Recent Developments in Integrated Diesel Exhaust Emission Control Technologies

Presented to the Mobile Sources Technical Review Subcommittee - 10/13/99

Manufacturers of Emission Controls Association

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Mobile Source Technical Review Subcommittee

October 13, 1999

Presentation Outline

• Introduction
• Targeted Emissions
• Control Technologies for PM and Toxic Emissions
• Control Technologies for NOx Emissions
• Control Systems
• Conclusions
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**Introduction**

- Significant Progress Has Been Made in Reducing Emissions from Diesel Engines
- Diesel Powered Vehicles Remain a Significant Source of NOx, PM, and Toxic HC Emissions
- Emission Control Technologies Exist to Substantially Reduce Emissions from Diesel Engines
- Technologies Can Be Used in Combination to Substantially Reduce All Emissions

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**The Future Diesel Challenge**

- Current Standards Focus on NMOG, NOx, PM, CO, and Formaldehyde Emissions in Terms of grams/bhp-hr or grams per mile
- California’s Toxic Air Contaminants and EPA’s Urban Air Toxics Initiatives
- Particle Number Issues
- Therefore, the Emission Challenge Will Be More Complex
  * >200 Species of HC
  * Three Major Species of NOx
  * PM (many species, size range <10 nm to >2 microns, number, liquid and gaseous HCs, solid carbon, carbon/organic combinations and sulfur oxides)
The Future Diesel Emission Challenge

• Can All Facets of the Diesel Emissions Issue Be Addressed?
  * Are Control Technologies Available to Remove Both Diesel PM and the Other HC-Based Toxic Emissions?
  * Are These Control Strategies Compatible with Further Reductions in NOx Emissions?
• Yes, If an Integrated Approach Is Used
  * Advanced Engines, Integrated Emission Control Technologies, and Clean Fuels

Technological Solutions

• Existing Emission Controls Can Greatly Reduce Diesel Emissions
  * Oxidation Catalysts, Particulate Filters, Fuel-Borne Catalysts in Combination with Exhaust Controls, Coatings, Modified Engine Components

• Advanced Emission Control Technologies
  * NOx Catalysts, SCR, Plasma Technology, Combined Systems

• New Engine Technologies
  * Common Rail Injection, EGR
Technological Solutions (Cont.)

- Advanced Fuels
  * Low Sulfur, Other Properties (Reductants)
- Integrated Emission Control Will Allow Diesel Engines to Meet the Future Challenges

Light Duty vs. Heavy Duty Catalyst Operating Temperatures

- Light Duty
  * LA-4 150-350C
  * USO6 250-550C
- Heavy Duty
  * Transient 180-450C
  * Supp EURO III 300-430C
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**Diesel Oxidation Catalysts**

- Oxidation Catalyst Control Capabilities
  * PM -- 20-50% Reduction
  * CO and HC -- >90%
  * Toxic HCs -- >70%

- Oxidation Catalyst Operating Experience
  * >5,000,000 Light-Duty Vehicles in Europe
  * >1.5 Million HDEs in the U.S.
  * >250,000 Nonroad Engines
  * Excellent Operating Experience

Oxidation Catalysts Oxidize CO, HC, and SOF to Reduce PM, CO, HC, and Toxic Emissions.
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**Diesel Oxidation Catalysts Are Proven Effective in Removing PM**

- 0.05 g/bhp-hr PM Emissions Can Be Achieved on Both Fuels
- Significant Reductions in CO and HC Emissions Can Be Achieved

![Graph showing PM emissions comparison](chart1.png)

Source: MECA 1999

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**Diesel Oxidation Catalysts Are More Effective when Used With Low Sulfur Fuel**

![Graph showing PM emissions comparison](chart2.png)

Source: MECA 1999
DOCs Destroy Large Fractions of Toxic Emissions

- Toxic Hydrocarbon Compounds Reduced by 68%
- PAH Emissions Reduced by 56%
- 368 ppm Sulfur Fuel

