VSS089

Advanced Heavy-Duty Engine Systems and Emissions Control Modeling and Analysis

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Lead, Vehicle and Systems Simulation and Testing (VSST)
Office of Vehicle Technologies
US Department of Energy

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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OVERVIEW

Timeline	**Barriers***
• Project start date: Oct. 2011 • Project end date: Continuing • Just started	• Risk aversion • Cost • Constant advances in technology • Computational models, design, and simulation methodologies **from 2011-2015 VTP MYPP*
Budget (DOE share)	**Partners**
• New project, no FY11 funding • FY12 (current) funding: $325k	• Meritor, Inc. (CRADA) • DOE Advanced Engine Crosscut Team • CLEERS Collaborators • Oak Ridge National Laboratory – Fuels, Engines, & Emissions Research Center – Power Electronics & Electric Machines Research Center – Center for Transportation Analysis

OBJECTIVE: Reduce petroleum consumption for heavy and medium duty trucks through advanced powertrain hybridization

"WHY"

- **Hybrid medium and heavy duty (MD and HD) powertrains offer large potential reductions in fuel consumption, criteria pollutants and green house gases.**
- **The most fuel efficient MD and HD combustion engines are advanced diesels, which require lean exhaust aftertreatment for emissions control.**
- **Diesel hybridization is challenging because the integrated aftertreatment , engine, and battery systems must be optimized to meet efficiency targets and simultaneously satisfy drive cycle and emissions constraints.**

"HOW"

- **Develop and validate accurate component models for simulating integrated engine, battery, and lean aftertreatment systems in diesel trucks.**
- **Evaluate the merits of specific alternative engine-battery-aftertreatment configurations and control strategies under realistic MD and HD drive cycle conditions.**
- **Identify promising paths for improving MD and HD truck drive-cycle energy efficiency, fuel mileage and emissions.**

> **"Without aftertreatment constraints in the simulation, the model might allow engine system operation outside the emission-constrained envelope."**
>
> – National Academy of Science study on reducing fuel consumption from MD and HD vehicles (ISBN: 0-309-14983-5)

RELEVANCE (1)*

- **Supports 3 major 21st Century Truck Partnership Goals:**
  - Develop advanced heavy vehicle systems models.
  - Develop methods to predict and measure the effects of idle reduction technologies.
  - Reduce non-engine parasitic energy losses.
- **Directly supports 3 VSST cross-cutting activities:**
  - Modeling and simulation; component & systems evaluations; heavy vehicle systems optimization.
- **Indirectly supports VSST laboratory and field vehicle evaluations.**
- **Addresses the following VSST Barriers:**
  - **Risk aversion**: Integrates model-based simulation and analysis with experimental measurements.
  - **Cost**: Utilizes ORNL VSI lab + data and models from other OVT projects and CLEERS.
  - **Constant advances in technology**: Emphasizes latest advanced high efficiency combustion and lean aftertreatment technologies.
  - **Computational models, design, and simulation methodologies:** Combines fundamental physics and chemistry with best available laboratory and dynamometer data to maximize accuracy.

***Reference: Vehicle Technologies Multi-Year Program Plan 2011-2015:**
http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

RELEVANCE (2): This activity exploits knowledge and tools generated in other parts of the Office of Vehicle Technologies and Office of Science

EERE VT Vehicle Systems Activities

Vehicle System Models Accountable for Emissions

EERE VT ACE, Fuels, and VSS Activities

Automotive Product Component Level Model Development (Engine-Input Ready)
[capable in real engine exhaust]

Coated Catalyst (Automotive Product) Studies and Model Development
[based on controlled simulated exhaust]

Office of Science Activities

Industry Access to Specialized Tools and Data

Basic Combustion and Surface Chemistry Measurement and Modeling
[CRF, CNMS, HTML, EMSL]

PreCompetitive R&D
[Catalyst chemistry studies for new formulations]

CLEERS
[Kinetics measurement, model development, model validation]

Diesel Emissions R&D
[Engine-based catalyst studies and model validation for advanced diesel engines]

Advanced Combustion R&D
[Engine-based combustion mode and stretch efficiency analysis and demonstration]

Other Supporting Projects:

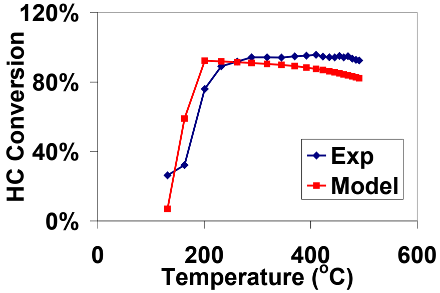
- Advanced LD Engines and Emissions Modeling
- Pathways for Efficient Emission Controls
- Neutron Imaging
- NPBF Fuels Program

