PHEV Engine and Aftertreatment Model Development

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Oak Ridge National Laboratory

2009 DOE OVT Peer Review

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U.S. DEPARTMENT OF ENERGY

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Overview

- **Timeline**
  - Start
    - 2005
  - Finish
    - Ongoing
- **Budget**
  - FY08 Funding
    - $725K
  - FY09 Funding
    - $700K
  - FY10 Request
    - $725K
- **Barriers**
  - PHEV utilization of high efficiency engines is limited by transient engine performance and emissions controls
  - Data and models available for analyzing transient advanced PHEV engines and emissions are very limited
- **Partners**
  - DOE Diesel Crosscut Team companies and CLEERS consortium of suppliers, national labs, and universities
  - Company and university participants in ACE/HCCI consortium
  - VSATT Team Participants

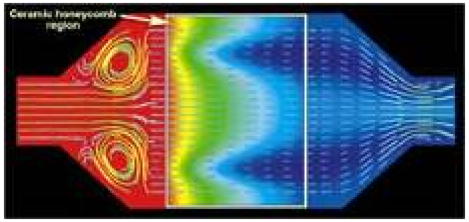
Objectives

- Enable and demonstrate simulation of emissions and fuel efficiency for current and leading edge hybrid vehicles under fully transient drive cycle conditions
- Apply simulation to assess fuel efficiency and emissions impact of:
    - Lean burn versus conventional gasoline engines
    - Advanced combustion (HCCI, PCCI) versus conventional combustion (SI, diesel)
    - Non-petroleum and bio-derived fuels
    - Alternative engine and emissions system control strategies
    - Alternative battery charging strategies
    - Alternative HEV and PHEV system configurations

Vehicles

Engines

Emissions Controls



Models

Relevance

Mission
The AVTAE team's mission is to evaluate the technologies and performance characteristics of advanced automotive powertrain components and subsystems in an integrated vehicle systems context.

Objective
The prime objective of the AVTAE team activities is to evaluate VT Program targets and associated data that will enable the VT technology R&D teams to focus research on areas that will maximize the potential for fuel efficiency improvements and tailpipe emissions reduction. AVTAE accomplishes this objective through a tight union of computer modeling and simulation, integrated component testing and emulation, and laboratory and field testing of vehicles and systems.

Evaluation of advanced hybrid technologies involves multiple factors:

- **Understanding of interactions among engine, aftertreatment, and fuel systems**
- **Integrated models suitable for vehicle simulations and parametric studies**
- **Validation of predictions for fuel efficiency and emissions against experimental data (engine dynamometer, vehicle, laboratory)**

Multiple OVT (inter-team) resources are available:

- **Leveraging with other DOE OVT projects and OEM collaborations (e.g., technology gaps analysis for DOE diesel crosscut team)**
- **Task 2a evolved from early AVTAE utilization of data from FreedomCAR advanced combustion engine projects**

Milestones

- **FY08 Milestone: Develop aftertreatment sub-models to conduct simulations that evaluate the impact of advanced combustion and aftertreatment technologies on the fuel economy and emissions of plug-in hybrids- September 30, 2008 (completed)**
- **FY09 Milestone: Implement an improved 3-way catalyst aftertreatment sub-model to conduct simulations that evaluate the impact of stoichiometric biofuel engines on the fuel economy and emissions of plug-in hybrids. September 30, 2009 (in progress)**

Approach

- **Stoichiometric HEVs & PHEVs**
  - Develop & validate maps for advanced gasoline & ethanol SI engines
  - Implement & validate accurate 3-way catalyst model
  - Demonstrate integrated 3-way cat & engine simulations for leading edge hybrids
- **Lean HEVs and PHEVs**
  - Develop & validate maps for most advanced lean engines (gasoline DI, diesel) using conventional & bio fuels
  - Adapt maps for advanced combustion modes (HCCI, PCCI)
  - Implement & validate accurate lean NOx/PM component models
  - Demonstrate lean engine maps & lean NOx/PM control for alternative hybrids
  - Compare efficiency benefits of lean versus stoichiometric HEVs and PHEVs
- **All**
  - Generate/utilize public domain lab, engine dynamometer, and chassis dynamometer data as a basis for all models & maps
  - Expand data to include effects of non-conventional and bio-derived fuels
  - Where experimental data are absent, utilize results from computer simulations based on WAVE, GTPower, KIVA, CHEMKIN, & in-house aftertreatment codes
  - Include global environmental compliance success as key simulation output
  - Address additional efficiency boosting concepts such as bottoming cycles, thermo-electrics, thermo-chemical recuperation, and thermal storage.