Diesel Particulate Filters Trap Carbon and Adsorbed SOF and Can Be Used to Oxidize CO, and HC to Reduce PM, CO, HC, and Toxic Emissions.
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**Diesel Particulate Filters**

- Filter Control Capabilities
  - PM -- >90% Reduction
  - CO and HC -- >90%
  - Toxic HCs -- >90% Reduction
- Based Filter Operating Experience
  - Several Thousand Trucks and Buses in Commercial Operation in Europe
  - Demonstration Programs in Taiwan, Korea, Sweden, Germany, England, and Other Countries
  - Peugeot Will Offer Filter-Equipped LDVs in 2000
  - Over 10,000 Nonroad Engines Equipped

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**Diesel Particulate Filters Nearly Eliminate PM**

![PM Emissions Graph]

- PM Emissions Well Below 0.02 g/bhp-hr Can Be Achieved on Both Fuels (0.008 with 54 ppm S Fuel)
- Significant Reductions in CO and HC Emissions Can Be Achieved

Source: MECA 1999
Filters Very Effective in Reducing Ultra-Fine Particles

- Ultra-Fine Particles Reduced by in Excess of 99.99 %

Source: VERT 1998

Filters More Effective when Used With Low Sulfur Fuel

Source: MECA 1999
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Filters Destroy Large Fractions of Toxic Emissions

- PAH Emissions Reduced by 89%

Source: MECA 1999

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NOx Abatement Strategies for Diesel Engines
Active HC-DeNOx-System

Exhaust

NOx

HC - Injection (secondary)

NOx Emissions Are Reduced in Two Steps By Up To 50%

NOx Traps

NO + ½O₂ Lean

CO₂

NO₂

Ba(NO₃)₂

Pt

BaCO₃

Al₂O₃
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NOx Traps

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NOx Storage Efficiency

Source: MECA 1999
Cell Geometry Has A Positive Impact on NOx Storage

Source: SAE 1999-01-1279

Urea-SCR Catalyst System

Hydrolysis Catalyst

Ammonia Generation:  
\[ DC(NH_4)_2 + H_2O \rightarrow CO_2 + 2 NH_3 \]

Selective NOx Reduction:  
\[ 4 NO + 4 NH_3 + O_2 \rightarrow 2 N_2 + 6 H_2O \]
\[ HC + O_2 \rightarrow CO (1/3) + CO_2 (2/3) + H_2O \]

Ammonia Blocking (anti slip):  
\[ 4 NH_2 + 3 O_2 \rightarrow 2 N_2 + 6 H_2O \]
\[ 2 CO + O_2 \rightarrow 2 CO_2 \]
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**SCR Temperature Window**

![Diagram showing SCR Temperature Window with different catalysts and their NOx conversion rates]

**PLASMA-ASSISTED CATALYTIC NOx REDUCTION SCHEME**

![Diagram showing plasma-generated catalyst and high energy electrons for NOx reduction]

- **Potential Reductions**
  - NOx and PM Reductions Up to 80% in Laboratory Environment Have Been Reported
  - Must Be Controlled to Prevent Undesirable Byproduct Formation (e.g. N₂O)
Plasma Reactor Types

- Electron Beam
- Microwave
- High Frequency (1kHz) Pulsed Corona Discharge
  * Can Be Used in Gas Phase
- Dielectric Barrier Discharge
  * Based on O₃ Generator Technology
  * Dielectric Barrier (Al₂O₃) Charges and Extinguishes Discharge
- Packed Bed
  * Material with High Dielectric Constant and Ferro-Electric Properties