APPROACH: Link component models in integrated MD/HD simulations

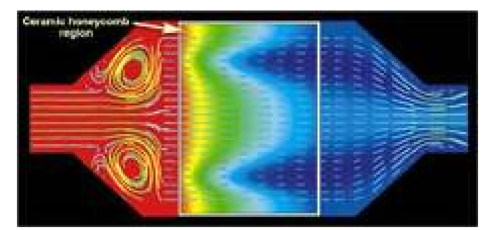
- **Engine component models**
  - **Steady-state and transient MD/HD engine maps from dyno measurements and advanced combustion models.**
- **Aftertreatment component models**
  - **Adapt previous LD models (LNT, SCR, DOC, DPF, and TWC) and new models (e.g., passive adsorbers).**
- **Evaluate advanced MD/HD hybrid technology hardware configurations and control options.**
- **Provide models to Meritor CRADA and utilize CRADA data for model improvements.**

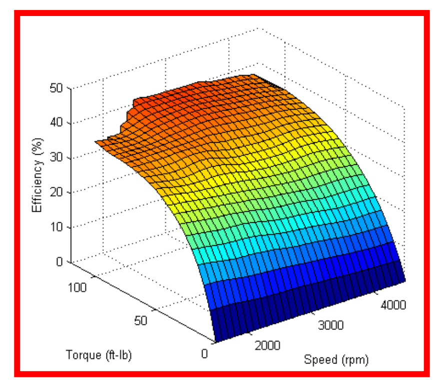
System Integration

Lab Measurements



Emissions Control Modeling





Combustion Engine Modeling

Dynamometer Measurements

Truck Simulation

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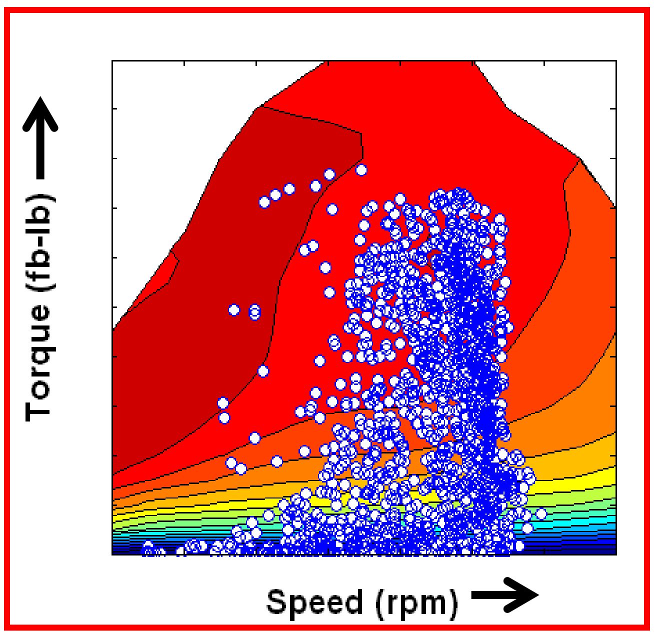
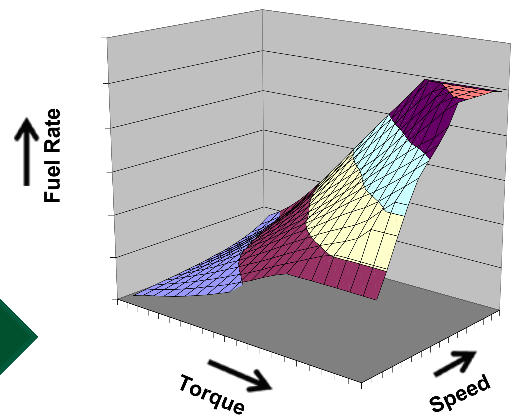
FY2012 MILESTONE

- **Demonstrate preliminary transient MD and HD drive cycle simulations with lean NOx and particulate emissions controls (September 30, 2012).**
  - **Develop and exercise representative steady-state and transient adjusted engine map.**
  - **Adapt existing urea-SCR, DOC, and DPF aftertreatment component models.**
  - **Link models and perform integrated drive cycle simulations in Autonomie.**

