Cummins/ORNL-FEERC CRADA: NO$_x$ Control & Measurement Technology for Heavy-Duty Diesel Engines

W.P. Partridge (PI), J.-S. Choi, J.E. Parks, R.M. Connatser
Oak Ridge National Laboratory

N. Currier (PI), S. Geckler (PI), A. Yezerets, K. Kamasamudram
Cummins Inc.

Presenter: Bill Partridge
partridgewp@ornl.gov

Project ID:
ACE032

2011 Vehicle Technologies Program Annual Merit Review
May 12, 2011, Arlington, Virginia

U.S. DOE Program Management Team:
Ken Howden, Gurpreet Singh, Steve Goguen

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
Overview

**Timeline**
- Start: FY1998
- Major Revisions: 2001, 03, 06, 10
- Current term: 2010-'12 revision
- Current end date: Sept. 2012
- ~47% Complete

**Budget**
- 1:1 DOE:Cummins cost share
- DOE Funding:
  - FY2009: $400k
  - FY2010: $400k + $250k (Aug. 2010)
  - FY2011: $450k + $400k

**Barriers**
- **Engine combustion**
  - Combustion uniformity
- **Emissions controls**
  - Catalyst fundamentals, design, control & diagnostics, (& efficiency)
- **Engine controls**
  - Variability & diagnostics
  - Fast PM & species diagnostics
- **Durability**
  - Fuel dilution of oil, (& efficiency)

**Partners**
- ORNL & Cummins Inc.
- Chalmers Univ. of Technology
- Inst. Chemical Tech., Prague
- Informal coordination with CLEERS
Objectives

**Self-Diagnosing SmartCatalyst (new focus in current term):**

- Enable closed-loop, on-board control & OBD of catalyst systems
  - Understanding the intra-SCR static and dynamic performance distributions & relationships
  - Developing diagnostic tools that measure those performance parameters

Improve catalyst design, control & diagnosis (OBD) for enhanced *efficiency, durability & emissions control*

**Combustion Uniformity:**

- Reduce cylinder-to-cylinder & cycle-to-cycle combustion variations
  - Understanding the origins of intake & combustion fluctuations

Enable improved *efficiency, control and emissions*

- Apply Fuel-in-Oil diagnostic to advanced engine technologies

Enable improved *durability, efficiency and emissions*

Lower development *cost & shorten development time*
Milestones

2010 Milestone:
✓ Characterize SCR-catalyst performance distribution under select operating conditions
✓ Demonstrate high-speed (sufficient for cylinder-resolved) measurement of 0-10% CO₂

2011 Milestones (on target for Sept. 2011 completion):
• Dynamic analysis of SCR-catalyst performance
  – E.g., NH₃ capacity distributions & transient response
  – Assess & refine analysis techniques
• Measurement of intake-EGR-charge distribution on engine
  – Build on knowledge from fast exhaust measurements
  – Proof-of-principle and refinement in early 2011
  – Follow-on applications for studying non-uniformity origins and mitigation strategies
Approach for addressing SCR Control Challenges

Catalyst Understanding

Evaluate static & dynamic catalyst nature

Understand chemical & spatiotemporal relationships

Identify Control Parameters

Improve models & designs

Understand chemical & spatiotemporal relationships

Identify Control Parameters

Diagnostic Tools

Develop lab diagnostics (T, species, Z, etc)

Prioritize high-potential diagnostics

Bench & engine evaluation

Understanding + Diagnostics for Real-Time Catalyst Control

Improved Fuel Economy, emissions & catalyst durability
Technical Progress: **Self-Diagnosing Smart Catalysts**

- **Distributed SCR Reactions & Ammonia Storage**
  - Study static and dynamic reaction/storage distributions
  - Evaluating commercial Fe- & model Cu-zeolite catalysts
    - *Responsive to 2010 Merit Review feedback*
  - Collaborative with Prof. Louise Olsson, Chalmers
    - Provided model Cu-zeolite catalyst
    - PhD student Xavier Auvray, 6 months at ORNL & ongoing

- **LNT NH$_3$ & N$_2$O chemistry**
  - Using CRADA data & continuing in CLEERS
  - Collaborative w/ Prof. Olsson, Chalmers
    - MS student Soran Shwan, “Modeling of NOx storage and reduction for emission cleaning from vehicles,” August ‘10 defense
    - Continuing with a new MS student
  - Collaborative w/ Dr. Petr Koci, Prague Inst. Chem. Technology
    - August 2010 at ORNL
    - Ongoing N$_2$O modeling work
    - Partnering to model & understand SpaciMS sampling details
Technical Progress: *Intra-SCR Measurements & Analysis*

- **MicroReactor redesigned mid 2010**
  - Improved SpaciMS capillary access
  - Improved temperature control
    - Separate gas preheat before mixing
    - Catalyst T uniformity > 99%
    - Capillaries > 195°C
  - 2x independent gas switching feeds
  - LabView microreactor control & monitoring

- **MatLab analysis:**
  - Steady state, transient & integrated analysis
Technical Progress: *Intra-SCR Distributed NH\textsubscript{3} Functions*

- **Protocol measurements:**
  - Static & Dynamic reactions
  - NH\textsubscript{3} utilizations and capacities

- **Focus on Cu-zeolite:**
  - 200, 325 & 400°C
  - Standard & Fast SCR reaction
  - Degreened & Aged conditions

