Measurement and Characterization of Lean NOx Adsorber Regeneration and Desulfation and Controlling NOx from Multi-mode Lean DI engines

Jim Parks (PI), Shean Huff, Mike Kass, and Vitaly Prikhodko

Oak Ridge National Laboratory

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Agreements: 9248 and 12249

Gurpreet Singh and Ken Howden
U.S. Department of Energy, FCVT

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Project ID: ace_31_parks
Overview

- **Timeline**
  - **Start**
    - #9248 (LNT): FY2003
    - #12249 (Multimode): FY2007
  - **Finish**
    - #9248 (LNT): FY2009
    - #12249 (Multimode): FY2010
  - **% Complete**
    - #9248 (LNT): ~94%
    - #12249 (Multimode): ~50%

- **Budget**
  - **FY08 Funding**
    - #9248 (LNT): $300k
    - #12249 (Multimode): $200k
  - **FY09 Funding**
    - #9248 (LNT): $300k
    - #12249 (Multimode): $200k
  - **FY10 Requests**
    - Transition to lean gasoline
    - #12249 (Multimode): $250k

- **Barriers**
  - Emissions regulations for advanced lean engine market penetration

- **Partners**
  - **Catalyst Suppliers**
    - Manufacturers of Emissions Controls Association (MECA)
    - AirFlow Catalysts
  - **CLEERS and PSAT**
    - Provide database and results to enable models
  - **Other ORNL Projects:**
    - Advanced Combustion
    - Joule Milestone
    - Health Impacts
Objectives: Enable efficient lean engine market penetration by meeting emission regulations with efficient, cost effective aftertreatment

- **Research of Lean NOx Trap Catalyst NOx and SOx Regeneration Chemistry and Performance (9248)**
  - Lower fuel penalty for regeneration
  - Characterize engine generated reductant utilization: H₂, CO, and HC’s
  - Develop stronger link between bench and full-scale system evaluations
  - Provide data to CLEERS to improve models; use models to guide research

- **Research of Multimode Engine Operation and Potential Synergies with Aftertreatment (12249)**
  - Characterize emissions from advanced engine combustion modes and define the synergies or incompatibilities with emissions control technologies
    - LNT, Urea SCR, HC-SCR, Lean NOx Catalysis, DPF, Oxidation
  - Study effect of multimode operation on system performance
Milestones

- **FY08 Milestones (completed):**
  - Couple advanced and conventional (multi-mode) combustion strategies with efficient emission control technologies to estimate FTP emissions from modal points (September 30, 2008)
  - Investigate feasibility of lowering platinum group metal content of lean NOx trap catalysts and determine performance impact. (September 30, 2008)

- **FY09 Milestones (planned and in progress):**
  - Exploit synergies of advanced and multi-mode combustion strategies with selective catalytic reduction emission control to estimate FTP efficiency and emissions from modal points in support of emissions part of ACEC goals. (September 30, 2009)
  - Characterize the reductant chemistry transitions through a combination lean NOx trap and selective catalytic reduction hybrid emission control system. (September 30, 2009)
Approach

**ORNL Emissions R&D**
- Multi-cylinder engine with prototype and model LNTs
- Multimode operation with various aftertreatment

**ORNL Engine Efficiency R&D**

**ORNL Health Impacts R&D**

**MECA**
- Aftertreatment Modeling

**Universities**

**Natl Labs**

**Industry**

**CLEEERS**

**Advanced Engine Combustion MOU**

**Universities**

**Industry**

**NREL**

**HEI**
Technical Accomplishments/Progress/Results

Since last review (February 2008):

- Repeated demonstration of synergies of LNT and HECC study with DPF
  - Tier 2 Bin 5 NOx emission levels estimated from weighted Ad Hoc load/speed points (reported at CLEERS, DEER, and Fall SAE)

- Characterized Multiwalled Carbon Nanotube HC-SCR catalyst in slipstream setup
  - With Mark Crocker and University of Kentucky team

- Characterized DOC oxidation efficiency for HECC
  - Model and AirFlow Catalyst DOCs control CO and formaldehyde/HCs except at low load points

- Installed 4-cylinder GM diesel engine
  - Working on Drivven controls system for GM platform