HD Drive Cycles



Transient HD Engine Maps



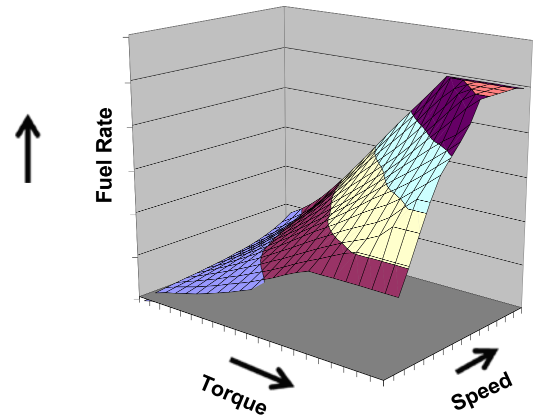
Transient HD Aftertreatment Models

Performance
- Fuel economy
- Emissions

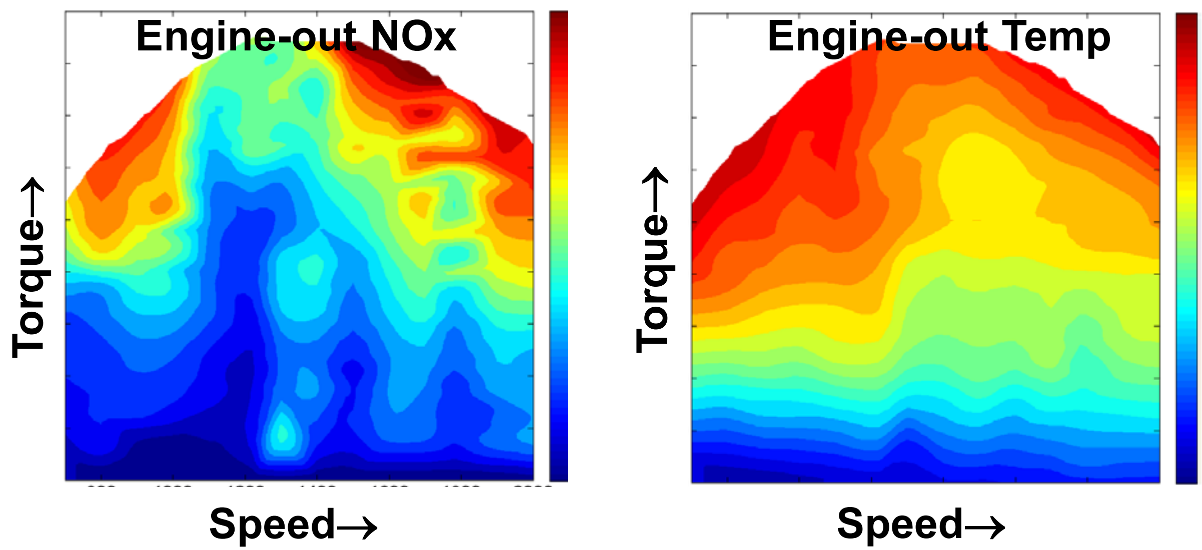
ACCOMPLISHMENT (1): Initial HD engine maps have been constructed

- Include fuel rate & engine out T, CO, HC, NOx, and PM
  - Steady-state baseline response surfaces
  - Dynamic correction factors for transients
- Initial HD diesel engine maps
  - 2003, 15-L, 6-cylinder, MBTE 41%, PT 2000 ft-lb
- Maps under development
  - 2007 15-L, 6-cylinder, MBTE 42%, PT 1650 ft-lb
  - 15.6-L CRADA Engine

