

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

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Vehicle Technologies Office

US Department of Energy

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OVERVIEW

Timeline

- Project start date: Oct. 2011
- Project end date: Continuing

Barriers*

- Risk aversion
- Cost
- Constant advances in technology
- Computational models, design, and simulation methodologies

**from 2011-2015 VTP MYPP*

Budget (DOE share)

- FY12 funding: \$325k
- FY13 (current expected) funding: \$300k

Partners

- 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 energy storage 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 and lean aftertreatment systems in diesel trucks.
- Evaluate the merits of specific alternative engine-energy storage-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)

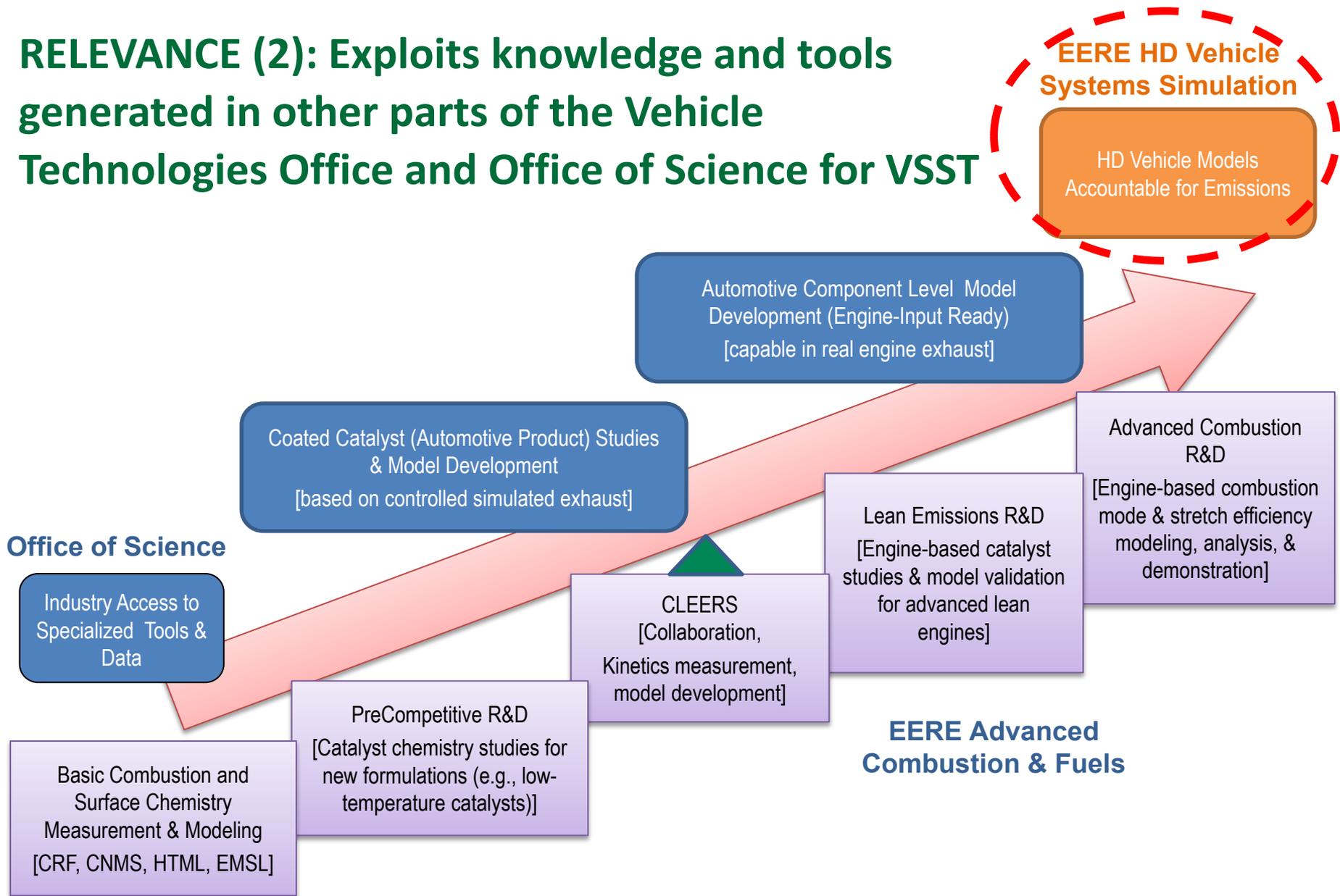
RELEVANCE (1)*

- **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; 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 Vehicle Systems Integration (VSI) Lab + data and models from other VTO 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:**

