Presentation Overview

- U.S. Emissions Requirements
  - Drivers of new technologies
- Common Rail Injection
- Diesel Particulate Filters
  - Regeneration Strategies
  - Plugging
- Biodiesel Fuel Dilution
- Critical Biodiesel Properties To Avoid DPF Plugging
- NO\textsubscript{x} After-Treatment
- Summary
Progression of US Highway Heavy Duty Emissions Requirements

1988 to 2010

~98% reduction in NOx
~99% reduction in PM
Impact of HD Soot Emissions Regulations in the US

Particulate Matter

Los Angeles

New York City

2007 0.01g/Bhp-Hr, 2,853 miles

1994 0.1g/Bhp-Hr, 285 miles

1988 0.6g/Bhp-Hr, 47 miles

1991 0.25g/Bhp-Hr, 114 miles

1988
475 pounds of P.M. in 120,000 miles

2007
9 pounds of P.M. in 120,000 miles

Photos Courtesy of Freightliner Trucks
Light Duty Gasoline and Diesel Must Now Meet The Same Emissions Regulations

- Both diesel and gasoline need to meet the same Tier 2 Bin 5 requirement
- Diesel fuel price and exhaust after-treatment differential presents the most significant barrier for light duty diesel engines in US vehicles

<table>
<thead>
<tr>
<th>US Federal Emission Standards</th>
<th>CO</th>
<th>NOx diesel</th>
<th>NOx gasoline</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FTP 75 cycle, (g/mi)</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Tier 1 phased in 1994-97</td>
<td>4.2</td>
<td>1.25</td>
<td>0.6</td>
<td>0.10</td>
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<tr>
<td>100,000 mi useful life</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Tier 2 EPA bin</td>
<td>4.2</td>
<td>0.20</td>
<td>0.07</td>
<td>0.01</td>
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<tr>
<td>phased in 2004-09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>120,000 mi useful life</td>
<td>4.2</td>
<td>0.15</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>4.2</td>
<td>0.04</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>0.02</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>0.00</td>
<td>0.07</td>
<td>0.00</td>
</tr>
<tr>
<td>OEM Fleet avg NOx, max</td>
<td>0.07</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Additional standards for NMOG (Non-Methane Organic Gas) and HCHO (formaldehyde)

California LEV 2 is similar to EPA Tier 2 bin 5
Partnership – A Necessity
Fuels, Lubricants, Additives and After-treatment to Achieve Diesel Emissions Targets
## U.S. Reducing Diesel Fuel Sulfur
Direct Correlation With PM Emissions

<table>
<thead>
<tr>
<th>Year</th>
<th>Sulfur Limit</th>
</tr>
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<tbody>
<tr>
<td>1993</td>
<td>500 ppm</td>
</tr>
<tr>
<td>June 2006</td>
<td>Off Highway 500 ppm, 95% On-Highway 15 ppm</td>
</tr>
<tr>
<td>2010</td>
<td>15 ppm On and Off Highway</td>
</tr>
</tbody>
</table>

To Reduce Particulate and for Compatibility With Diesel Particulate Filter (DPF)
Fuel Sulfur Levels, Hardware Changes, and Engine Oils Have Had To Change To Meet Regulations

[Diagram showing various emissions levels and regulations over time, with labels for CJ-4, CI-4, CF-4, CG-4, and CH-4, and color-coding for emissions limits.]
Alternate Emissions Technology Solutions to Meet On-Highway Emission Limits

HD Exhaust Emission Standards

- 1996 Euro 2
- 2000 Euro 3
- US 2004
- 2008 Euro 5
- 2000 Euro 3
- US 2007
- US 2010

Particulate Matter (g/kWh)

NOx (g/kWh)

De-NOx

DPF

SCR

NOx/PM trade-off
Lowering NO\textsubscript{x} Through In-Cylinder Techniques
Exhaust Gas Recirculation (EGR)
Common Rail Direct Injection For Improved Combustion
Reduced Emissions and Better Fuel Economy

