Emissions from In-Use NG, Propane, and Diesel Fueled Heavy Duty Vehicles

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Presented By: Kent Johnson
Co-Authors: Thomas Durbin, J. Wayne Miller

University of California, Riverside
Bourns College of Engineering
Center for Environmental Research and Technology
Outline

• Motivation, background, methods

• Results and comparisons to previous studies

• Discuss formation mechanism and root cause

• Impact and discussions
Motivation and Background

- Alternate strategies exist to meet 2010 heavy duty emission standards such as natural gas (NG) and propane fuels

- University of Denver showed high ammonia NH$_3$ (1500 ppm) emissions from NG vehicles (Gary Bishop, CRC 2009)

- Ammonia (NH$_3$) can form ammonium nitrate particulate matter (PM$_{2.5}$) in the atmosphere

- What is the current in-use impact of NH$_3$ emissions between heavy duty fuel applications?
## Test Methods: Vehicles

<table>
<thead>
<tr>
<th>Type</th>
<th>Count</th>
<th>Mfg/Model</th>
<th>Disp</th>
<th>MY</th>
<th>Fuel</th>
<th>A/F</th>
<th>ATS</th>
<th>ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>School Bus</td>
<td>5</td>
<td>GM/8CLFH08</td>
<td>8.1</td>
<td>2008</td>
<td>LPG</td>
<td>SI stoich</td>
<td>TWC</td>
<td>LPG_st_TWC</td>
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<tr>
<td>Box Truck</td>
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<td>GM/7CLFH08</td>
<td>8.1</td>
<td>2007</td>
<td>LPG</td>
<td>SI stoich</td>
<td>TWC</td>
<td>LPG_st_TWC</td>
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<tr>
<td>Shuttle Bus</td>
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<td>GM/BCLFE06</td>
<td>6.0</td>
<td>2009</td>
<td>LPG</td>
<td>SI stoich</td>
<td>TWC</td>
<td>LPG_st_TWC</td>
</tr>
<tr>
<td>Transit Bus</td>
<td>1</td>
<td>CUM/ISL-G280</td>
<td>8.9</td>
<td>2009</td>
<td>CNG</td>
<td>SI stoich</td>
<td>TWC</td>
<td>CNG_st_TWC</td>
</tr>
<tr>
<td>Refuse Truck</td>
<td>1</td>
<td>CUM/CG-250</td>
<td>8.3</td>
<td>2001</td>
<td>CNG</td>
<td>SI lean</td>
<td>OC</td>
<td>CNG_In_OC</td>
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<tr>
<td>Transit Bus</td>
<td>1</td>
<td>JD/6081H</td>
<td>8.1</td>
<td>2003</td>
<td>CNG</td>
<td>SI lean</td>
<td>OC</td>
<td>CNG_In_OC</td>
</tr>
<tr>
<td>Class 8</td>
<td>2</td>
<td>CUM/ISL-G320</td>
<td>8.9</td>
<td>2008</td>
<td>LNG</td>
<td>SI stoich</td>
<td>TWC</td>
<td>LNG_st_TWC</td>
</tr>
<tr>
<td>Yard Tractor</td>
<td>2</td>
<td>CUM/CG-250</td>
<td>8.3</td>
<td>2005</td>
<td>LNG</td>
<td>SI lean</td>
<td>OC</td>
<td>LNG_In_OC</td>
</tr>
<tr>
<td>Class 8</td>
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<td>CUM/ISX450</td>
<td>15</td>
<td>2008</td>
<td>Diesel</td>
<td>CI</td>
<td>DOC/DPF</td>
<td>D_DPF</td>
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<tr>
<td>Class 8</td>
<td>1</td>
<td>DDC/S60</td>
<td>15</td>
<td>1998</td>
<td>Diesel</td>
<td>CI</td>
<td>CRT/SCR</td>
<td>D_CRT/SCR</td>
</tr>
</tbody>
</table>

*Disp* - displacement liters,  *MY* - model year,  *A/F* - air-to-fuel ratio type,  *ATS* - after treatment system


*SI stoich* - spark ignition stoichiometric combustion,  *SI lean* - lean combustion,  *CI* - compression ignition

*TWC* - three way catalyst,  *OC* - oxidation catalyst,  *DPF/SCR* - diesel particulate filter / selective catalytic reduction
Test Methods: Test Repeatability Controlled with UCR’s Chassis Dyno

- Performance
  - 5,000 lb 0-15 mph
  - 600 hp 45-80 mph
  - 200 hp 15 mph
- Acceleration 6 mph/sec
- Inertia Simulation
  - 10 lb increments
  - 10,000 lb – 80,000 lb range
  - 45,000 lb base inertia
- Speed accuracy +/- 0.01 mph
- Acceleration accuracy +/- 0.02 mph/sec
- Response time 44 to 100 ms

(durbin 2010 CRC)
Test Methods: Laboratory Measurements Used

- Mobile emissions laboratory (MEL) established (CO, CO2, THC, CH4, NMHC, PM2.5, NOx) (Cocker 2004 Part I ES&T, Johnson AE 2009, and Johnson ES&T 2010)
- NH3: Integrated tunable diode laser (TDL) spectroscopy (Johnson 2009 CRC)
- Carbonyls: DNPH (Cocker 2004 Part II ES&T)
- Particle size distribution: SMPS (Shaw 2005 ES&T)
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## Results Averaged over Cycles and Vehicles

Each data row represents the average of all vehicles and cycles (UDDS, CBD and Cruise) to highlight ATS affects.