- Demonstrated potential benefit of HECC for fuel savings due to lower desoot frequency
  - Lower soot loading from HECC results in lower frequency of desoot and reduces desoot fuel penalty from 4.2% (conventional case) to ~3.1% (mixed mode HECC +conventional)

- Characterizing (ongoing) NH₃ formation and utilization in LNT-SCR hybrid system
  - Tracking fast pulse of NH₃ from LNT regeneration with UV spectroscopy technique

Details Presented On These Topics
Experiments made use of engine conditions developed by Ad Hoc working group

<table>
<thead>
<tr>
<th>Point</th>
<th>Speed / Load</th>
<th>Weight Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1500 rpm / 1.0 bar</td>
<td>400</td>
<td>Catalyst transition temperature</td>
</tr>
<tr>
<td>2</td>
<td>1500 rpm / 2.6 bar</td>
<td>600</td>
<td>Low speed cruise</td>
</tr>
<tr>
<td>3</td>
<td>2000 rpm / 2.0 bar</td>
<td>200</td>
<td>Low speed cruise w/ slight acceleration</td>
</tr>
<tr>
<td>4</td>
<td>2300 rpm / 4.2 bar</td>
<td>200</td>
<td>Moderate acceleration</td>
</tr>
<tr>
<td>5</td>
<td>2600 rpm / 8.8 bar</td>
<td>75</td>
<td>Hard acceleration</td>
</tr>
</tbody>
</table>

• Represents speed-load points for light-duty
• No cold-start or other transients
• Method for estimating drive-cycle emissions


• Modified 1.7-liter, 4-cylinder
• High-pressure common rail
• Full-pass control system (8 event)
• Variable geometry turbocharger
• Cooled EGR with low and high flow valves and electronic throttling
Previous study focused on LNT regeneration

Emissions and efficiency measured for HECC and LNT system (vs. conventional combustion) at Ad Hoc points, and...

...weighted performance results used to estimate FTP emissions and efficiency.

SAE 2008-01-2493
Frequent Desoot observed in new production diesel vehicles with advanced emission controls

**Dodge Cummins System (HD Pickup Truck)**

[Ken Price (Umicore), *CLEERS Telecon* (2009), *SAE LD Symposium* (2008)]

- DPF desoot at ~600°C for 10-15 min. during ~13% of operating time (<4% fuel penalty)
- Desoot:deSulfate Ratio = 6:1

**Mercedes E320 System**

[Owen Bailey (Umicore), *CLEERS* (2008)]

- DPF desoot at ~700°C for ~6-8 min. during ~2% of operating time
- Desoot:deSulfate Ratio = 2:1

**Volkswagen - Jetta System**

[Ing. J. Hadler et al., *Internationales Wiener Motorensymposium* (2008)]

- DPF desoot at ~650°C for <15 min.
- Desoot:deSulfate Ratio = 4:1
Question: Are there potential benefits of lower PM from HECC for Multimode operation?