NOx Technology Concepts Overview

<table>
<thead>
<tr>
<th>Technology</th>
<th>Performance Range</th>
<th>Potential Commercial Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Lean NOx</td>
<td>NOₓ 25-50  CO &gt;70  HC &gt;70  PM ~ 30</td>
<td>2000</td>
</tr>
<tr>
<td>NOx Adsorber</td>
<td>NOₓ 50-70  CO &gt;70  HC &gt;70  PM &gt; 30</td>
<td>2004</td>
</tr>
<tr>
<td>SCR Urea</td>
<td>NOₓ &gt;80  CO &gt;50  HC &gt;70  PM ≥ 30</td>
<td>2000</td>
</tr>
<tr>
<td>Compact SCR</td>
<td>NOₓ &gt;90  CO &gt;70  HC &gt;70  PM ≥ 30</td>
<td>2004</td>
</tr>
<tr>
<td>Plasma / NOx Cat.</td>
<td>NOₓ &gt;65  CO &gt;50  HC &gt;50  PM ~ 30</td>
<td>Post - 2004</td>
</tr>
</tbody>
</table>
**NOx Technologies Operating Experience**

- Passive Lean-NOx Catalysts Used on PC in Europe
- NOx Adsorbers Have Been Used in Vehicle Trials
- SCR Used on Stationary Sources, Marine Vessels, Locomotives and Have Been Used in Truck Demonstration Programs
- Plasma Technology Is in the Laboratory Stage

**Examples of Integrated Systems**
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**Diesel Oxidation Catalysts Combined with an Electrically-Powered Supercharger Reduce PM Emissions**

- A 50% Reduction in PM Emissions Can Be Achieved

Source: MECA 1999

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**SCR With DOC and DPF Performance**

- PM Emission Levels Below of 0.01 g/bhp-hr with DPF Technology using 368 ppm S fuel
- PM Emissions less than 0.05 g/bhp-hr Can Be Achieved with DOC Technology and 54 ppm S Fuel

Source: MECA 1999
SCR With DOC and DPF
Performance

Combined with the Low PM Emissions, NOx + HC Levels Below 1.5 g/bhp-hr NOx Can Be Achieved on 368 ppm S Fuels

Source: MECA 1999

System Configuration No.1

Urea

Engine

CATALYST/FILTER

SCR

Oxidation Cat

Removal of HC, CO, PM

Removal of NOx

Removal of NH₃ slip if required

4-way conversion
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**System Configurations No.2**

**Engine**

**Heat Exchanger**

Enhances Catalyst Performance

**Lean-NOx**

Removal of NOx

**Catalyst/Filter**

Removal of HC, CO, PM

4-way conversion

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**Performance of System No.2**

- Reductions in CO, NOx, and HC Were Achieved

Source: SAE Paper 1999-01-2924
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Sulfur Effects

- $SO_2$ → $SO_3$ → $H_2SO_4$ → Sulfate Make
- $SO_4^{2-}$ → Sulfate Poisoning
- Precious Metal
- Transition Metal
- Zeolite or Refractory Oxide Support

Summary of Influence of Fuel Sulfur on Diesel Exhaust Emission Control Devices

- Control Technology
  - Oxidation Catalyst
  - Lean NOx (DeNOx) Catalyst
  - SCR with Urea
  - Catalytic Particulate Filters
  - Particulate Filters with NOx Conversion Catalyst
  - Non-Thermal Plasma
  - NOx Adsorbers

- Sensitivity to Sulfur
  - Moderate
  - Moderate to Extremely High
  - Low, but May Require Oxidation Catalyst for NH$_3$ slip
  - Moderate
  - High When Diesel Fuel Sulfur Exceeds 50 ppm
  - Thought to be Low
  - Extremely High (near zero may be necessary)

Note: To meet upcoming particulate and NOx emission levels and beyond, combinations of devices may be required.

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**Conclusions**

- Further, Significant Diesel Emission Reductions Are Possible for Both Onroad and Nonroad Vehicles
- Exhaust Emission Controls Are Currently a Largely Untapped Source for Significant Emission Reductions (Simultaneous PM, Toxic HC, and NOx Control)
- NOx Abatement Technologies are Advancing and Several Control Strategies Are Expected to Be Available in the 2004 Time Frame
- Ultra-Low Sulfur Fuel Would Open Significant Additional Opportunities for the Control of Diesel Emissions