Background

- HEVs and PHEVs can have either stoichiometric or lean-burn engines
  - Stoichiometric engines
    - Heaviest emissions during cold start, transients
    - Limited data for alternative fuels
    - 3-way catalyst technology still evolving (e.g., lower PGM)
  - Lean-burn engines
    - More fuel-efficient than stoichiometric engines (focus of advanced engine development at OEMs and in DOE)
- 3-way catalyst technology not suitable for lean-NOx and PM
  - Up to now lean emission controls have been left out of hybrid studies
  - Lean emissions control technology still under intense development
  - Need to minimize fuel penalty without hurting emissions
  - Advanced combustion regimes still under development (potentially large fuel efficiency increases and emissions reductions)
  - Limited engine and emission data for alternative fuels
- For both engine types, drive cycle transients can greatly impact emissions controls (aftertreatment devices)
  - Catalytic reactions are highly temperature dependent
  - Hybrids have unique engine on/off cycling transients

Accomplishments/Progress/Results

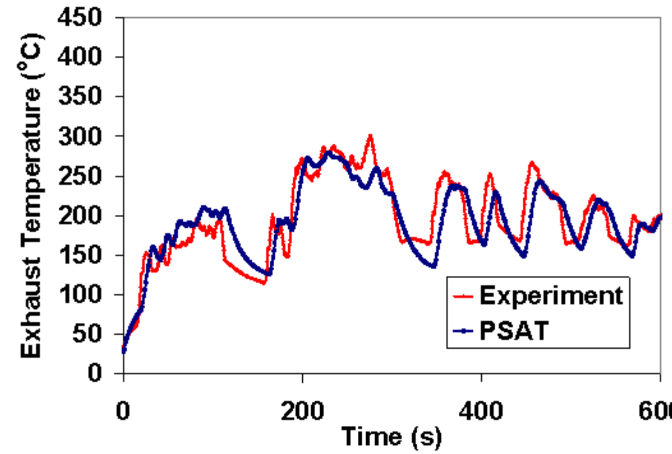
Since 2008 Review last February:

- Generated first public map for leading edge 1.9-L research diesel engine (reference engine for MOU) with inclusion of PCCI combustion modes
- Tested preliminary DPF and SCR lean aftertreatment models
- Improved and demonstrated external heat loss and thermal transients methodology for integrated engine and aftertreatment simulations
- Constructed and validated (with Saab and industry collaborator data) new 3-way catalyst model for stoichiometric engines
- Demonstrated capability for making comparisons of stoichiometric versus lean engine HEVs and PHEVs
- Began case studies of the impact of lean NOx and PM controls on potential efficiency advantage of diesel PHEVs
- Demonstrated PHEV simulation with diesel HECC combustion

Example details follow

Example Details from Recent Results

Our method for simulating transient engine exhaust temperature and emissions compares well with observations



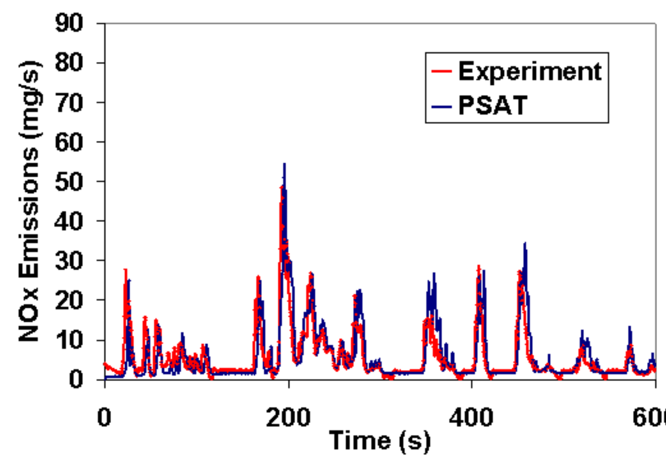
Simulation parameters:

- Mercedes 1.7L diesel engine
- UDDS cycle with cold start
- Civic vehicle configuration

Results:

- Integrated mileage and engine-out emissions

	Mileage (mpg)	CO (g/mi)	HC (g/mi)	NOx (g/mi)	PM (g/mi)
Experiment	40.3	2.28	0.54	0.74	0.14
Simulation	40.4	2.29	0.54	0.89	0.12



Successfully handles cold/warm start transients for both gasoline and diesel engines.