- **325°C, Standard SCR**
  - ~3 min to reach steady state
  - Active NH\textsubscript{3} capacity in front 1/16L
  - SCR distributed over front 1/4L
    - Max in front w/ active NH\textsubscript{3}
    - Parasitic NH\textsubscript{3} oxidation increases through SCR zone to ~15%
      - Apparently proportional to NH\textsubscript{3}

- **400°C, Standard SCR**
  - Parasitic oxidation in very front
  - Greater SCR gradient

---

**Static & dynamic reaction distributions**

**NH\textsubscript{3} utilization & capacities**

**Real-time catalyst state assessment & control**
Approach for Advancing Engine-System Efficiency

Develop & apply advanced diagnostics for engine system characterization to enable & support model validation and engines controls for fuel efficient engines

ORNL Diagnostics Development & Applications to Cummins Engine Systems

- Fast Air & Exhaust Handling
- Fuel in Oil Measurements
- Exhaust Gas Chemistry

Clean Fuel-Efficient Engines in the Marketplace
Technical Progress: Combustion Uniformity

- Developing tools to validate intake EGR-mixing
  - Fast intake CO$_2$ fluctuations measurements
  - Critical to fuel efficiency & emissions
  - Very relevant to high-EGR systems

Enables improved *engine efficiency & control, and reduced emissions*

- Sensing exhaust species for improved control
  - Combustion uniformity, catalyst control

Enables improved *efficiency & durability*

- Applying Fuel-In-Oil diagnostic to advanced engine applications
  - 2011 National FLC Excellence in Technology Transfer Award
    - Da Vinci Emissions Services commercializing DAFIO

Enables improved *engine calibration, durability, efficiency & emission; and lowers development costs*
Tech. Progress: *Fast Intake CO₂ Measurements*

$$\frac{f_{\text{CO}_2}}{f_{\text{ref}}} = \frac{S(\text{CO}_2)}{S(\text{ref})}$$

**Picture of bench-top setup**

LED<sub>ref</sub> $f=50$ kHz

LED<sub>CO₂</sub> $f=77$ kHz
**Tech. Progress: Fast Intake CO₂ Calibration & Speed**

### Calibration

- **Noise~ 0.074% CO₂**

### Speed Demonstration

- 400Hz chopper in IR path
- Plastic over every 3rd window
- Plastic simulates greater [CO₂]

**On-Engine Application at Cummins Tech Center April 11-15, 2011**
Collaborations & Coordination

- **Cummins**
  - CRADA Partner

- **Cummins SuperTruck Program**
  - CRADA-developed tools support SuperTruck project

- **Prof. Louise Olsson, Chalmers**
  - SCR measurements & modeling, (PhD student, Xavier Auvray)
  - LNT modeling NH\(_3\) & N\(_2\)O chemistry (MS student)

- **Dr. Petr Koci, Prague Institute of Chemical Technology**
  - LNT modeling N\(_2\)O chemistry
  - SpaciMS capillary sampling modeling

- **CLEERS**
  - LNT NH\(_3\) measurements & modeling, SCR measurements

- **Dr. Alex Goguet, Queen’s University Belfast**
  - SpaciMS invasive nature under varying conditions (MS student)
  - Developing Time-of-Flight SpaciMS

- **Dr. Kent Froelund, Da Vinci Emissions Services**
  - DAFIO licensed for commercial sales
Future Work

2011 Work:

• Other conditions (e.g., SV, NH$_3$:NO$_x$, NO:NO$_2$) to study performance impact
• Mine spatial & temporal species distributions for control relationships
• Fiber-based NH$_3$ and other diagnostics
• Fuel-in-oil applications to advanced engine technologies
• Mid-IR laser for improved intake-CO$_2$ SNR
• SCR, LNT & SpaciMS modeling (joint w/ CLEERS, Chalmers & ICT Prague)

2012 Work:

• Inhibitor & Inhibition impact on SCR catalyst reaction and storage distributions
• Correlate control relationships w/ performance parameters
  – Identify strategies for SCR-catalyst control & diagnostics
• Apply diagnostics to understand combustion variations
  – Correlating intake and combustion variations
Summary

- **On path to Self-Diagnosing SCR Catalyst**
  - Focusing on Cu-zeolite catalyst *(cf. 2010 Review feedback)*
  - Intra-SCR static & dynamic performance distributions *(2010 milestone)*
  - Enhance design, modeling, specification, control & OBD for *improved efficiency, durability & emissions*

- **Studying intake variations impact on combustion uniformity**
  - Build on cylinder-resolved exhaust CO₂ measurements *(2009 milestone)*
  - Synergistic with Cummins’ SuperTruck program
  - Evaluates engine variations and mitigation strategies for *improved efficiency, control and emissions*

- **CRADA-developed Fuel-In-Oil Diagnostic nationally recognized**
  - 2011 National FLC Excellence in Technology Transfer Award
  - Applying to advanced engine technologies
  - Commercially available as DAFIO from Da Vinci Emissions Services
  - Applied at Cummins for *improved durability, efficiency and emissions*

- **CRADA approach consistently yields practical techniques and solutions**
  - E.g., EGR mixing, Fuel dilution, Catalyst & Engine control, Models, SpaciMS, OBD

- **Future work focuses on:**
  - Understanding distributed intra-SCR chemistry & performance for OBD applications
  - Studying engine variations and mitigation strategies
  - Advanced variation diagnostics for catalyst, combustion & engine characterization