Steady-State Fuel Rate

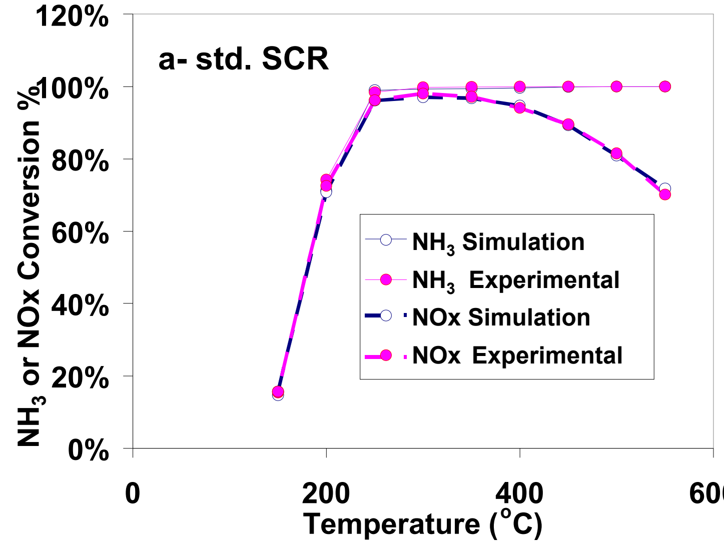


Example HD Diesel maps

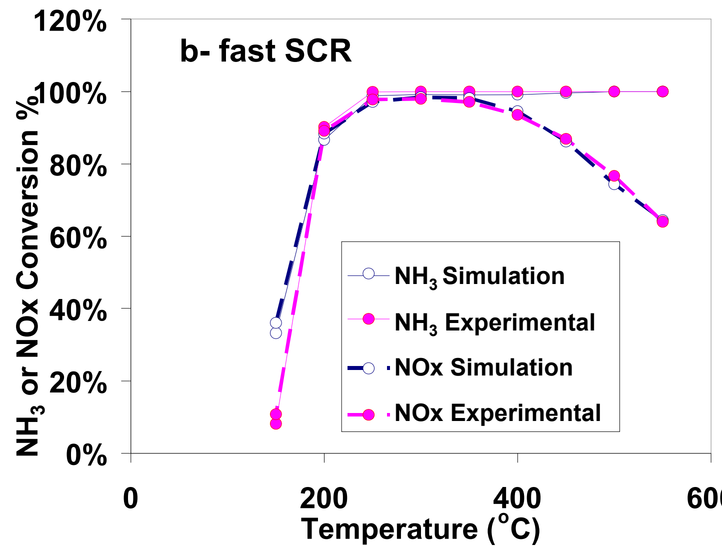


ACCOMPLISHMENT (2): Our SCR component model has been adapted and updated for MD/HD diesel application

- **SCR model key features**
  - 1-D transient Simulink module
  - NH_3 adsorption/desorption
  - NO only and NO_2 only SCR reactions
  - 'Fast' SCR reaction (NO + NO_2)
  - NO oxidation
  - NH_3 oxidation



- **Model calibration**
  - Calibrated for commercial Cu chabazite catalyst (currently sold on trucks)
  - Kinetic parameters from CLEERS lab protocol
  - Parameters and reaction details updated as data become available
  - Example comparison between model and lab measurements at 60,000 1/hr space velocity
    - a: NH_3/NO=1 (no NO_2), "standard" SCR
    - b: NH_3/NOx=1 & NO_2/NO=1, "fast" SCR



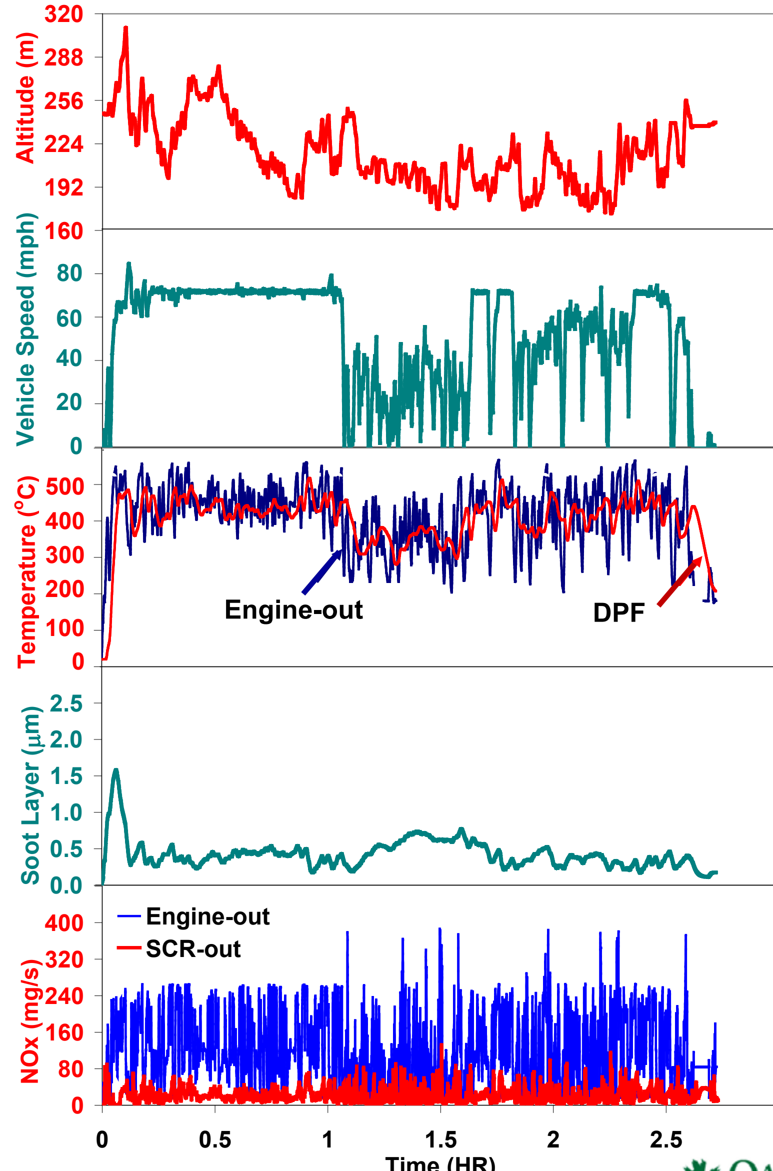
ACCOMPLISHMENT (3): We linked DOC, SCR and DPF models together to study fully integrated aftertreatment in Autonomie