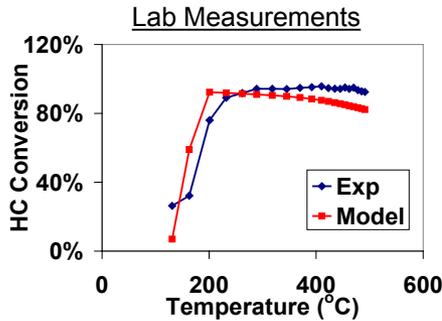
http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

RELEVANCE (2): Exploits knowledge and tools generated in other parts of the Vehicle Technologies Office and Office of Science for VSST

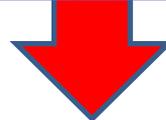


APPROACH: Link component models in integrated MD/HD simulations

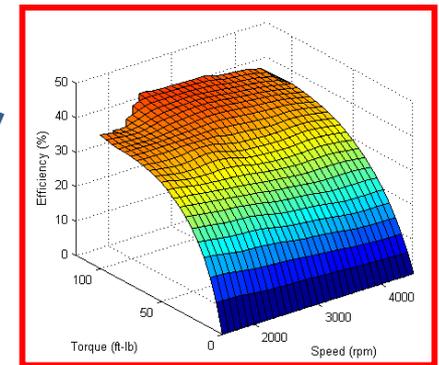
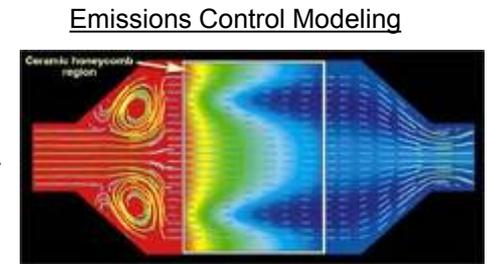
- Engine component models
 - Steady-state and transient MD/HD engine maps from dyno measurements and advanced combustion models.
- Aftertreatment component models
 - Adapt previous LD models (LNT, SCR, DOC, DPF, and TWC) and new models (e.g., passive adsorbers).
- Evaluate advanced MD/HD hybrid technology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



Dynamometer Measurements



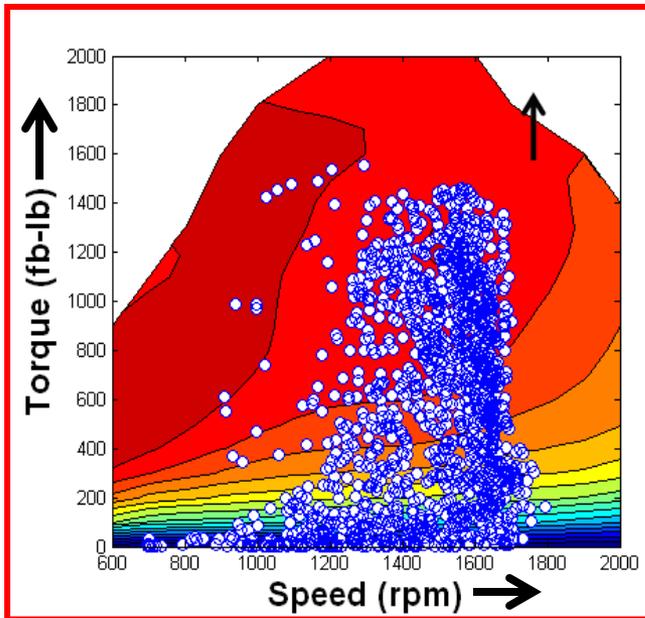
Truck Simulation



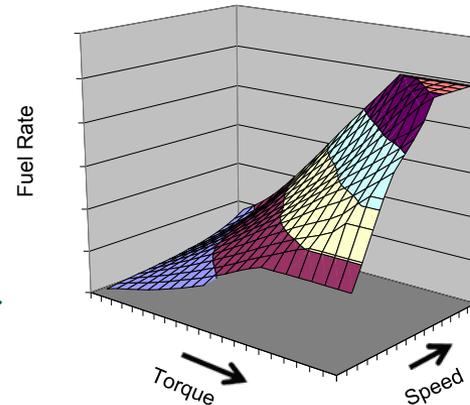
FY2013 MILESTONE

- Demonstrate transient HD hybrid drive cycle simulations with lean NOx and particulate emissions controls based on ORNL dynamometer measurements of 15L Cummins ISX engine certified to be compliant with 2010 emissions limits with aftertreatment (September 30, 2013).
 - Initial 2010 engine maps have been created and shared with Meritor CRADA
 - HD hybrid drive cycle simulations with updated HD aftertreatment train system started