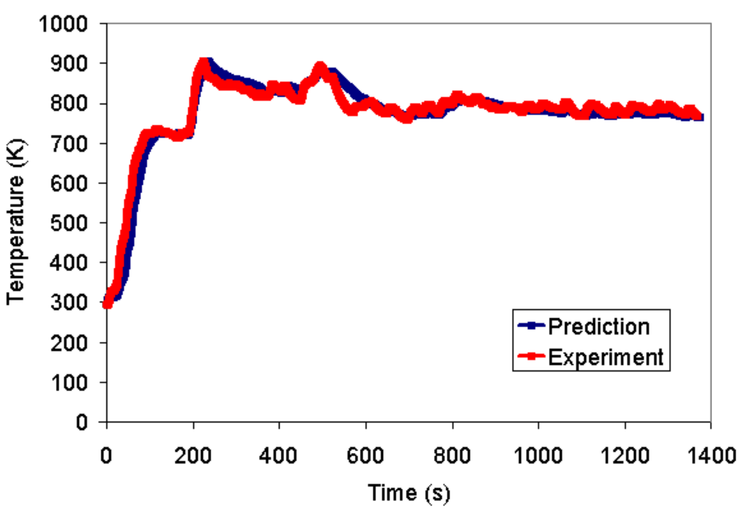
Our transient TWC model has been validated against independent OEM data

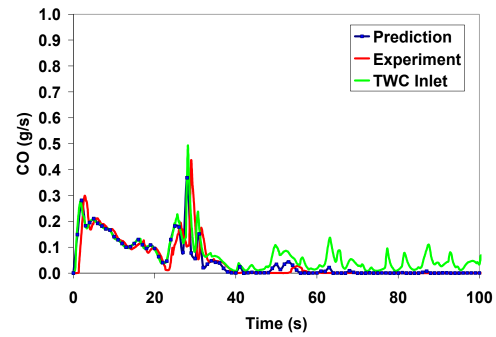
Model validation conditions:

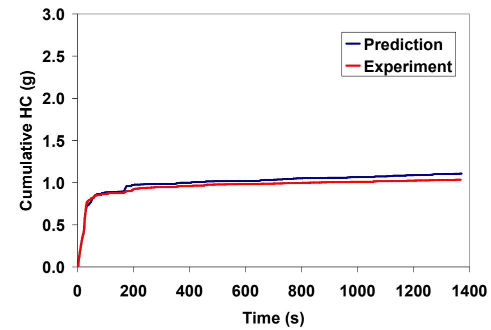
- Vehicle chassis data for gasoline engine
- Supplied by OEM collaborator
- UDDS cycle, cold start

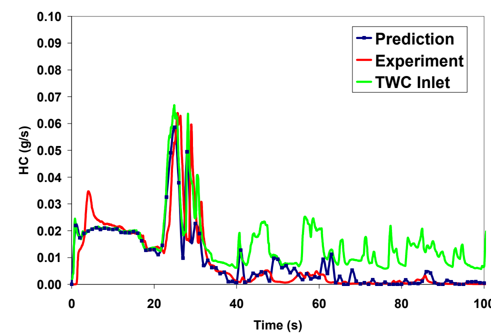
Integrated emissions:

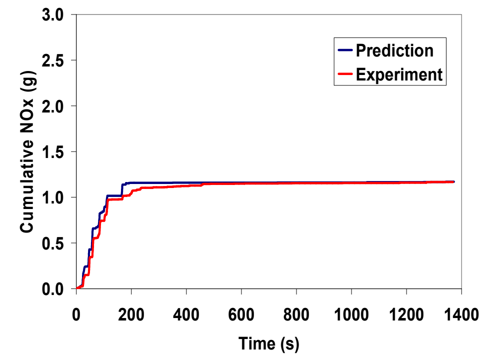
- CO (g/mi): 0.833 (exp) vs. 0.836 (model)
- NOx (g/mi): 0.156 (exp) vs. 0.157 (model)
- HC (g/mi): 0.139 (test) vs. 0.148 (model)

