Assessment of self-pollution of school buses with various retrofit technologies

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13th ETH Conference on Combustion Generated Nanoparticles, Zurich
June 22-24, 2009
Background

- More than 24 Million children in USA commute by school buses every day
- Studies have shown adverse health effects of traffic exhaust exposure
- Elevated levels of PM$_{2.5}$ and BC inside school buses in Connecticut (Wargo, ‘05), Los Angeles (Behrentz, ‘05; Sabin, ‘05) and Seattle (Adar, ‘08; Zielinska, ‘08)
Motivation

• Most diesel exhaust particles on buses are attributable to bus itself - self-pollution. (Fitz 03; Sabin 05)

• Ireson (2004) reported little self-pollution from the tailpipe

• UW’s bus self-pollution (SP) study; in year 2005 with 2 Seattle buses without CCV (closed crankcase ventilation)

• Liu (2008) and Zielinska (2008) show crankcase contribution greater than tailpipe
Remaining Questions ??

• Can we generalize these results on bus self-pollution?

• Does CCV reduce the crankcase emissions effectively?

• Does DOC (diesel oxidation catalyst) help at all?

• What is the effect of windows open/ closed on bus self-pollution?
Locations and bus routes
## Bus selection

*(Null, DOC, CCV, DOC+CCV)*

<table>
<thead>
<tr>
<th>Bus ID</th>
<th>DOC</th>
<th>CCV</th>
<th>Model year</th>
<th>Engine model</th>
<th>Engine location</th>
<th>Mileage</th>
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<tbody>
<tr>
<td>Seattle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1DC</td>
<td>Y</td>
<td>Y</td>
<td>2002</td>
<td>T444E</td>
<td>F</td>
<td>42,492</td>
</tr>
<tr>
<td>1DX</td>
<td>Y</td>
<td>N</td>
<td>2002</td>
<td>T444E</td>
<td>F</td>
<td>42,492</td>
</tr>
<tr>
<td>2XC</td>
<td>N</td>
<td>Y</td>
<td>2002</td>
<td>T444E</td>
<td>F</td>
<td>49,550</td>
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<tr>
<td>2XX</td>
<td>N</td>
<td>N</td>
<td>2002</td>
<td>T444E</td>
<td>F</td>
<td>49,550</td>
</tr>
<tr>
<td>Tahoma</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5DC</td>
<td>Y</td>
<td>Y</td>
<td>1993</td>
<td>DT360</td>
<td>F</td>
<td>149,605</td>
</tr>
<tr>
<td>6DX*</td>
<td>Y</td>
<td>N</td>
<td>1993</td>
<td>5.9L</td>
<td>R</td>
<td>168,000</td>
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<tr>
<td>7DX**</td>
<td>Y</td>
<td>N</td>
<td>1993</td>
<td>DT360</td>
<td>F</td>
<td>144,201</td>
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<tr>
<td>8DC</td>
<td>Y</td>
<td>Y</td>
<td>1993</td>
<td>DT360</td>
<td>F</td>
<td>160,200</td>
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<tr>
<td>8DX</td>
<td>Y</td>
<td>N</td>
<td>1993</td>
<td>DT360</td>
<td>F</td>
<td>160,200</td>
</tr>
</tbody>
</table>

* Donaldson CCV unit disconnected prior to the tests
* Strong odors reported coming from rear engine compartment into bus during operation
** Engine failure (turbo seals ??) during emission testing; testing aborted
Study design - In-cabin, Lead Vehicle and Source sampling

• A 3-week study (Aug 14-Sep 1, 2006)
• Sampling on 6 buses with total 9 configurations

• **On bus**: Collocated PM$_{2.5}$ samplers at 120 L/min, and PM$_1$ sampler at 16.7 L/min
• Simultaneous sampling of tailpipe and crankcase emissions using two parallel dilution tunnels in most runs

• **On bus and Lead Vehicle**: pDR, Ptrak and EcoChem
Sampling Schematic

1DX
- Without CCV
  - In-cabin sampling
    - Windows closed
    - Two 1-hour samples
  - Source sampling
    - Windows open
    - Two 1-hour samples

1DC
- With CCV (Racor)
  - In-cabin sampling
    - Same as without CCV
  - Source sampling
    - Three 30-min samples from crankcase and tailpipe
    - One 30-min tunnel blank sample

Bus 1 (DOC retrofitted)
Chemical Analysis

- **PM$_{2.5}$** Teflon filters: gravimetric and INAA for Iridium

- **PM$_{2.5}$** quartz filters: detailed organics
  - OC and EC using the TOR-IMPROVE protocol
  - Speciated organic analysis including d-alkane (C$_{36}$D$_{74}$) with GC/MS

- **PM$_{1}$** filters: gravimetric and XRF for trace elements
Estimating self-pollution using tracers

\[ \text{PM}_{2.5, \text{SP}} = \text{PM}_{\text{Tailpipe}} + \text{PM}_{2.5, \text{Crankcase}} \]

\[ = \text{Ir}_{\text{in-cabin}} \frac{\text{PM}_{\text{TP}}}{\text{Ir}_{\text{TP}}} + \text{d-alkane}_{\text{in-cabin}} \frac{\text{PM}_{2.5, \text{Ck}}}{\text{d-alkane}_{\text{Ck}}} \]

- Organo-metallic Ir complex added in diesel fuel as tracer for tailpipe emissions
- d-alkane (C\text{36}D\text{74}) added in lubricating oil as tracer for crankcase emissions
In-cabin total PM$_{2.5}$

