New Technology Diesel Engines - Exhaust Emission Control and Animal Toxicology Study

Dr. John C. Wall
Dr. Jacob McDonald

CARB Chairman’s Research Seminar Series
February 28, 2012
Chairman’s Seminar: New Technology Diesel

• Evolution of Diesel Emission Control Technologies and Characteristics of New Technology Diesel Exhaust – John Wall

• Advance Collaborative Emissions Study (ACES) – The First Animal Toxicology Study of NTDE – Jacob McDonald
Recognize the significant progress we have made together

Regulations driving technology

New Technology Diesel

Technology enabling regulations
Our Products Must Meet Customer Requirements

Low Emissions
Our Products Must Meet Customer Requirements

- High Performance
- Low Noise and Emissions
- Reliable and Durable
- Low Initial Cost
- Fuel Efficient
- Connected and Integrated Systems
- Low Maintenance
Terminology

• TDE – “Traditional Diesel Exhaust”

• NTDE – “New Technology Diesel Exhaust”
Historical Perspective

“So much has been written and said about the diesel engine in recent months that it is hardly possible to say anything new.”

Rudolf Diesel, c. 1910
Evolution of US Heavy Duty Diesel Emission Standards

**On-Highway**
- 1994: 500 PPM (10/93)
- 1998: FUEL SULFUR
- 2002: ULSD 15 PPM (10/06)
- 2014 Tier 4B: ULSD 15 PPM (10/06)

**Off-Highway**
- 1994: 500 PPM (6/07)
- 1998: FUEL SULFUR
- 2002: ULSD 15 PPM (9/10)
- 2014 Tier 4B: ULSD 15 PPM (9/10)
Diesel Technology Development: Critical Subsystems
Evolution of Diesel Technology

- Turbocharged / Aftercooled / 4Valve / 4 Stroke
- Electronic Fuel Systems
- Cooled Exhaust Gas Recirculation
- Diesel Particulate Filter / Oxidation Catalyst
- Selective Catalytic Reduction
- CO₂
Evolution of Diesel Technology

The “revolutionary” step

Ultra-Low Sulfur Fuel

Diesel Particulate Filter / Oxidation Catalyst

Electronic Fuel Systems

Cooled Exhaust Gas Recirculation

Selective Catalytic Reduction

Turbocharged / Aftercooled / 4 Valve / 4 Stroke

1990 2000 2010 2020
2007 And Beyond . . .
Integrating Engine and Aftertreatment

Active Particulate Filter
2007 And Beyond . . .
Integrating Engine and Aftertreatment

Active Particulate Filter
Key to Emissions Reductions in NTDE
Wall-flow Diesel Particulate Filter

Reductions:
- 99+% PM
- 80 to 100% HC, CO
- 80 to 99+% PAH, toxins

Adapted from MECA May 2000
Transition to Clean “New Technology” Diesel: Advanced Component Technologies and System Integration

Fuel Systems
Air Handling
Combustion
Controls
Exhaust Aftertreatment
Ultra Low Sulfur Fuel

New Technology Diesel
New Technology Diesel

• PM levels in New Diesel Technology Exhaust (NTDE) are more than 100-fold lower than in TDE
  – NTDE NOx and PM mass emissions are comparable to CNG and gasoline

• NTDE PM is chemically different from TDE PM
NTDE: Lower Particulate Emissions

CARB Study: Herner et al., EST 43:5928-5933, 2009, data from Table 2. Transit Buses: UDDS Test Cycle
Cummins Certification Emissions Levels

Cold/Hot Composite Results over FTP, Negative Test Results Set to Zero, Deterioration Factor and UAF Applied

<table>
<thead>
<tr>
<th>Year</th>
<th>Model</th>
<th>NOx</th>
<th>PM x 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>C8.3G</td>
<td>3.04</td>
<td>0.037</td>
</tr>
<tr>
<td>2012</td>
<td>ISL G</td>
<td>0.13</td>
<td>0.002</td>
</tr>
<tr>
<td>1990</td>
<td>6CTA8.3 Diesel</td>
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Cummins Certification Emissions Levels

Cold/Hot Composite Results over FTP, Negative Test Results Set to Zero, Deterioration Factor and UAF Applied

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<thead>
<tr>
<th>Year</th>
<th>Engine Type</th>
<th>NOx (g/hp-hr)</th>
<th>PM x 10 (g/hp-hr)</th>
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BS Emissions, (g/hp-hr)
Cummins and Others - Certification Emissions Levels