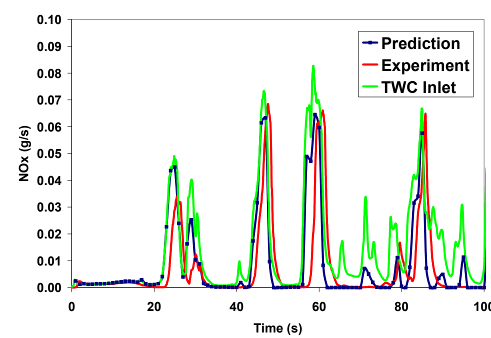


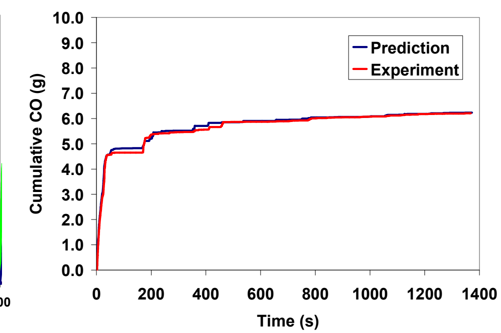








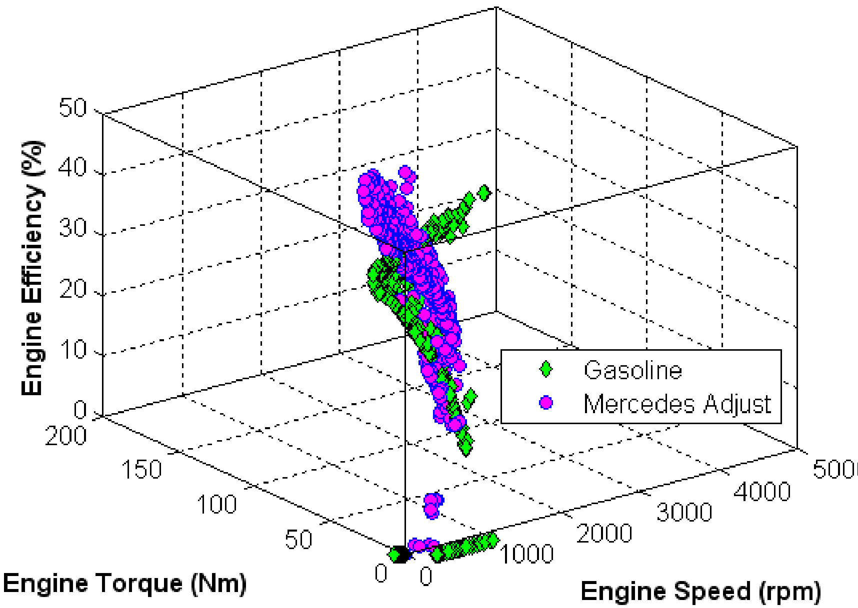




Std. gasoline vs. diesel baseline HEV comparison indicates large diesel fuel economy benefit

Simulation parameters:

- Prius HEV, 28% serial- 72% parallel
- Hot start UDDS cycle
- 1.3 kWhr battery charge (65%)
- 1.5 L stoichiometric gasoline engine with Atkinson cycle, TWC
- 1.5 L diesel scaled from 1.7 L Mercedes A170 reference, no valving adjustments, no NOx/PM control



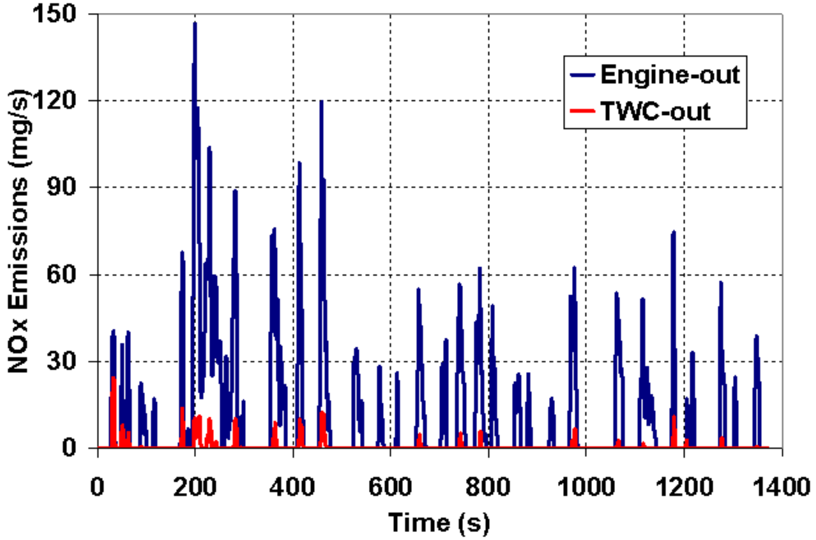
Results:

- 84.2 mpg diesel vs. 70.7 mpg gasoline (SAE 2007-01-0281 reports 71.2 mpg for Prius)
- Max engine efficiency: 41% diesel vs. 37% gasoline
- Cycle average engine efficiency: 36% diesel vs. 34% gasoline
- Diesel (without aftertreatment) has 19% better MPG, 5.4% better energy efficiency

However, lean NOx control has a big impact on expected diesel HEV efficiency advantage

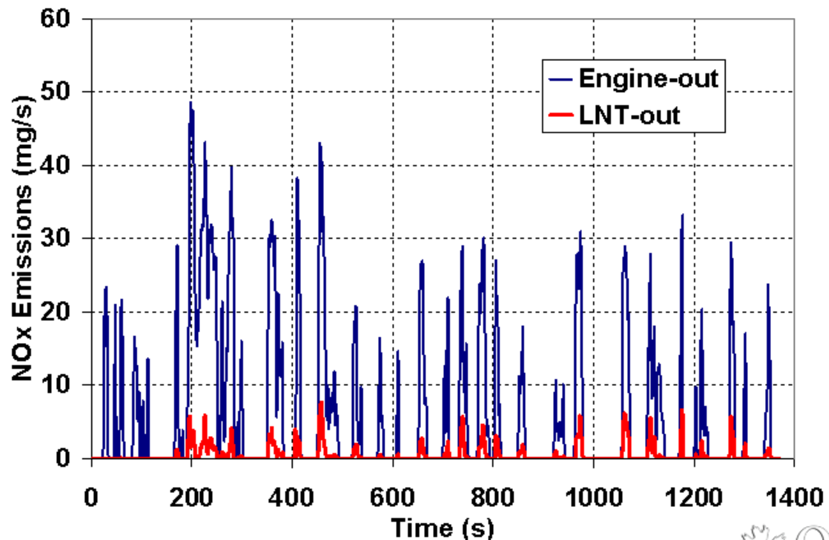
Simulation parameters:

