Characteristics and Effects of Lubricant Additive Chemistry and Exhaust Conditions on Diesel Particulate Filter Service Life and Vehicle Fuel Economy

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Alexander Sappok, Victor W. Wong, Maureen Murage

Massachusetts Institute of Technology
Sloan Automotive Laboratory
Cambridge, MA
Ash Impacts Diesel Particulate Filter Performance

- Ash Sources
  - Lubricant additives (Zn, Ca, Mg, S, P)
  - Engine wear, corrosion, trace metals in fuels

- Ash Mitigation
  - CJ-4 oil specification - limits sulfated ash to 1.0% maximum
  - Novel DPF designs and substrates – asymmetric, membranes, and others
  - Reduced engine oil consumption

Fundamental Understanding of Ash Properties Lacking
Most of Material Trapped in DPF is Ash

After only 33,000 miles over 50% of material trapped in DPF is ash.

- Ash @ 42 g/l:
  - 75% ash in end-plug (vol.)
  - -27% DPF channel area
  - -40% DPF channel length

No Ash

Ash
Experimental Apparatus – DPF Performance Testing

Cummins ISB used for DPF performance evaluation before and after ash loading tests on accelerated test rig.

- **Cummins ISB 300**
  - Variable geometry turbocharger
  - Cooled EGR
  - Common rail fuel injection
  - Fully electronically controlled

- **Gaseous Emissions**
  - CAI 300 HFID – Hydrocarbons
  - CAI 400 HCLD – NO/NOx
  - CAI 602P NDIR – CO/CO2/O2
  - API 100 E – SO2

- **Particulate Emissions**
  - Sampling and comparison to burner

Cummins ISB 300 with DPF
Accurately Simulate Key Oil Consumption Mechanisms

- Each parameter independently variable
- Precise control of quantity and characteristics of ash generated

**System Specifications**

- Exhaust heat exchangers – counter flow
- Centrifugal blower – backpressure control
- D5.66” x 6” DPF

**Accelerated Ash Loading System**

**System Specifications**

- Exhaust heat exchangers – counter flow
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- D5.66” x 6” DPF
**Key Test Parameters**

**DPF Specifications**
- Substrate – Cordierite D5.66” x 6” 200/12, catalyzed

**Lubricant Composition**
- All oils except pure base oil formulated to 1% sulfated ash

<table>
<thead>
<tr>
<th>Lubricant</th>
<th>ASTM D5185</th>
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<tbody>
<tr>
<td>CJ-4</td>
<td>586</td>
</tr>
<tr>
<td>Base Oil</td>
<td>1</td>
</tr>
<tr>
<td>Base Oil + Ca</td>
<td>3</td>
</tr>
<tr>
<td>Base Oil + ZDDP</td>
<td>1</td>
</tr>
</tbody>
</table>

**Test Fuel** - ULSD (Metals below ICP MDL ~1.0 – 0.05 ppm)

**DPF Ash Loading**
- Ash loading to max 42 g/l (equivalent on-road exposure ~ 240k miles)
- Periodic regeneration cycle
Typical Accelerated Ash Loading Cycle

- **Loading Cycle**
  - 55 cycles
  - 1 hour loading @ 250 °C inlet
  - 15 min. regen @ 600–620 °C inlet
  - Constant exhaust flow rate
  - Exhaust temp. varied via heat exchangers

Temperature Cycles

- Time [hr]
- Pressure Drop [kPa]
- Temperature [°C]

ΔP Cycles
DPF Post-Mortem Analysis

- **DPF Sectioned**
  - (4) Axial sections: 1.5” long
  - (5) Radial samples: ~140 – 180 cells
  - (20) samples per DPF

- **Sample Measurements**
  - Ash weight
  - Ash layer thickness and volume
  - Ash composition XRD, SEM-EDX
Individual Additive Effects on Pressure Drop (Ash)

- Lubricant additive chemistry affects ash properties and pressure drop
- Ca-based ash shows much larger effect on pressure drop than Zn ash

* Assumes: 15 g/hr avg. oil consumption, avg. speed of 40 mph, and full size DPF of 12 L volume
Ash First Accumulates Along DPF Channel Walls

- Ash preferentially deposited in end-plug during later stages of ash build-up
Ash Layer Thickness Profiles Similar for All Lubricants

- **Ash Layer Thickness**
  - Ca and Zn ash show slightly thicker ash layer vs. CJ-4 oil despite lower ash levels
  - Ash deposits on walls before forming ash plug

- **Channel Open Area**
  - Channel area reduced 27% to 40%
  - Despite similar deposit profiles, Zn ash showed much lower pressure drop
  - Ash properties (K) affected by lube chemistry
Additive Chemistry Affects Ash Packing Density

- Significant difference in packing density for ash along wall vs. plug
- Ash in end-plug less densely packed than ash along channel wall for CJ-4 oil
- Variation in packing density less pronounced for Ca and Zn ash

Packing Density [g/cm³]

- 0.30
- 0.25
- 0.20
- 0.15
- 0.10
- 0.05
- 0.00

Axial Distance [mm]

- 57
- 133

CJ-4 42 g/l
Ca 29 g/l
Zn 28 g/l

Zn₂Mg(PO₄)₂, CaSO₄
CaSO₄
Zn₂(P₂O₇), Zn₃(PO₄)₂

[Graph showing packing density at different axial distances with labels for CJ-4, Ca, and Zn]
Ash loaded DPFs exhibit non-linear pressure drop response to PM loading
- Ash decreases pressure sensitivity to low PM loads <0.5 g/l
- Ash increases pressure sensitivity to PM loads >3.0 g/l
Individual Additive Effects: Pressure Drop Sensitivity

Ca and Zn base oils show similar effects on pressure drop sensitivity, particularly for soot loads < 3.0 g/l.

Fully-formulated CJ-4 oil shows largest effect on pressure drop sensitivity.
Ash and Soot Effects on Fuel Economy (CJ-4)

- FEP estimate assumes adiabatic expansion of ideal gas through turbo
- Model inputs from experimental data
- Soot + ash results in largest increase in FEP

\[ FEP \approx \frac{\Delta W_{\text{turbo}}}{W_{\text{engine}}} \times 100 \]
Conclusions

Additive Chemistry Effects on DPF Pressure Drop

- Ash accumulation is a dynamic process – Ash first primarily accumulates along channel walls before forming end plugs at the back of the DPF
- Increase in DPF pressure drop 2X more severe with Ca ash than Zn
- Similar ash properties and pressure drop trends between CJ-4 oil and Ca oil indicate CaSO_4 may be most detrimental ash component

Ash + Soot Effects on DPF ΔP and Fuel Economy

- Ash decreases pressure sensitivity to low soot loads (<0.5 g/l)
- Ash increases pressure sensitivity for soot loads > 3g/l
- Increase in pressure drop sensitivity most severe with fully-formulated oils
- Ash alone results in only small increase in backpressure and fuel economy
- Soot accumulated in ash-loaded DPF results in largest FEP
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