HD Drive Cycles



Transient HD Engine Maps



Transient HD Aftertreatment Models



Performance
• Fuel economy
• Emissions

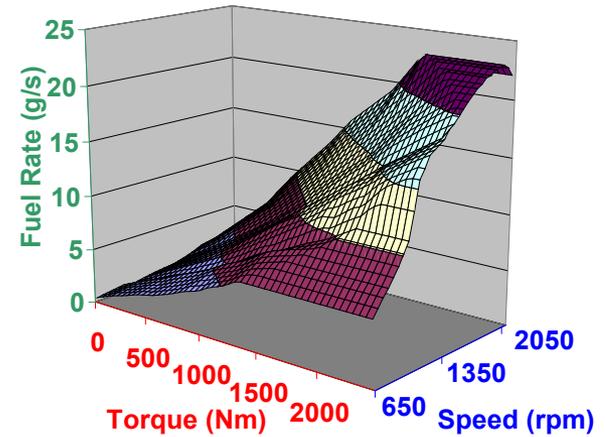
ACCOMPLISHMENT (1): 2010 HD engine maps constructed

- Include fuel rate & engine out T, CO, HC, NOx, and PM
 - Steady-state baseline response surfaces
 - Dynamic correction factors for transients
- Previous HD diesel engine maps
 - 2003, 15-L, 6-cylinder, MBTE 41%, PT 2000 ft-lb
 - 2007 15-L, 6-cylinder, MBTE 42%, PT 1650 ft-lb
- HD maps generated this FY
 - 2010 15-L CUMMINS ISX50 Engine, MBTE 45%, PT 1770 ft-lb

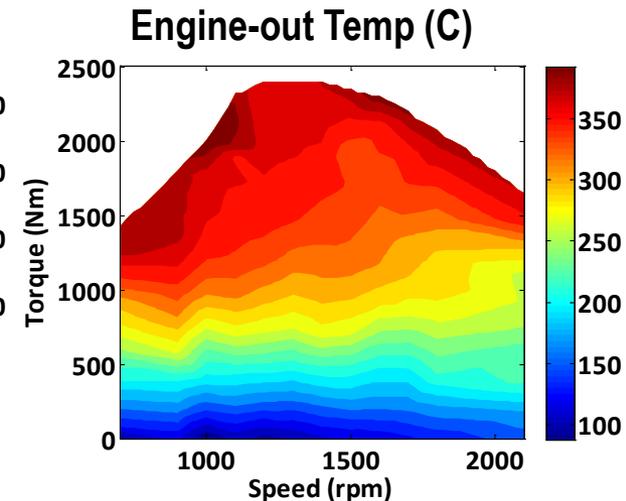
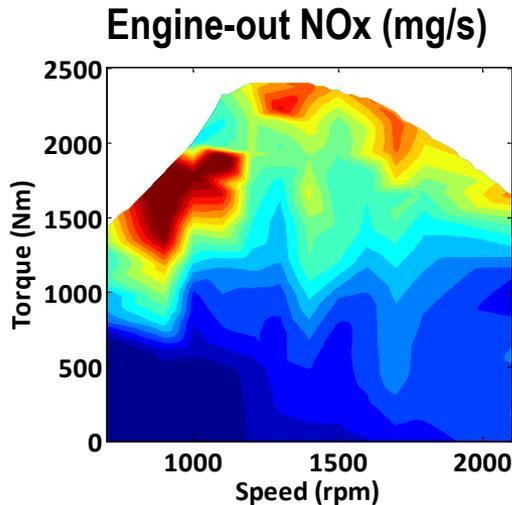


Changes from 2003→2010 indicate more reliance on aftertreatment for improved fuel economy