- Prius HEV
- Hot start UDDS drive cycle
- 1.3 kWhr battery charge (65%)
- 1.5-L gasoline and diesel engines
- 2.2-L TWC and 2.2-L LNT



Results:

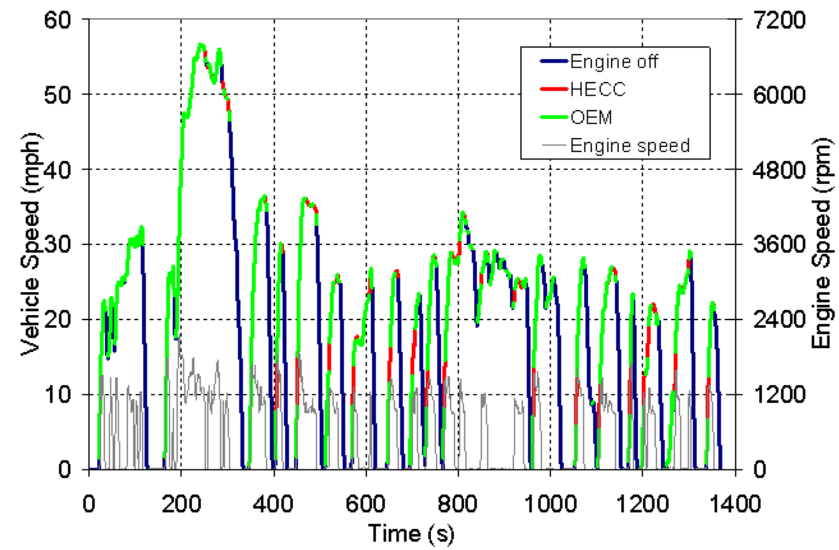
- 81.6 mpg diesel vs. 70.7 mpg gasoline
- 0.09 g/mile NOx vs. 0.10g/mile NOx
- 92% NOx reduction vs. 96% NOx reduction
- LNT fuel penalty for diesel 3.1%
- With LNT diesel efficiency advantage just over 2%



Current High Efficiency Clean Combustion (HECC) only has modest HEV efficiency benefit

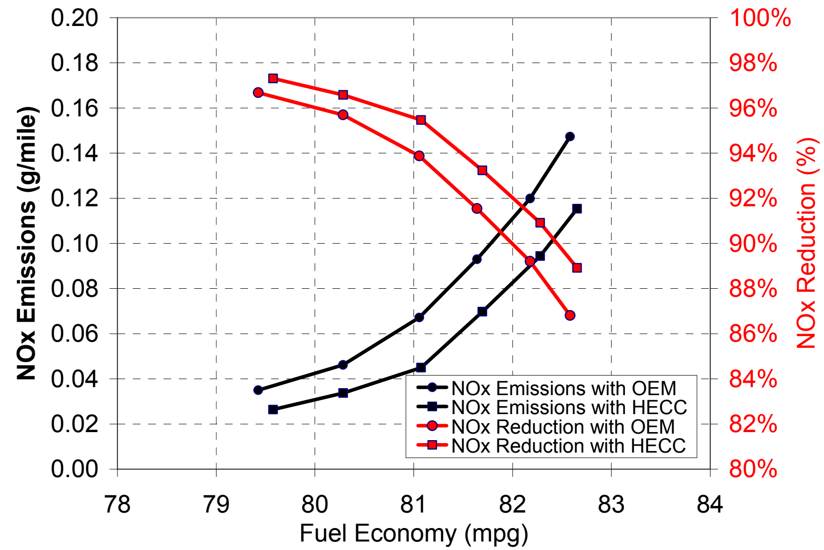
Simulation parameters:

- Prius HEV
- Hot start UDDS drive cycle (1372s and 7.45mile)
- 1.3 kWhr battery charge (65%)
- 1.5-L diesel HECC-capable engine
- 2.2-L LNT NOx control
- Variable regeneration duration (3-8s)



Results:

- HECC boosts fuel economy around 0.8% (82.3 vs. 81.6 mpg)
- HECC benefit limited by small operating range:
  - Total engine on time: 560s
  - HECC on time: 120s (20% total engine on time)
- Demonstrates need for increasing HECC range (under intense development)