Differences due to vehicles was relatively low.

<table>
<thead>
<tr>
<th>ID</th>
<th>NMHC</th>
<th>CO</th>
<th>NOx</th>
<th>NH3</th>
<th>PM</th>
<th>NH3</th>
</tr>
</thead>
<tbody>
<tr>
<td>n/a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NG Ln OC</td>
<td>0.002</td>
<td>0.113</td>
<td>9.530</td>
<td>0.007</td>
<td>0.001</td>
<td>2.4</td>
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<tr>
<td>LPG Ln OC</td>
<td>0.004</td>
<td>0.029</td>
<td>3.932</td>
<td>0.007</td>
<td>0.001</td>
<td>2.0</td>
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<tr>
<td>NG St TWC</td>
<td>0.001</td>
<td>4.042</td>
<td>0.051</td>
<td>0.397</td>
<td>0.001</td>
<td>151.6</td>
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<td>LPG St TWC</td>
<td>0.001</td>
<td>1.462</td>
<td>0.051</td>
<td>0.135</td>
<td>0.004</td>
<td>97.1</td>
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<td>CRT+SCR</td>
<td>0.034</td>
<td>0.261</td>
<td>1.488</td>
<td>0.005</td>
<td>0.004</td>
<td>1.2</td>
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<tr>
<td>DOC/DPF</td>
<td>0.015</td>
<td>0.030</td>
<td>1.590</td>
<td>0.002</td>
<td>0.001</td>
<td>0.5</td>
</tr>
</tbody>
</table>

1 refer to previous table for description of ID's

2 draft data
Heavy Duty > Light Duty NH$_3$ Emissions on Mile Basis

### NH$_3$ Emissions g/mi

- ln_OC
- st_TWC
- d_CRT+SCR
- DOC/DPF
- 1 TIER 0
- 1 TIER 1
- 1 TLEV
- 1 LEV
- 1 ULEV
- 1 SULEV
- 1 LEV II

1 light duty data source from Livingston et al 2009 AE
Heavy Duty NH₃ Emissions Similar to LD on g/hp-h basis

1 light duty data source from Livingston et al 2009 AE
2 light duty brake specific data estimated from FTP length, time and nominal 30 hp load
Heavy Duty NG NH₃ Emissions is Higher than LPG

1 light duty data source from Livingston et al 2009 AE
2 light duty brake specific data estimated from FTP length, time and nominal 30 hp load
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Why is NH$_3$ High for the Alt Fueled Vehicles?

- Research suggest that NH$_3$ is formed from the water-gas shift reaction (Bradow, 1977 SAE and Cadle et al 1979 SAE)

\[
CO + H_2O \rightarrow CO_2 + H_2
\]

\[
2NO + 2CO \rightarrow 2NH_3 + 2CO_2
\]

\[
2NO + 5H_2 \rightarrow 2NH_3 + 2H_2O
\]

- Several researchers reported that NH$_3$ emissions were present on light duty gasoline vehicles equipped with TWC under rich conditions (Durbin et al, 2000 ES&T and Huai et al, 2003 ES&T)

- GM research suggested controlling NO$_x$ emissions using NH$_3$ formation over the catalyst (Viola et al, 2010 DEER)
NG Vehicles Show High NH₃ and CO During Cruise

NH₃

SCR Diesel, Diesel

LNG = 250 ppm NH₃

2000 Diesel

LNG#1 3Way Catalyst

SCR Diesel = 2 ppm NH₃

2008 Diesel = <1 ppm NH₃

CO

LNG #1 3Way Catalyst

1998 SCR/DPF Diesel Retrofit

2000 Diesel

LNG #2 3Way Catalyst

LNG = 0.3 g/s CO (400 ppm)

30 times more CO => Rich cond.

SCR & Diesel = <0.01 g/s CO <15 ppm
Light Duty High NH$_3$ Spikes Occurs at Tip-In

- NH$_3$ emissions in real time show issue occurs during transients accels (US06 cycle 5 times > than FTP: ULEV light-duty gasoline truck)
- Once the vehicle A/F is controlled NH$_3$ is minimal
- Advanced air-fuel ratio controls for SULEV’s show minimal NH$_3$ spikes (Kitagawa et al, 2000)
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Why Does it Matter to Have High NH$_3$ Emissions?

- Urban areas have high congestion and sufficient NO

\[
\begin{align*}
NO + O_3 & \rightarrow NO_2 \\
NO_2 + OH & \rightarrow HNO_3 \\
NO_3 + HNO_3 & \rightarrow NO_2 \\
NH_3 + HNO_3 & \leftrightarrow NH_4NO_3(s)
\end{align*}
\]
Conclusions

• NG and propane vehicles, with SI stoichiometric control, can produce high NH$_3$ emissions over a TWC

• Heavy duty NG NH$_3$ emissions are significantly higher on a g/mi basis, but closer on a g/hp-h basis compared to light duty vehicles

• Propane vehicles produced less NH$_3$ emissions than NG, but still slightly more than LD vehicles

• High NH$_3$ release is associated with high CO
Future Work

- WVU and UCR working together
- 3 more propane and 6 more diesel added to matrix
- Total vehicles 34