Urea SCR and DPF System for Diesel Sport Utility Vehicle Meeting Tier 2 Bin 5

DOE and Ford Motor Company Advanced CIDI Emission Control System Development Program (DE-FC26-01NT41103)

Diesel Engine Emission Reduction Conference

Christine Lambert

August 25, 2005
Presentation Overview

• Program Overview
• Results with Fresh Catalysts
• System Durability
• Improved Oxidation & NOx Catalyst Development
• Exhaust Gas Sensor Development
• Urea Infrastructure Study
• Conclusions
Urea SCR and DPF System for Diesel Sport Utility Vehicle Meeting Tier 2 Bin 5

Program Overview
DOE Ultra-Clean Fuels Program

Outline of Ford’s program to achieve Tier 2 FTP emission standards for 2007 using low sulfur diesel fuel as an enabler for a high efficiency aftertreatment system.

Primary Contractor

<table>
<thead>
<tr>
<th>Research and Advanced Engineering</th>
<th>Phase I - Initial build/test phase (July 01-July 02)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Establish baseline emission control system</td>
<td></td>
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<tr>
<td>Deliver engine dynamometer NOx and PM test results</td>
<td></td>
</tr>
<tr>
<td>Deliver prototype vehicle NOx and PM test results</td>
<td></td>
</tr>
<tr>
<td>Deliver urea delivery (infrastructure) prototype</td>
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</table>

Subcontractors

<table>
<thead>
<tr>
<th>ExxonMobil</th>
<th>Phase II - System/component optimization phase (July 02-July 04)</th>
</tr>
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<tbody>
<tr>
<td>Research and Engineering</td>
<td></td>
</tr>
<tr>
<td>Define final system hardware components</td>
<td></td>
</tr>
<tr>
<td>Deliver NOx and PM performance data from fresh system</td>
<td></td>
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</tbody>
</table>

Catalyst Suppliers

<table>
<thead>
<tr>
<th>Engelhard</th>
<th>Phase III - Durability phase (July 04-Dec 05)</th>
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<tbody>
<tr>
<td>jmCat</td>
<td>Definition of durability test procedure</td>
</tr>
<tr>
<td>Johnson Matthey</td>
<td>Final NOx and PM emission levels</td>
</tr>
<tr>
<td>umicore</td>
<td>Final report for the completed program</td>
</tr>
</tbody>
</table>
FEV Program

**Engine Dynamometer**
- Urea SCR/CDPF optimization
- Transient FTP testing

**Emission Control System Durability**
- 120K miles on engine dyno
ExxonMobil Program

**Urea Infrastructure**
- Co-fueling concept
- Cold-climate urea usage
- Infrastructure studies

**Fuel Development**
- Make and use fuel, which will be typical of 2007 production with 15 ppm sulfur cap
### Diesel Fuel Properties

- ExxonMobil blended 14,000 gallon batch to represent typical 2007 ULSD

<table>
<thead>
<tr>
<th>Fuel Property</th>
<th>Est. Avg. ‘06 Diesel Properties</th>
<th>Proposed DOE Program Min/Max</th>
<th>Program Delivered</th>
<th>Proposed 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulfur, ppm</td>
<td>15*</td>
<td>10 / 15</td>
<td>12.5</td>
<td>7 / 15</td>
</tr>
<tr>
<td>Density, kg/m³</td>
<td>850</td>
<td>820 / 850</td>
<td>841.1</td>
<td>839 / 865</td>
</tr>
<tr>
<td>Aromatics, vol. %</td>
<td>32</td>
<td>25 / 32</td>
<td>29.5</td>
<td>27 min</td>
</tr>
<tr>
<td>Polyaromatics, wt. %</td>
<td>10</td>
<td>6 / 11</td>
<td>11.0</td>
<td>no spec</td>
</tr>
<tr>
<td>Cetane number</td>
<td>46</td>
<td>44 / 48</td>
<td>44.9</td>
<td>40 / 50</td>
</tr>
<tr>
<td>T50, C</td>
<td>267</td>
<td>250 / 280</td>
<td>249</td>
<td>243 / 282</td>
</tr>
<tr>
<td>T90, C</td>
<td>306</td>
<td>300 / 320</td>
<td>307</td>
<td>293 / 332</td>
</tr>
</tbody>
</table>