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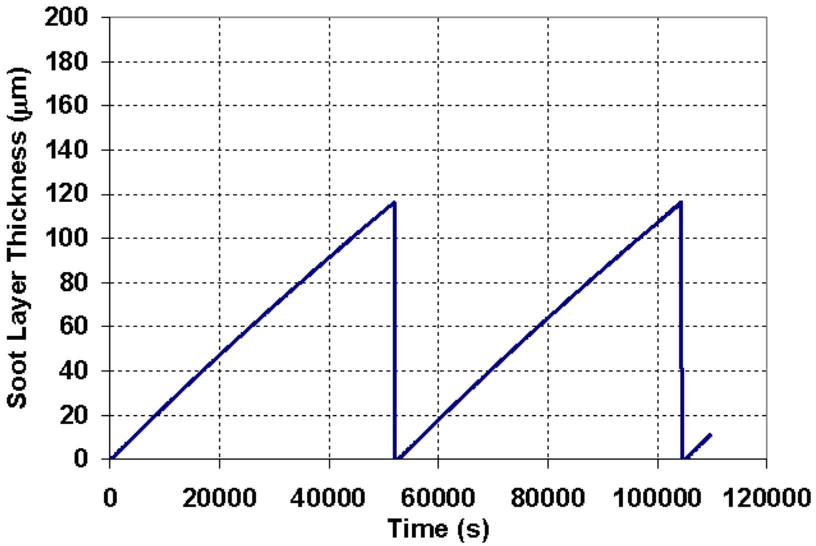
DPF particulate control also has a big impact on diesel HEV efficiency

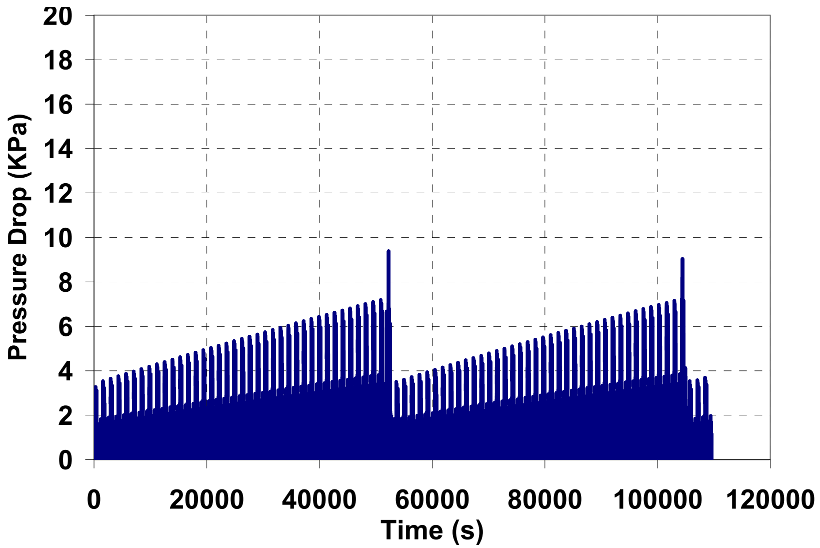
Simulation condition:

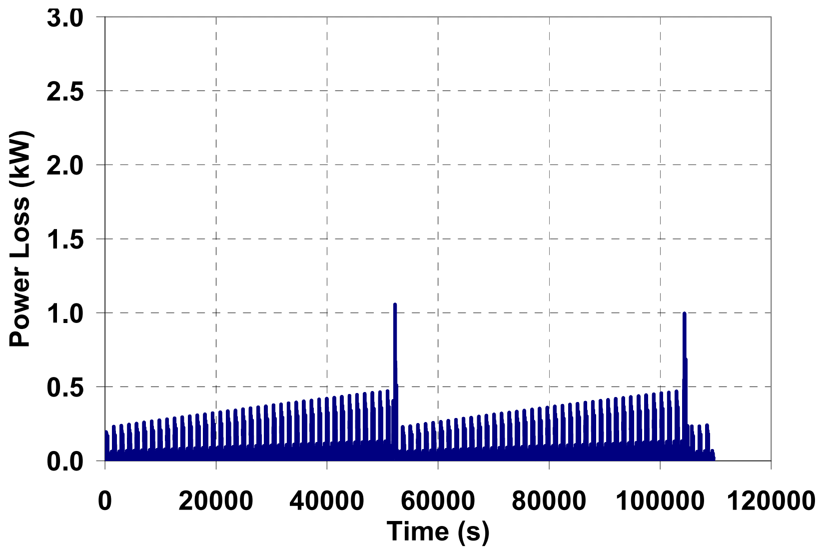
- Prius HEV
- Eighty consecutive UDDS drive cycles (~316 miles)
- Cold start and 1.2kWh battery charge
- 1.5-L diesel engine
- 2.1 L Non-catalytic DPF
- DPF regen 600s duration per SAE 2007-01-3997



Results:

