Lubricant Formulation and Consumption Effects on Diesel Exhaust Ash Emissions: Measurements and Sample Analyses From a HD Diesel Engine

Michael Plumley
Massachusetts Institute of Technology
US Coast Guard Academy
Motivation and Project Objective

- **Motivation**
  - DPF fouling by incombustible ash
  - Detrimental chemical and/or physical effects of ash-related compounds on DPT/DPF catalysts

- **Objective**
  - To determine the effects of lubricant based sulfur and ash-related compounds on particulate emissions
  - To correlate lube-oil consumption and composition to emissions of ash-related species using a rapid test method
Lubricant, Additives, Fuel

Engine

Particulates (incl Ash)
NOx, HC, CO, CO₂, SO₂, etc

Engine-Out Emissions

Exhaust Aftertreatment System:
• Trap (DPF), DOC
• NOx (SCR, LNT, LNC, etc.)
• Combinations

“Clean” Emissions

To Tail Pipe

• DPF fouling by Ash
• Detrimental chemical effects of ash-related compounds on DPT/DPF catalysts may occur

Slide courtesy of Dr Victor Wong
Diesel Particulate Ash

- Not specifically defined
  - ASTM E2403, ASTM 874, D482
  - Regeneration techniques vary

- Composition not fully understood
  - Lubricant metallics a major contributor
  - Sulfated Ash increase = Exhaust Ash increase
  - Engine wear may contribute
  - Sulfur effects
ENGINE

- MY 2002 Cummins ISB 300
  - 5.9L inline 6 cyl
  - Holset variable geometry turbocharger (VGT)
  - Bosch common rail fuel injection
  - Cooled exhaust gas recirculation (EGR)
Test Equipment

Gas Analysis

- Antek SO$_2$ analyzer
- CAI Gaseous Emissions Analyzers
  - 400 HCLD – NO/NOx
  - 300 HFID – Hydrocarbons
- 602P NDIR – CO/CO$_2$/O$_2$
Test Equipment

Electronic Controls

- Calterm II v 7.63
- ECM v. 850
- Extensive DAQ
**Test Equipment**

**Particulate Collection**

- Borosilicate glass fiber filters
- Quartz fiber filters
- PTFE filters
- Sampled undiluted @ 50 to 70 deg C
- Filters conditioned in controlled environment
**Test Equipment**

**Thermogravimetric analysis:**
- VOF
- Ash

**Limited elemental & molecular identification:**
- X-ray diffraction
- X-ray fluorescence
- Gas chromatography
- X-ray photoelectron spectroscopy
Lubricants and Fuels Tested

**Lubricants:**
- **Low Sulfur/Low Sulfated Ash**
  - 0.35% Sulfur
  - 1.0% ash by supplier (1.14% by independent lab ASTM 482, 1.1% MIT TGA)
- **High Sulfur/High Sulfated Ash**
  - 1.45% Sulfur
  - 1.8% ash by supplier (1.65% MIT TGA)

**Fuels:**
- **Syntroleum Fischer-Tropsch (FT) Diesel** - zero sulfur content
  - Comparison to 15ppm & 400ppm Low Sulfur diesel conducted at MIT

**Engine Operating Conditions:**
- Based on Euro-III 13 Mode Test
  - Subset chosen to represent realistic operating conditions
  - A50 (1680 RPM), B75 (2000 RPM), C75 (2345 RPM)
Results: Oil Consumption

- 25% Load
- 75% Load
- 90% Load
- 100% Load
- Expected 75% Load
Results: Oil Derived SO$_2$

SO$_2$ exhaust levels measured w/ 1.5% Sulfur Oil and Zero Sulfur Fuel. Typical oil is only .5% S
Results: PM Emission vs. Oil Chemistry

- Low Sulfur Oil
- High Sulfur Oil

(g/kW-hr)

1000 RPM; 25% Load
1000 RPM; 75% Load
1680 RPM; 50% Load
2000 RPM; 25% Load
2000 RPM; 75% Load
2400 RPM; 75% Load
Test Method: TGA VOF & Ash

Low Sulfur Oil, 1680 RPM, 50% Load

Mass %

Temp (C)

Highly Volatile
VOF
Ash
Results: Ash Emission vs Oil
Sulfated Ash content

- Low Sulfur Oil
- High Sulfur Oil
Results: Raw PM, LOC, Ash

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Lubricant</th>
<th>Raw PM (g/kw-hr)</th>
<th>LOC (g/hr)</th>
<th>Ash (g/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A50 Low S</td>
<td>0.011</td>
<td>5.8</td>
<td>0.099</td>
<td></td>
</tr>
<tr>
<td>A50 High S</td>
<td>0.011</td>
<td>5.8</td>
<td>0.128</td>
<td></td>
</tr>
<tr>
<td>B75 Low S</td>
<td>0.007</td>
<td>7.5</td>
<td>0.102</td>
<td></td>
</tr>
<tr>
<td>B75 High S</td>
<td>0.010</td>
<td>7.5</td>
<td>0.154</td>
<td></td>
</tr>
<tr>
<td>C75 High S</td>
<td>0.008</td>
<td>12.5</td>
<td>0.328</td>
<td></td>
</tr>
</tbody>
</table>

(Each test utilized FT fuel)
### Preliminary Advanced Results: Raw PM, LOC, Ash

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Condition</th>
<th>Raw PM (g/kw-hr)</th>
<th>LOC (g/hr)</th>
<th>Ash (g/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A50</td>
<td>FT Fuel, Low S lubricant</td>
<td>.011</td>
<td>5.8</td>
<td>.099</td>
</tr>
<tr>
<td>A50</td>
<td>FT Fuel, High S lubricant</td>
<td>.011</td>
<td>5.8</td>
<td>.128</td>
</tr>
<tr>
<td>A50</td>
<td>FT Fuel doped w/ .2% L/O</td>
<td>.009</td>
<td>36.0</td>
<td>.124</td>
</tr>
<tr>
<td>A50</td>
<td>FT fuel, gasket material on sample</td>
<td>.011</td>
<td>5.8</td>
<td>.143</td>
</tr>
<tr>
<td>A50</td>
<td>High S Fuel*</td>
<td>.010</td>
<td>7.5</td>
<td>.173</td>
</tr>
<tr>
<td>A50</td>
<td>H₂SO₄ doped PM prior to TGA</td>
<td>.010</td>
<td>7.5</td>
<td>.173</td>
</tr>
</tbody>
</table>

(* test utilized Low S lubricant, all others High S)
Conclusions

- Use of FT fuel increases effectiveness of SO$_2$ tracer technique
- High Sulfur/Sulfated Ash oil contributes to PM increase
- Increased lubricant sulfated ash content and/or oil consumption contributes to increase of ash
- High ash capture rates and preliminary advanced results suggest additional potential sources of ash including:
  - Sulfur contribution
  - Metallics
  - Chemical structure of sulfate or sulfated metallics
Acknowledgements

Victor Wong, PHD
Alexander Sappok
Questions...