**Seattle buses**

- No Retrofit
- DOC
- CCV
- DOC+CCV
- DOC
- DOC
- DOC
- CCV+DOC
- CCV+DOC

**Tahoma buses**

- Windows closed
- Windows open

<table>
<thead>
<tr>
<th>Bus ID and configurations</th>
<th>In-Cabin PM$_{2.5}$ ($\mu g/m^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2XX</td>
<td>20.0</td>
</tr>
<tr>
<td>1DX</td>
<td>15.0</td>
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<tr>
<td>2XC</td>
<td>20.0</td>
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<td>1DC</td>
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<tr>
<td>6DX</td>
<td>60.0</td>
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<tr>
<td>7DX</td>
<td>40.0</td>
</tr>
<tr>
<td>8DX</td>
<td>30.0</td>
</tr>
<tr>
<td>5DC</td>
<td>20.0</td>
</tr>
<tr>
<td>8DC</td>
<td>15.0</td>
</tr>
</tbody>
</table>
In-cabin crankcase PM\textsubscript{2.5}

Seattle buses

- No retrofit
- DOC
- CCV
- CCV+DOC

Tahoma buses

- 2XX
- 1DX
- 2XC
- 1DC
- 6DX
- 7DX
- 8DX
- 5DC
- 8DC

Bus ID and configurations

In-Cabin PM\textsubscript{ck} (μg/m\textsuperscript{3})

Windows closed
Windows open
In-cabin tailpipe PM$_{2.5}$

Seattle buses

<table>
<thead>
<tr>
<th>Bus configurations</th>
<th>In-Cabin PM$_{tp}$ (g/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No retrofit 2XX</td>
<td>Windows closed</td>
</tr>
<tr>
<td>DOC 1DX</td>
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</tr>
<tr>
<td>CCV 2XC</td>
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</tr>
<tr>
<td>CCV+DOC 1DC</td>
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<tr>
<td>DOC 6DX</td>
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<tr>
<td>DOC 7DX</td>
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<tr>
<td>DOC 8DX</td>
<td></td>
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<tr>
<td>CCV+DOC 5DC</td>
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<tr>
<td>CCV+DOC 8DC</td>
<td></td>
</tr>
</tbody>
</table>

Tahoma buses

Windows closed

Windows open
In-cabin OC conc.

Seattle buses

Tahoma buses

Bus ID and configurations

In-Cabin OC (µg/m³)

Windows closed

Windows open

- No Retrofit
- DOC
- CCV
- DOC+CCV
- DOC
- DOC
- DOC+CCV
- DOC
- CCV+DOC
- CCV+DOC

Bus ID:
- 2XX
- 1DX
- 2XC
- 1DC
- 6DX
- 7DX
- 8DX
- 5DC
- 8DC
In-cabin EC conc.

Seattle buses

Tacoma buses

In-Cabin EC (μg/m³)

Bus ID and configurations

Windows closed

Windows open

No Retrofit

DOC

CCV

DOC+CCV

DOC

DOC

DOC

CCV+DOC

CCV+DOC

2XX 1DX 2XC 1DC 6DX 7DX 8DX 5DC 8DC
Continuous measurements

- **PM$_{2.5}$**
  - Windows closed
  - Windows open

- **PN**
  - Windows closed
  - Windows open

Equations:
- \( y = 0.6957x + 1901.8 \)  \( R^2 = 0.9425 \)
- \( y = 0.5375x + 1416.3 \)  \( R^2 = 0.7223 \)
- \( y = 0.6957x + 1901.8 \)  \( R^2 = 0.9425 \)
Comparisons with previous findings

<table>
<thead>
<tr>
<th>Parameters</th>
<th>This study</th>
<th>Liu et al., 2008</th>
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<tbody>
<tr>
<td></td>
<td>Seattle</td>
<td>Tahoma</td>
</tr>
<tr>
<td></td>
<td>No CCV</td>
<td>CCV</td>
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<tr>
<td>Windows closed</td>
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<tr>
<td>SP (μg/m³)</td>
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<td>% PMck/SP</td>
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<td>25</td>
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<tr>
<td>% SP/PM2.5</td>
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<tr>
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<tr>
<td>SP (μg/m³)</td>
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<td>0.3</td>
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<tr>
<td>% PMck/SP</td>
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<td>7</td>
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<tr>
<td>% SP/PM2.5</td>
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</tbody>
</table>

- In our 2005 bus SP study (Liu, 2008), bus model year were 2002 and 1999
- Both had DOC and none CCV
Summary

- Self-pollution ranged 1-8.2 μg/m³ when windows closed; 0.3-3.9 μg/m³ when windows open (wo).
- In-cabin PM$_{2.5}$ and OC were higher when windows closed (wc).
- In newer (2002) buses, crankcase contribute 77 and 87% of SP (wo,wc), while ~30, 55% of SP (wo,wc) in older (1993) buses.
- Crankcase PM$_{2.5}$ ~5-10 times higher than tailpipe PM inside the bus.
- Retrofit CCV control effectively reduced in-cabin PM$_{2.5}$ and OC emissions; DOC did not.
- In cabin PN track roadway levels very well and about 50% of roadway background (wc) and 70% (wo).
Acknowledgements

- National Institute of Environmental Health Sciences (NI EHS) (#1R01ES12657-01A1)
- Gift fund from the International Trucks and Engine Inc. to the University of Washington
- Department of Energy (DoE) office of FreedomCAR and Vehicle Technologies through the National Renewable Energy Lab (NREL)
- Puget Sound Clean Air Agency
- The Seattle School District and its Transportation Department