Cold/Hot Composite Results over FTP, Negative Test Results Set to Zero, Deterioration Factor and UAF Applied

BS Emissions, (g/hp-hr)

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<th>Model</th>
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<th>PM x 10</th>
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<td>2012</td>
<td>ISL9 Diesel</td>
<td>Diesel</td>
<td>0.21</td>
<td>0.002</td>
</tr>
<tr>
<td>2012</td>
<td>Ford 6.8 Gasoline</td>
<td>N/A</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>GM 6.0 Gasoline</td>
<td></td>
<td>0.181</td>
<td>0.005</td>
</tr>
</tbody>
</table>
NTDE: Lower Particulate Numbers

Particles 1e+12/BHP-hr

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDE</td>
<td>304</td>
</tr>
<tr>
<td>NDTE regeneration</td>
<td>33</td>
</tr>
<tr>
<td>NDTE no regeneration</td>
<td>3.9</td>
</tr>
</tbody>
</table>

ACES Study: Khalek et al., CRC, 2009.
NTDE: Less PM and Composition Very Different

[Kittelson, 1998]  [ACES, 2009]
Particulate Matter Composition Breakdown

Pre-Trap: 
- Sulfate/Nitrate: ≥0.1 g/bhp-hr
- Hydrocarbons (Fuel + Lube derived): ≤0.01 g/bhp-hr
- Elemental Carbon + Ash: ≤0.01 g/bhp-hr

Post-Trap: 
- Sulfate/Nitrate: ≤0.01 g/bhp-hr
- Hydrocarbons (Fuel + Lube derived): ≤0.01 g/bhp-hr
- Elemental Carbon + Ash: ≤0.01 g/bhp-hr

-99% Mass

Cummins ISM 2007; Liu et al., Aerosol Science and Technology, 43/11: 1142-52 2009
NTDE: Lower Volatile Organic Compound and Aldehyde Emissions

Hesterberg et al., ES&T 42:6437-45, 2008, data from Tables 5 & 7: transit bus

<table>
<thead>
<tr>
<th>Compound</th>
<th>TDE</th>
<th>NTDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formalde...</td>
<td>5.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Butadiene</td>
<td>4.3</td>
<td>2.3</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>2.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Ethylbenzene</td>
<td>2.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Benzene</td>
<td>1.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Toluene</td>
<td>0.3</td>
<td>0.1</td>
</tr>
</tbody>
</table>
NTDE: Lower Polycyclic Aromatic Hydrocarbon Emissions

Hesterberg et al., ES&T 42:6437-45, 2008, data from Tables 8 & 9: transit bus
Comprehensive exhaust chemical assays have been published documenting orders of magnitude reduction in complex hydrocarbon and nitro-PAH concentrations for NTDE ...
NTDE Reduces Emissions Across a Broad Spectrum of Compounds

<table>
<thead>
<tr>
<th>Category</th>
<th>Reduction Relative to TDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Ring Aromatics</td>
<td>82%</td>
</tr>
<tr>
<td>PAH</td>
<td>79%</td>
</tr>
<tr>
<td>Alkanes</td>
<td>85%</td>
</tr>
<tr>
<td>Hopanes/Steranes</td>
<td>99%</td>
</tr>
<tr>
<td>Alcohols &amp; Organic Acids</td>
<td>81%</td>
</tr>
<tr>
<td>Nitro-PAHs</td>
<td>81%</td>
</tr>
<tr>
<td>Carbonyls</td>
<td>98%</td>
</tr>
<tr>
<td>Inorganic Ions</td>
<td>71%</td>
</tr>
<tr>
<td>Metals &amp; Elements</td>
<td>98%</td>
</tr>
<tr>
<td>Organic Carbon</td>
<td>96%</td>
</tr>
<tr>
<td>Elemental Carbon</td>
<td>99%</td>
</tr>
<tr>
<td>Dioxins/Furans</td>
<td>99%</td>
</tr>
</tbody>
</table>

Khalek et al. 2010, Table 6
Conclusions

• New Technology Diesel Engines, specifically engines operating on Ultra Low Sulfur Diesel fuel and employing oxidation catalysts and wall-flow particulate filters, have fundamentally different (and significantly better!) exhaust characteristics than Traditional Diesel Engines
  – 99+% reduction in particulate mass
  – Chemically different particulate composition
Conclusions

• The best emissions policy and technology come through effective and deep collaboration between government regulatory agencies and industry...
... and Meet the Needs of Our Customers

- High Performance
- Low Noise and Emissions
- Reliable and Durable
- Low Initial Cost
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Low Initial Cost
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