Steady-State Fuel Rate

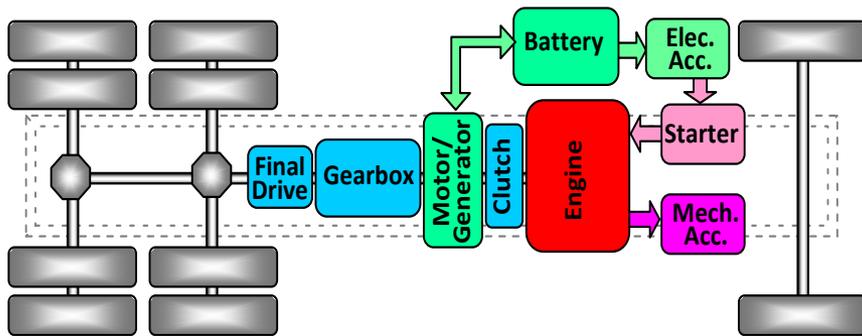


Example 2010 HD Diesel maps



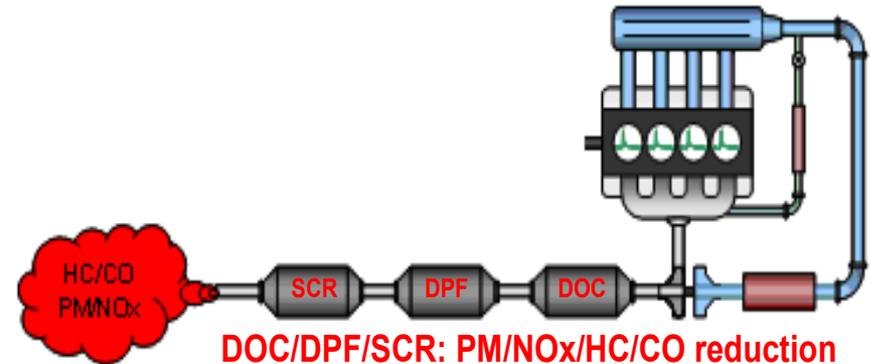
ACCOMPLISHMENT (2): Models for NO_x, CO, hydrocarbon, and particulate controls linked with the engine model and vehicle for conventional and hybrid drive cycle simulations

Simulated parallel HD hybrid



- Baseline mild pre-transmission hybrid powertrain configuration
- 150 kW electric motor, 180 kW battery
- Default Autonomie supervisory controller with charge-sustaining operation
- Compare with conventional truck
- Conventional truck model validated with chassis dynamometer measurements

Aftertreatment configuration



- 5.8-L Diesel oxidation catalyst (DOC)
- 19-L catalyzed diesel particulate filter (DPF)
- 24-L selective catalytic reduction (SCR) with urea injection
- Chemistry & physics based, fully transient
- Parameters based on open literature and CLEERS data

ACCOMPLISHMENT (3): Fuel consumption & emissions of class 8 HD hybrid vs. conventional trucks for 5 different drive cycles