- Overall (80 cycle) fuel penalty for DPF 2.9%
- Penalty from regen fueling boost and DPF ΔP





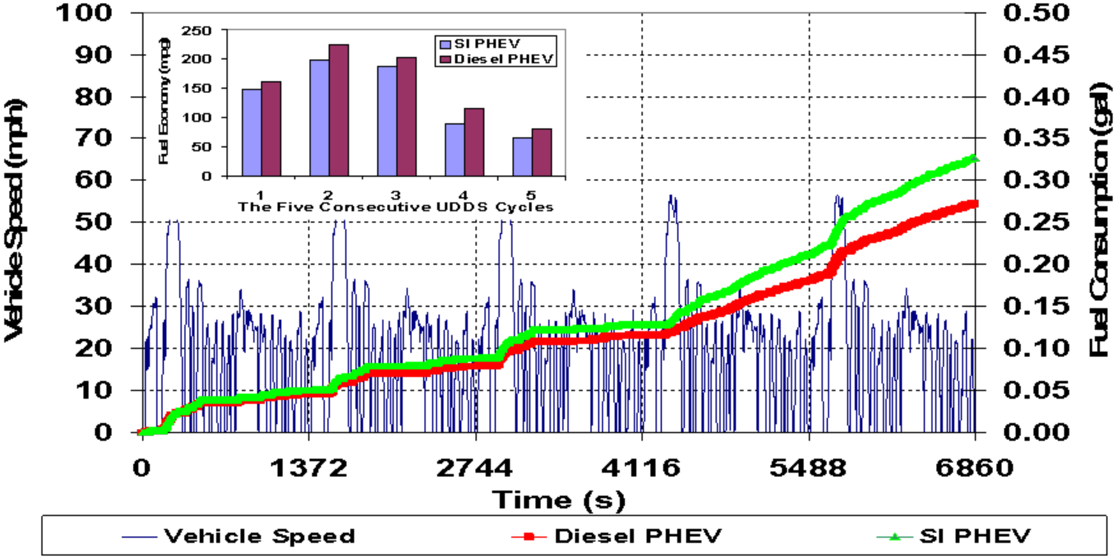
PHEV baseline comparison indicates large potential diesel efficiency benefit similar to HEV

Simulation condition:

- Prius PHEV
- 5 consecutive UDDS cycles
- Cold start, 5 kWh charge (100%)
- 1.5-L gasoline engine w TWC
- 1.5-L diesel engine w no NOx/PM control

Results:

- Overall 19.9% better mpg for diesel (6% higher energy efficiency)



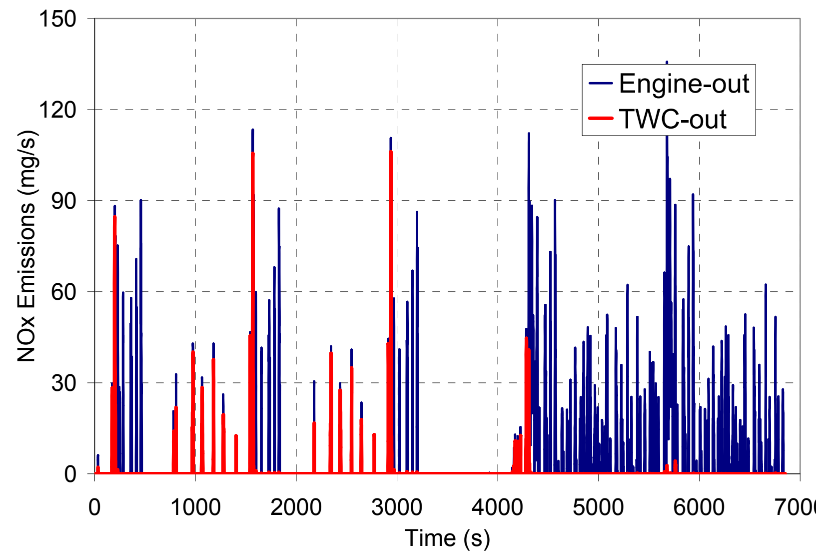
UDDS Cycle number		1	2	3	4	5	Total
Fuel economy (mpg)	Gasoline	147.1 (148*)	197.2 (200*)	188.2 (187*)	88.1 (74*)	65.0 (66*)	113.8 (108.9*)
	Diesel	161.3	224.7	202.0	115.2	80.9	136.5
Battery energy consumption (kWh)	Gasoline	0.74 (0.93*)	0.95 (0.96*)	0.92 (0.94*)	0.47 (0.23*)	0.03 (-0.12*)	3.11 (2.94*)
	Diesel	0.72	0.93	0.87	0.54	0.02	3.08

* data from SAE 2007-01-0283

However, NOx control likewise significantly impacts expected diesel PHEV efficiency

