-3} \text{)} \]

\[ D_p \text{ (nm)} \]

Graph showing the distribution of particle number per unit volume (dN/d\log D_p) as a function of particle diameter (D_p) in nanometers, with data points for different conditions.
CNG buses: Tunnel Blanks

Mini Diluter

CVS

Cummins w/Oxi Cat
DDC CNG-3 w/Oxi Cat
DDC CNG-3
CNG buses: Steady-State 55 MPH

Mini-diluter

CVS

- Cummins w/Oxi Cat
- DDC CNG-3 w/Oxi Cat
- DDC CNG-3
Observations 1

- At low-load (IDLE), Cummins engine emits very high nanoparticle concentrations, independent of dilution conditions.

- On mini-diluter, at high-load (SS55) Cummins 100x lower than IDLE; DDC +/- Oxi. Cat. small change IDLE to SS55.

- Mini-diluter gives more reproducible particle size distributions on all steady cycles examined, compared to CVS tunnel.
Observations 2

• CNG nanoparticle mode (~ 20 nm) can exceed diesel OEM emissions.
  – ?what is source of NP mode when have Oxi.Cat.?

• Evidence for possible nucleation in CVS under high-load (SS55) only for CNG buses equipped with oxidation catalysts.

• Tunnel blank role/subtraction very important for low-emission vehicles.
  – Temperature effects on TB vs. cycle
Thank You!

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