- Precise fuel control
- Working pressures to 32,000 psi
- 1µM plunger clearance. Human hair is ~50 µM
- Fuel cleanliness critical
Diesel Particulate Filters (DPF) to Meet PM Requirements
Heavy Duty Trucks 2007 & Passenger Car 2009

Diesel Particulate Filter (DPFs) on All Diesels
Diesel Particulate Filter (DPF) Shown With Wall-Flow Filter Substrate

Removes ~ 97% of Particulate (Carbon)
Diesel Particulate Filter Chemical Reactions

\[ 2\text{NO} + \text{O}_2 \rightarrow 2\text{NO}_2 (~500 \text{ deg F}) \]
\[ \text{PM} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} (~1,000 \text{ deg F}) \]
\[ 2\text{NO}_2 + 2\text{C} \rightarrow \text{N}_2 + 2\text{CO}_2 \]
Active Regeneration
diesel particulate filter (DPF)

- Fuel injection to heat exhaust gas
- Auxilary fuel burner system to heat exhaust gas
- Late post injection with common rail fuel system

Engine exhaust

Clean exhaust

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DPF Regeneration With Dosing Injector
System Used In Most Heavy Duty Truck Applications
2007 Caterpillar ACERT On-Highway Engine Configuration
Combustor for DPF Regeneration

- 2 Fuel Lines (~250 psi)
- 2 Coolant Lines (in/out)
- 1 Air Line
- Spark Plug Igniter
Late Post-Injection in DPF Vehicles Leads to Higher Levels of Fuel Dilution
Multiple Injection Strategy to Control Combustion

- Late post injection is typically used in light duty diesels equipped with Diesel Particulate Filters (DPF)

Source: Robert Bosch GmbH
Crankcase Fuel Dilution With Biodiesel
Properties of Biodiesel Lead to Higher Fuel Dilution Levels Than Mineral Diesel

- Surface Tension
  - Diesel: 22.5
  - RME Biodiesel: 25.4

- Specific Gravity
  - Diesel: 0.852
  - RME Biodiesel: 0.874

- Viscosity, cSt at 100°C
  - Diesel: 1.3
  - RME Biodiesel: 2.4

Late post-injection leads to higher levels of fuel dilution.

Diesel – normal droplet size

Larger fuel spray droplet size

Late post-injection leads to higher levels of fuel dilution.
Late Post Injection Leads to Higher Levels of Fuel Dilution
Crankcase Fuel Dilution With Biodiesel

Higher and Narrower boiling range of biodiesel makes it more persistent once it enters the crankcase.

- OEMs have reported 15-20% fuel dilution (FAME) at oil drain
- OEMs often reduce drain intervals when Biodiesel blends are used
Oil Dilution During Particular Trap Regeneration

Source: Volkswagen
DPF Collects Lubricant Derived Materials

- Impurities and ash forming compounds in diesel fuel collect in the DPF too
DPF Service Life

For Heavy Duty Trucks, EPA has mandated a minimum DPF servicing interval of 150,000 miles and a minimum DPF life of 435,000 miles (10 years or 6,000 hours)

- Soot may be eliminated through oxidation
- Ash must be physically removed
- Engine makers are responsible for DPF maintenance cost if maintenance cycle less than 150,000 miles
### Critical Biodiesel Properties and Specifications
#### DPF Ash Loading

<table>
<thead>
<tr>
<th>Property</th>
<th>ASTM D6751 Limits</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calcium and Magnesium</td>
<td>5 max</td>
<td>EN 14538</td>
</tr>
<tr>
<td>Water and Sediment</td>
<td>0.05 max</td>
<td>D 2709</td>
</tr>
<tr>
<td>Sulfated Ash</td>
<td>0.02 max</td>
<td>D 874</td>
</tr>
<tr>
<td>Carbon Residue</td>
<td>0.050 max</td>
<td>D 4530</td>
</tr>
<tr>
<td>Phosphorous Content</td>
<td>0.001 max</td>
<td>D 4951</td>
</tr>
<tr>
<td>Sodium and Potassium, Combined</td>
<td>5 max</td>
<td>EN 14538</td>
</tr>
</tbody>
</table>
**NO\textsubscript{x} Emissions Control Trends**