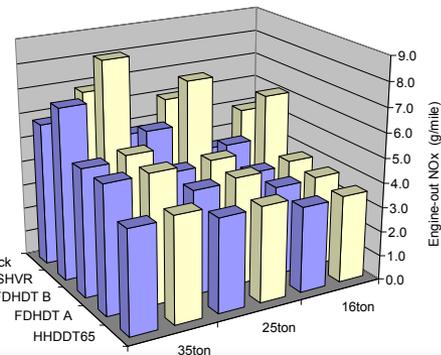
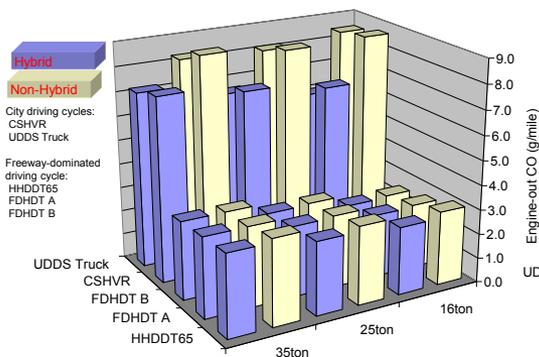
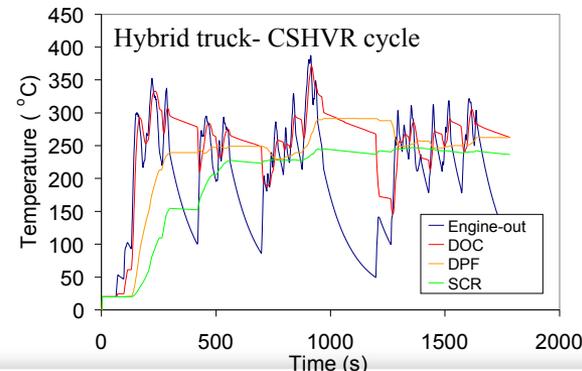
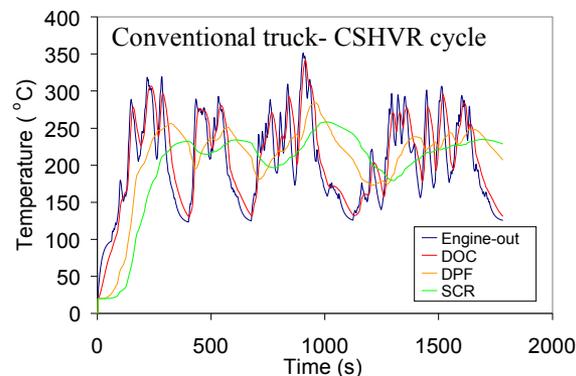
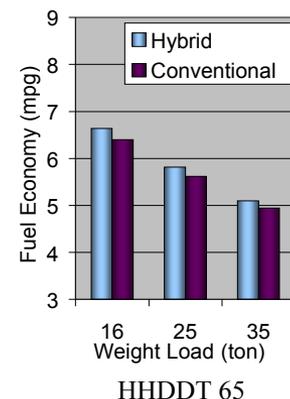
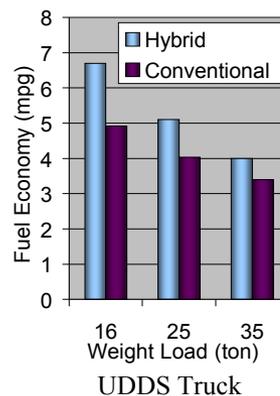
• Example case study

- 16,000, 25,000, and 35,000 kg total weight
 - 400 kg added weight for battery, motor, accessories
 - 2007 certified 15-L diesel & 10-speed manual transmission
 - 2 urban cycles UDDS truck & CSHVR
 - 3 highway cycles HHDDT65, FDHDT A* and FDHDT B*
- (*ORNL Freeway Dominant HD Truck Cycles with different grades)

- Aftertreatment: Non-optimized DOC, urea-SCR, DPF

Observations

- Overall hybrid fuel & emissions benefits are greater in city driving conditions
- Hybrid benefits decrease with increasing load
- Passive DPF regen reduces highway fuel penalty for both conventional and hybrid HD trucks
- Hybrid aftertreatment temperatures lower but smaller fluctuations



See SAE 2013-10-1033 for details

ACCOMPLISHMENT (4): Simulated fuel consumption & emissions for class 8 HD hybrid with 2010 certified engine

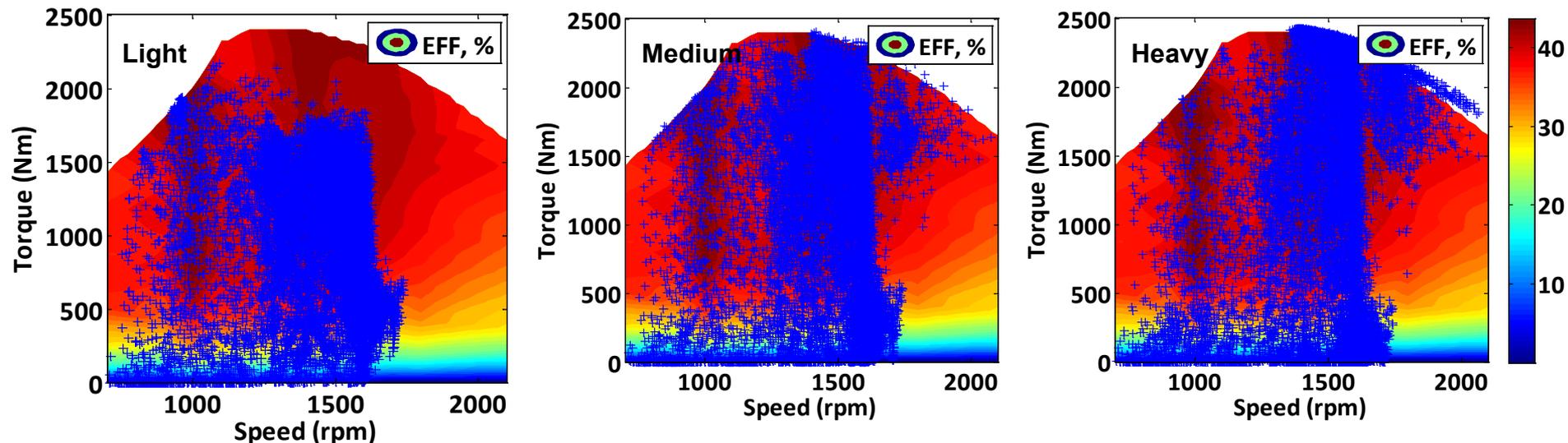
- Example case study
 - 2010 certified 15-L Cummins engine
 - ORNL Freeway Dominant HD Truck Cycle with grade
 - 16,000, 25,000, and 35,000 kg total weight
 - 400 kg added weight for battery, motor, accessories
 - Aftertreatment: Non-optimized DOC, DPF, urea-SCR

