VSS140

Impacts of Advanced Combustion Engines

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2014 U.S. DOE Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting

June 16-20, 2014

Center for Transportation Analysis

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Oak Ridge National Laboratory
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

OVERVIEW

Timeline

- Project start date: Oct. 2013
- Project end date: Continuing
- Activity scope changes to address DOE & industry *needs*

Barriers for VSST* and ACE*

- Constant advances in technology (VSST)
- Computational models, design, and simulation methodologies (VSST)
- Lack of modeling capability for combustion and emission control (ACE)
- Lack of actual emissions data on future engines (ACE)

**from 2011-2015 VTP MYPP*

Budget (DOE share)

- FY14 (current expected) funding: $150k
- FY15 (current expected) funding: $250k

Partners

- DOE ACE and FLT research projects
- DOE Advanced Engine Crosscut Team
- CLEERS Collaborators
- Oak Ridge National Laboratory
  - Fuels, Engines, & Emissions Research Center
  - Center for Transportation Analysis

<u>OBJECTIVE</u>: Evaluate the benefits and challenges of advanced combustion concepts on a vehicle systems basis

"WHY"

- **Advanced combustion achieves high thermal efficiency with low engine-out emissions**
- **Transient/drive cycle benefits and challenges of advanced combustion in light-duty vehicles is not well understood**
- **Evaluation and analysis are important for supporting U.S. automakers to meet 2025 CAFE standards and EPA Tier III emissions regulations**

"HOW"

- **Generate experimental steady-state advanced engine maps**
- **Integrate engine maps into transient vehicle models along with full aftertreatment-trains**
- **Evaluate fuel economy and emissions of multi-mode combustion using vehicle systems simulations over realistic light-duty drive cycle conditions**
- **Identify promising paths for improving LD energy efficiency, fuel mileage and emissions with advanced combustion modes in conventional and hybrid-electric vehicle powertrains**

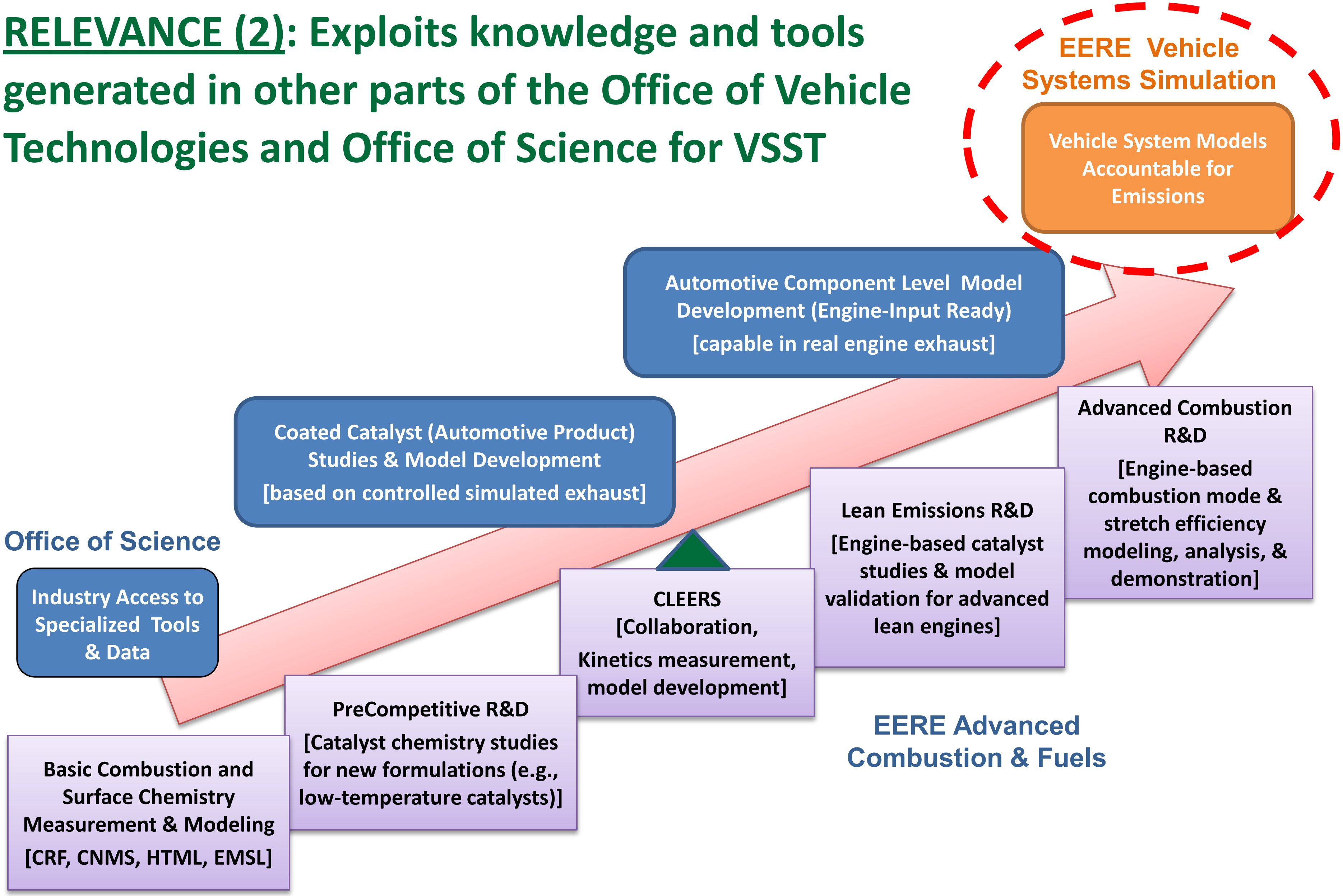
> **"Without aftertreatment constraints in the simulation, the model might allow engine system operation outside the emission-constrained envelope."**
>
> – National Academy of Science study on reducing fuel consumption from MD and HD vehicles (ISBN: 0-309-14983-5)