- Experiment designed to characterize benefit of lower PM from HECC:
  - Measure dP rise rate for HECC as compared with conventional (OEM level EGR) combustion
  - Use standard point (1500 rpm, 5.0 bar) to compare total backpressure change consistently
    Experiments conducted with LNT regeneration frequency to achieve equal tailpipe NOx
  - DPF desoot accomplished with post injection from standard point start (~10-15 min at ~600ºC)

```
Step 1: Measure dP at standard

Step 2: Load DPF at Set Point

Step 3: Measure dP at standard

Step 4: desoot
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![Diagram showing the process with DOC, SiC DPF, MECA LNT, and a graph showing delta P across DPF over time.](image-url)
DPF backpressure rise rate lower for HECC

- Rate of backpressure rise across DPF measured at various load points for Conventional (OEM EGR level) and HECC combustion
  - Higher PM from conventional combustion leads to higher rise rates
  - LNT regeneration adds to rise rates

All dP/dt data based on before and after measurements at standard condition

Note: checkered pattern indicates without LNT regeneration
Lower DPF loading saves fuel for multimode

- Less PM from HECC leads to less frequent desoot & lower desoot fuel penalty
  - Also results in less time at high temperature for catalysts

- Lower desoot fuel penalty helps multimode with HECC compete with conventional combustion on BSFC basis

- HECC gives lower NOx, but other issues remain: EGR fouling, stability, high CO/HCs

Conv=Conventional
Multi=Multimode

<table>
<thead>
<tr>
<th>Speed/Load</th>
<th>Conventional</th>
<th>Multimode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 rpm/1.0 bar</td>
<td>OEM*</td>
<td>HECC*</td>
</tr>
<tr>
<td>1500 rpm/2.6 bar</td>
<td>OEM</td>
<td>HECC</td>
</tr>
<tr>
<td>2000 rpm/2.0 bar</td>
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<td>OEM</td>
</tr>
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<td>2600 rpm/8.8 bar</td>
<td>OEM</td>
<td>OEM</td>
</tr>
</tbody>
</table>

*no regeneration of LNT (low temp)
Study of NH$_3$ formation and utilization in hybrid LNT-SCR system

- **Focus on characterization of utilization reductants (from engine to LNT to SCR):**
  - DOC and DPF (SiC) in same can upstream of LNT-SCR
  - LNT and SCR catalysts provided by MECA; model LNT also studied (results shown here)
  - Current LNT and SCR SV=25-40k/hr; plan to reduce SV for further study

- **Measurement of reductants with variety of techniques:**
  - Standard analyzers for CO (NDIR) and HC (FID) reductants (and CLD for NOx)
  - Magnetic sector SpaciMS for H$_2$
  - FTIR for NH$_3$, N$_2$O, NOx, HCs, and other species
  - UV spectroscopy for fast in-line measurement of NH$_3$, NOx, and HCs

![Diagram of D2 Light, UV Spectrometer, and In-Line UV Spectroscopy]
SCR reduces NOx that breaks through LNT

- 1500 rpm, 50 ft-lbs, Lean=30sec, Rich=1-5sec
- Constant cycling with start and stop to observe NH$_3$ storage effects
- SCR benefits overall NOx reduction when LNT NOx reduction not complete
- Excess NH$_3$ stored by SCR enables more NOx reduction after cycling ends

**Example Raw Data**

**During Cycling**

**Rich Duration (sec)**

<table>
<thead>
<tr>
<th>lean</th>
<th>lean-rich cycling</th>
<th>lean</th>
</tr>
</thead>
</table>

**NOx (ppm)**

**LNT Out**

**SCR Out**
SCR stores excess NH₃ generated

- NH₃ generation occurs when excess reductant supplied to LNT
- Extending rich duration increases NH₃ production
  - Timing consistent with bench studies
- For specific cycle, low amount of NH₃ used by SCR for NOx reduction
- NH₃ not utilized during cycle is stored
- Stored NH₃ beneficial for future NOx reduction in transient scenario
Similar fuel penalty for equivalent NOx reduction

- 1500 rpm, 50 ft-lbs, EGR=24%
- Lean Period – Rich Period: 90sec-3sec vs. 30sec-1sec
- For cases where LNT is effective, no fuel penalty benefit is gained by LNT-SCR system (on cycle basis)
- Trade-off between frequency and duration of regeneration
NH₃ production limits SCR NOx reduction

- LNT temperature varied by selecting 3 engine conditions (engine out NOx not equivalent)
- When LNT NOx capacity is lower, less NH₃ is produced
- At low temperature (207°C), more hydrocarbons slip past LNT
Future Work

• Remainder of FY2009
  – Continue NH₃ Utilization Study
  – Develop controls for GM engine
  – Study urea SCR synergies with multimode operation
  – Transition to lean gasoline (project #9428)
  – Present Results at CLEERS, NAM, DEER, Fall SAE

• FY2010
  – Integrate emissions database into Joule milestone efforts (efficiency + emissions goals)
  – Install lean gasoline engine and characterize exhaust conditions and LNT performance
Summary

• Engine-based studies of emission control technologies focus on:
  • Synergies with advanced combustion
  • Reductant utilization and fuel efficiency

• Engine out reductions of both NOx and PM emissions lead to fuel efficiency benefits for HECC and multimode operation
  • Lower PM emissions lead to less frequent desoot operation, and thereby, fuel savings (vs. conventional)

• NH₃ produced by LNT during regeneration can be utilized by SCR in hybrid system to enable higher NOx reduction efficiency

Jim Parks
parksjeii@ornl.gov