Observations

- Passive DPF regen sufficient for particulate control
- Fuel consumption and emissions increase with load
- Most NH₃ slip occurs during sharp engine transients

Total weight	FE	Engine BTE	CO	HC	NOx	PM	NH ₃	Urea cost (% of Fuel)
ton	mpg	%	g/mile	g/mile	g/mile	g/mile	g/mile	%
16.4	6.79	40.5%	0.141	0.013	1.254	0.0003	0.006	2.52
25.4	5.76	40.4%	0.175	0.020	1.336	0.0008	0.017	2.37
35.4	4.92	40.6%	0.188	0.024	1.426	0.0013	0.032	2.35

Cumulative fuel consumption and tailpipe emissions



2010 engine operating points for the light, medium, and heavy load cases.

COLLABORATION AND COORDINATION

- **Meritor CRADA/Industrial Collaboration**
 - HD engine dynamometer measurements in ORNL-VSI lab (fuel rate, emissions, temperature).
 - Transient-capable engine maps in Autonomie.
 - Class 8 emulated vehicle in ORNL-VSI Lab with DMHP hardware and 15-L CUMMINS 2010 ISX engine.
 - Models for development of optimal DMHP control.
- **CLEERS Collaboration**
 - Multiple engine OEMs, suppliers, universities, national labs.
 - DOE Advanced Engine Crosscut Team.
 - USDRIVE Advanced Combustion and Emissions Control Tech Team.
- **Related VTO activities at ORNL and other labs**
 - ORNL Heavy Truck Duty Cycle database & NREL Fleet DNA data repository (**including grade**).
 - Neutron Imaging of Advanced Engine Technologies.
 - High Efficiency Engine Systems Development and Evaluation.
 - Fuel Effects on Emissions Control Technologies.
 - Electrically-Assisted Diesel Particulate Filter Regeneration.
 - Biofuels Impact on DPF Durability.
 - Durability of Diesel Engine Particulate Filters.

PROPOSED FUTURE WORK

- **FY2013**

- Complete representative 2010 emission compliant HD engine map (emissions and temperature) with transient parameters derived from ORNL VSI measurements.
- Implement refined steady-state and transient maps in Autonomie.
- Update HD DOC, DPF, and urea-SCR models in Autonomie with VSI measured data and more recent device model parameters.
- Continue 2010 engine HD drive cycle simulations in Autonomie over wider range of drive cycles.

- **FY2014**

- Support investigation of alternative hybrid configurations and control strategies for powertrain optimization.
- Evaluate impact of fuel quality variations (e.g., biodiesel blending) on fuel consumption and emissions.
- Include waste heat management options in HD simulations.

SUMMARY: Significant progress has been made toward simulating fuel consumption and emissions for HD hybrid trucks

- **HD hybrid truck simulations with full aftertreatment have been implemented for 2003, 2007, and 2010 compliant 15L diesel engines.**
- **The current simulation tools are providing a firm foundation for exploring options in powertrain configuration, aftertreatment configuration, and hybrid control for maximizing the benefits of hybridization and identifying the biggest opportunities for utilizing hybrid technology in the HD sector.**
- **We continue to expand the capabilities of our engine and aftertreatment models to enhance their accuracy, flexibility, and relevance to the most advanced engine and emissions technology.**

ACKNOWLEDGEMENTS

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