RELEVANCE (1)*

- **Directly supports ACE R&D program goals including a JOULE level milestone**
- **Directly supports FLT R&D program goals including a JOULE level milestone**
- **Directly supports 3 VSST cross-cutting activities:**
  - Modeling and simulation; component & systems evaluations; vehicle systems optimization.
- **Directly supports US Drive ACEC/VSATT activities**
- **Addresses the following VSST Barriers (2.2.1 e,f):**
  - **Computational models, design and simulation methodologies**
  - **Constant advances in technology.**
- **Addresses the following ACE/FLT Barriers (2.3.1 a,c,d,f):**
  - **Lack of fundamental knowledge of advanced combustion regimes**
  - **Lack of modeling capability for combustion and emission control**
  - **Lack of effective engine controls for LTC**
  - **Lack of actual emissions data on future engines**

***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 Office of Vehicle Technologies and Office of Science for VSST



Milestones

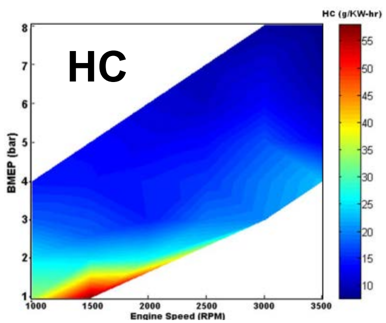
All Milestones Completed or On-Track

Date	Milestone/Deliverables	Status
June 2014	Complete fuel economy simulations of RCCI-enabled HEVs subjected to standard drive cycles	**On track**
Sept 2014	Complete vehicle level simulations for cold-start RCCI-enabled light duty HEV emissions control	**On track**

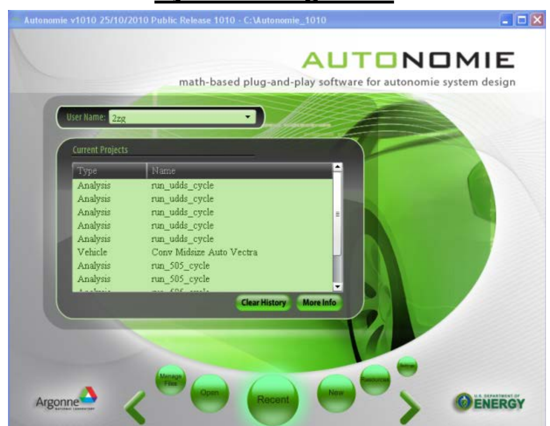
APPROACH (1): Vehicle Systems Simulations with Advanced Combustion

- **Advanced combustion engine maps**
  - **Steady-state advanced combustion engine maps from dyno measurements with exhaust species**
- **Evaluate advanced combustion engine operation in conventional and hybrid LD powertrains**
  - **Fuel economy potential of advanced combustion engine multi-mode concepts**
- **Evaluate the effect of fuels on advanced combustion engine drive cycle coverage**
  - Complete drive-cycle coverage has implications on aftertreatment requirements for multi-mode operation