* As delivered to the vehicle
Urea SCR and DPF System for Diesel Sport Utility Vehicle Meeting Tier 2 Bin 5

Results with Fresh Catalysts
Exhaust System for 6000 lb Prototype LDT

Targets: 0.07 g/mi NOx, 0.01 g/mi PM

- Engine-out NOx lowered by 40% with increased EGR*
- Low tailpipe NOx achieved with rapid warm-up strategy
  - lower thermal mass upstream of catalyst system
  - engine calibration changes during cold start (post injection & inc. idle speed)

* Tradeoffs for lower engine-out NOx include lower fuel economy & higher PM.
FTP-75 Tailpipe Emissions and Conversions

Fresh catalysts on Engine Dyno

- PM ~ 1 mg/mi
- Fuel penalty for NOx control is <1%

<table>
<thead>
<tr>
<th>Bag 1</th>
<th>Bag 2</th>
<th>Bag 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>THC</td>
<td>CO/10</td>
<td>NOx</td>
</tr>
<tr>
<td>0.037 (98%)</td>
<td>0.031 (87%)</td>
<td>0.023 (84%)</td>
</tr>
<tr>
<td>0.030 (97%)</td>
<td>0.032 (97%)</td>
<td>0.044 (93%)</td>
</tr>
<tr>
<td>0.015 (96%)</td>
<td>0.015 (91%)</td>
<td>0.005 (99.9%)</td>
</tr>
<tr>
<td>0.015 (97%)</td>
<td>0.006 (98%)</td>
<td>0.0002 (99.9%)</td>
</tr>
<tr>
<td>0.0005 (99.9%)</td>
<td>0.0005 (99.9%)</td>
<td>0.0005 (99.9%)</td>
</tr>
<tr>
<td>NMOG</td>
<td>0.083 (97%)</td>
<td>0.044 (93%)</td>
</tr>
</tbody>
</table>
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System Durability
**Durability Test Definition**

**Ford High Speed Cycle (HSC)**

- average speed = 47 mph
- max speed = 75 mph
Engine Dynamometer Durability Testing
50K Mile Performance Evaluation

Tailpipe Emission Levels Over Simulated FTP-75 Vehicle Cycle
Urea SCR and CDPF Emission Control System

Tier 2 – Bin 5 Standard, 120k

- THC
- CO
- NOx
Vehicle Testing of 50K mi Catalysts

6000 lb LDT FTP-75 Emissions

NO RAPID WARM-UP

<table>
<thead>
<tr>
<th></th>
<th>THC</th>
<th>NMHC</th>
<th>CO</th>
<th>NOx</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bag 1</td>
<td>0.043</td>
<td>0.024</td>
<td>0.091</td>
<td>0.050</td>
</tr>
<tr>
<td></td>
<td>(94%)</td>
<td>(83%)</td>
<td>(84%)</td>
<td>(65%)</td>
</tr>
<tr>
<td>Bag 2</td>
<td>0.037</td>
<td>0.017</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(97%)</td>
<td>(94%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bag 3</td>
<td>0.017</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(90%)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

PM ~ 2-5 mg/mi

Tier 2 - Bin 5 Standard, 120k (Catalyst efficiency)
Vehicle Testing
Predicted NOx Emissions with 50K mi Catalysts and Rapid Warm-up on 6000 lb LDT
Urea SCR and DPF System for Diesel Sport Utility Vehicle Meeting Tier 2 Bin 5

Improved Oxidation & NOx Catalyst Development
Oxidation Catalyst Evaluation

NO → NO₂ Conversion

120K mi Simulated Aging

% NO₂ of Total NOx

Temperature (C)

- AB002
- AA002
- AF002

30K h⁻¹
Improved Oxidation Catalyst Evaluation
HC Conversion
120K mi Simulated Aging

Conversion Efficiency

Temperature (Deg C)

0% 25% 50% 75% 100%

AB003
AA013
AF005

30K h⁻¹
Comparison of Improved SCR Catalysts
Aged 64 hrs at 670°C, Evaluated with NO only

NO Conversion (%) vs. Temperature (°C) for Catalysts A, B, C, D at 30K h⁻¹
Comparison of Improved SCR Catalysts
Aged 64 hrs at 670°C, Evaluated with NO only

![Graph showing NO conversion vs. temperature for different catalysts and reaction rates.]