U.S. Off-highway Emissions Standards 130<kW<225 (175<hp<300)

The combination of

• **EGR**
• **SCR & Urea** (or NO\textsubscript{x} Adsorber, Light Duty Diesel)
• **TC – Two Compressor (Turbo’s)** and Two Intercoolers

Tier 4 will require ULSD & exhaust after treatment

Tier 1 – 1996

Tier 2 – 2003

Tier 3 – 2007

Tier 4 – 2012 => 2014
Alternate Emissions Technology Solutions to Meet On-Highway Emission Limits

HD Exhaust Emission Standards

- 1996 Euro 2
- 2000 Euro 3
- US 2004
- 2005 Euro 4
- US 2007
- 2008 Euro 5
- US 2010
- CCR
- De-NOx
- DPF

NOx (g/kWh)

Particulate Matter (g/kWh)
In-Cylinder and After Treatment Systems for On- and Off-Highway Heavy Duty

EGR
- Air to Air Cooler
- Two Stage Turbos and Two Stage Intercoolers
- Common Rail Fuel System
- Exhaust Dosing Injector
- Closed Crankcase

Closed Catalyzed Particulate Filter
- SCR Catalyst
- Ammonia Slip Catalyst
- Atomized Urea Solution
- Aqueous Urea Solution Tank (Diesel Exhaust Fluid - DEF)

Chemical Reactions:
1. $4\text{NH}_3 + 4\text{NO} + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}$
2. $2\text{NH}_3 + \text{NO} + \text{NO}_2 \rightarrow 2\text{N}_2 + 3\text{H}_2\text{O}$
Compact DPF-SCR-Urea to Meet Particulate and NOx Standards
Lean NOx Trap Being Used in VW Clean Diesels

- Lean NOx traps highly sensitive to fuel sulfur levels and other contaminants
- Fuel economy penalty as fuel is consumed in after-treatment system
# Diesel Exhaust After-Treatment Systems

<table>
<thead>
<tr>
<th></th>
<th>Positives</th>
<th>Negatives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Particulate Filter (DPF)</td>
<td>✓Scalable to all engine sizes and applications</td>
<td>✓Increased back pressure impacts fuel economy</td>
</tr>
<tr>
<td></td>
<td>✓Highly efficient</td>
<td>✓Periodic maintenance to clean out ash</td>
</tr>
<tr>
<td>Selective Catalyst Reduction (SCR) - Urea</td>
<td>✓Good fuel economy</td>
<td>✓Infrastructure for Diesel Exhaust Fluid (DEF)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>✓Difficult to downsize</td>
</tr>
<tr>
<td></td>
<td></td>
<td>✓Doesn’t work well in city driving mode</td>
</tr>
<tr>
<td>Lean NOx Trap (LNT)</td>
<td>✓No extra fluid required</td>
<td>✓Worse fuel economy</td>
</tr>
<tr>
<td></td>
<td>✓Not sensitive to driving mode</td>
<td>✓Sensitive to sulfur</td>
</tr>
<tr>
<td></td>
<td></td>
<td>✓Reliability for HD applications</td>
</tr>
</tbody>
</table>
Summary

- Emissions regulations are driving new hardware, fuels, and lubricants technologies into the market.
- A systems approach is required in order to meet sometimes conflicting requirements simultaneously.
- The introduction of Common Rail Injection systems has lead to reduced emissions, noise, and fuel consumption but requires very clean fuel.
- Exhaust after-treatment devices are required to meet the latest Particulate Matter (PM) and NOx emissions requirements.
- In-use compliance requirements can result in the OEM being responsible for emissions system performance for 10+ years.
- Late-post injection can lead to elevated levels of biodiesel fuel dilution.
- Diesel Particulate Filters (DPF) require regeneration and can plug due to ash forming compounds.
- The Energy Independence and Security Act of 2007 has a provision for OEMs to capture CAFÉ credits if they produce B20 vehicles (similar to E85 credit for FlexFuel vehicles).