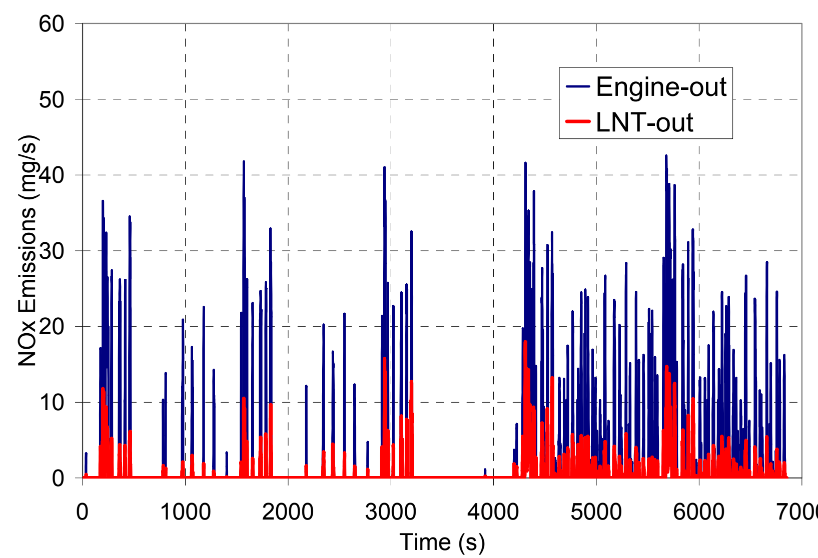
Simulation condition:

- **Prius PHEV**
- **5 UDDS drive cycles**
- **Cold start, 5 kWhr initial charge (100%)**
- **1.5-L stoichiometric gasoline engine w TWC**
- **1.5-L diesel engine w LNT**



Results:

- **Diesel mpg drops from 136.5 to 132.4 (3% LNT fuel penalty)**
- **Diesel still 3% better than gasoline**
- **NOx emissions drops 80% to 0.11g/mile**



Technology Transfer

Industry is continuing feedback and data sharing via:

- **Advanced Combustion Memorandum of Understanding (MOU)- Includes Cummins, Caterpillar, Chrysler, DDC, Ford, GE, GM, John Deere, Volvo, International, BP, ConocoPhilips, ExxonMobil, Chevron, Shell**
- **Advanced Combustion and Emission Control (ACEC) Tech Team – USCAR Ford, GM, Chrysler**
- **DOE Diesel Crosscut Team -DDC, Cummins, Volvo, GM, Ford, Chrysler, Caterpillar, John Deere, International, EPA, TACOM**
- **Crosscut Lean Exhaust Emission Reduction Simulation (CLEERS) collaboration- Crosscut Team, Delphi, Umicore, Johnson Matthey, BASF, Bosch, Corning (see www.cleers.org)**

Above interactions also provide opportunities for industry to test and comment on VSATT model utilization (e.g., PSAT implementation with proprietary in-house component models added as in the Delphi CRADA)

Planned Future Activities

- **Stoichiometric hybrid simulation (e.g., Prius-type engines)**
  - Continue speed-up and validation of 3-way catalyst model
  - Update 3-way cat model for reduced PGM loadings and advanced control strategies
  - Improve emission transients model predictions of unburned HC (cold and warm start)
  - Develop second generation transients model with coolant thermal storage included
- **Lean hybrid simulation (e.g., VW Rabbit, GM 1.9-L-type engines)**
  - Demonstrate hybrid vehicle simulations with lean HCCI and direct-injected combustion
  - Continue comparisons of diesel and SI HEV fuel efficiency and emissions
  - Evaluate impact of PCCI diesel operation on HEV fuel efficiency and emissions
  - Expand studies of DPF PM control for diesel HEV
  - Evaluate Urea-SCR NOx control for diesel HEV
  - Update available algorithms for engine scaling
- **Exhaust heat recovery simulation**
  - Define and implement reference simulation for thermo-electrics impact
  - Define and test simulation of thermo-chemical recuperation
  - Define and test simulation of Rankine bottoming cycle
- **Coordination**
  - Close coordination with Combustion MOU, ACEC, DCC Team, CLEERS to maintain relevance to latest engine/emissions technology and industry needs

Summary

- It appears feasible to model the critical features of engine exhaust temperature and emissions transients that occur in HEV and PHEV drive cycles.
- It appears feasible to model the impact of these engine transients on both TWC and lean exhaust emissions control devices in integrated systems simulations.
- Systems simulations indicate that diesel engines offer significant potential fuel efficiency advantages for HEVs and PHEVs, but these advantages are likely to be reduced by fuel requirements for lean NOx and PM control.
- Studies are needed to determine if urea-SCR lean NOx control may be a better option for lean HEVs and PHEVs.
- Comparative studies are needed for HEVs and PHEVs powered by lean gasoline engines vs. diesel engines.

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