- **Example case study**
  - 21000kg class 8 HD truck
  - 15-L, 6-cyl. diesel & 10-speed manual transmission
  - Interstate driving (Distance: 139.1 miles; Time: 2.71 hours; Altitude varying: 175 m -305 m)
  - Aftertreatment: 5.8-L DOC, 24.3-L SCR, 19.1-L CDPF
  - Non-optimized NOx and PM controls

Preliminary Observations

- Engine output: 1450 MJ vs. 1465 MJ (Autonomie)
- Fuel economy: 5.22 mpg vs. 5.00 mpg (Autonomie)
- CDPF predicted to be passively regenerated
- NOx emissions predicted to be reduced 83%

Emissions	Engine-out	Tailpipe
CO (g/mile)	1.695	0.466
HC (g/mile)	0.303	0.022
NOx (g/mile)	8.038	1.394
PM (g/mile)	0.395	0.005



COLLABORATION AND COORDINATION

- **Meritor CRADA (VSS072)**
  - HD engine dynamometer measurements in ORNL-VSI lab (fuel rate, emissions, temperature).
  - Transient-capable engine maps in Autonomie.
  - Class 8 test vehicle in-use measurements with prototype Dual-Mode Hybrid Powertrain (DMHP).
  - Models for development of optimal DMHP control.
- **CLEERS Collaboration**
  - Multiple engine OEMs, suppliers, universities, national labs (ACE022).
  - DOE Advanced Engine Crosscut Team.
  - USDRIVE Advanced Combustion and Emissions Control Tech Team.
- **Related ORNL Activities**
  - ORNL Heavy Truck Duty Cycle "real world" database (including grade).
  - Advanced LD Engine Systems and Emissions Control Modeling and Analysis (VSS041)
  - Neutron Imaging of Advanced Engine Technologies (ACE052).
  - High Efficiency Engine Systems Development and Evaluation (ACE017).
  - Non-Petroleum-Based Fuels: Effects on Emissions Control Technologies (FT007).
  - Electrically-Assisted Diesel Particulate Filter Regeneration (PM041).
  - Biofuels Impact on DPF Durability (PM040).
  - Durability of Diesel Engine Particulate Filters (PM010).

PROPOSED FUTURE WORK

- **FY2012**
  - Complete representative 2007 emission compliant HD engine map (emissions and temperature).
  - Implement steady-state and transient maps in Autonomie.
  - Implement and verify HD urea-SCR, DPF, and DOC models in Autonomie.
  - Carry out preliminary HD drive cycle simulations in Autonomie.

- **FY2013**
  - Refine HD engine maps based on ORNL VSI Lab measurements.
  - Evaluate fuel efficiency and emissions for alternate aftertreatment and drive train configurations.
  - Support DMHP data analysis and powertrain optimization.

SUMMARY: Advanced engine and emissions system modeling provides critical information for optimizing fuel-efficient and emissions-constrained HD hybrid powertrains

- HD hybrid powertrain optimization requires a system level understanding of interactions among energy sources and energy sinks.
- Simulation has an important role in developing and utilizing that understanding.
  - Key to rapid component development, characterization, and commercialization.
  - Essential for efficient investigation and identification of optimal control strategies.
- Simulation of advanced MD and HD hybrid vehicles involves several key steps.
  - Accurate component modeling of advanced engines and aftertreatment devices.
  - Validation with data from lab and full prototype systems in real world drive cycles.
  - Detailed analysis of dynamic component-to-component interactions.
  - Flexibility for implementing local and global control strategies.

ACKOWLEDGEMENTS

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