- C, 30K h⁻¹
- C, 100K h⁻¹
- D, 30K h⁻¹
- D, 100K h⁻¹

Temperature (°C)

NO Conversion (%)
Comparison of Improved SCR Catalysts
Ammonia Stored on Degreened Catalysts

NH₃ stored (mg/in³)

Catalyst temperature (°C)

30K h⁻¹
350ppm NH₃
Comparison of Improved SCR Catalysts
Ammonia Stored on Aged Catalysts
64h at 670°C

Catalyst temperature (°C)
NH₃ stored (mg/in³)

A, dg
A, HT aged
B, dg
B, HT aged

30K h⁻¹
350ppm NH₃
Comparison of Improved NOx Catalysts
Alternative Ammonia-based Catalyst Systems

**Rich Operation:**

- NOx stored on LNT is released during rich event and reduced to N₂ and NH₃.
- Desorbed NOx + NH₃ react over SCR during rich event.
- Excess ammonia is stored on SCR.

**Lean Operation:**

- During lean operation NOx slip through LNT is consumed by NH₃ stored on SCR.
Comparison of Improved NOx Catalysts
Alternative Ammonia-based Catalyst Systems
Flow reactor, 40s lean, 5s rich, 120K mi aged

% Gross NOx Conversion vs Inlet Temperature (°C)

- LNT
- LNT-SCR
- LNT A
- LNT A-LNT A
- LNT A-SCR 1
- LNT A-SCR 2

2-LNT
Urea SCR and DPF System for Diesel Sport Utility Vehicle Meeting Tier 2 Bin 5

Exhaust Gas Sensor Development
Little sensitivity to water for NH$_3$ > 50 ppm.
Exhaust Gas Sensor Development

Vehicle Data with Ammonia Sensor

FTP-75 Emission Cycle

![Graph showing NH₃ ppm over time](image)
Urea SCR and DPF System for Diesel Sport Utility Vehicle Meeting Tier 2 Bin 5

Urea Infrastructure Study
Urea Infrastructure Study
Co-fueling Hardware Status

• Co-fueling hardware completed
  – Improved co-axial nozzle with fill-neck insert provided by a major nozzle manufacturer
  – Urea pumping system with flow meter
  – Urea tank integral with dispenser
  – Urea heating system
  – 32.5 wt% urea in water assumed
Urea Infrastructure Study

Co-fueling Hardware Testing

• Tested diesel fuel / urea solution co-fueling using a co-axial nozzle system

• Testing of improved nozzle and insert showed better alignment and improved sealing
  • 1st version: 0.5 vol.% leak rate of urea into diesel
  • 2nd version: < 0.1 vol.% leak rate of urea into diesel

• Cross contamination of urea into diesel remains a concern for co-axial design due to urea line connection within the diesel re-fueling stream
Conclusions

- The objective of 0.07 g/mi NOx and 0.01 g/mi PM on the FTP was met with a fresh emission control system of Urea SCR and CDPF.
- HC, CO & PM emissions at 50K mi met Tier 2 Bin 5.
- NOx emissions at 50K mi were 0.09 g/mi and were predicted to be 0.05 g/mi (Bin 5) if rapid warm-up during cold-start had been available.
- Current DOC AB had highest NO₂ production after aging. New DOC AF had lower HC lightoff T but less NO₂ production.
- New SCR catalysts were developed that have improved NOx conversion after 120K mi equivalent aging.
- Long-term lean aging at 670°C decreases the ability of base metal/zeolite SCRs to store ammonia.
- SCR catalysts were used downstream of reduced size LNTs with favorable results.
- Prototype NH₃ sensors were successfully tested on a vehicle.
- Cross contamination of urea into diesel remains a concern for co-axial design due to urea line connection within the diesel re-fueling stream.
Acknowledgements

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