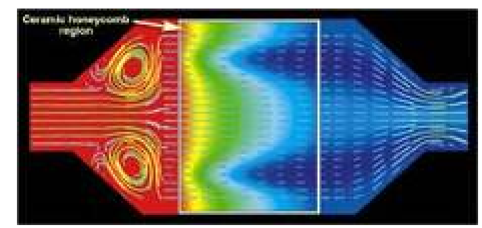
Lab Measurements

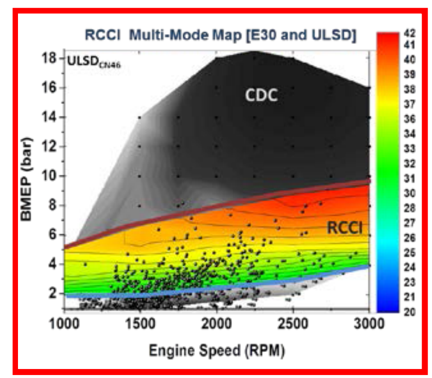


System Integration



Emissions Control Models





Multi-Mode Map Integration

Dynamometer Measurements

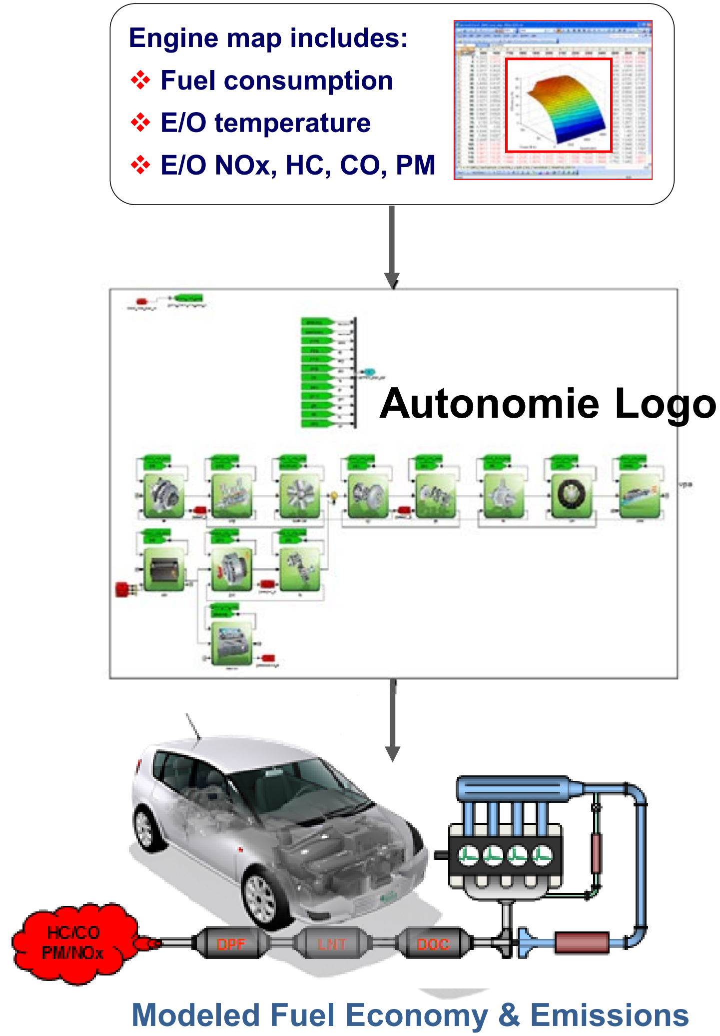
Vehicle Simulation

APPROACH (2): ORNL's comprehensive approach to vehicle systems research

- **2007 GM 1.9-L multi-cylinder diesel engine**
  - OEM (CR 17.5) and modified RCCI pistons (CR 15.1)
  - Dual-fuel system with PFI injectors
- **Aftertreatment integration & emissions characterization**
  - Modular catalysts / regulated and unregulated emissions
- **Vehicle systems simulations using Autonomie**
  - **Create multi-mode engine maps and controls**
  - **Experimental engine maps used for drive cycle simulations**
  - **Comparison between 2009 PFI, diesel and diesel/RCCI**
  - **Multi-mode (RCCI to conventional diesel combustion) used for areas of the drive cycle outside the RCCI operating range**

– **Model Details**

- Simplified low-order correction methodology to estimate transient exhaust properties from steady-state engine maps *(Gao et.al., Int. J. Engine Res., 11(2), 2010)*
- Other simulation details available from Gao et. al., "Light-Duty Drive Cycle Simulations of Diesel Engine-Out Exhaust Properties for an RCCI-Enabled Vehicle," 8th U. S. National Combustion Meeting (& backup slide)

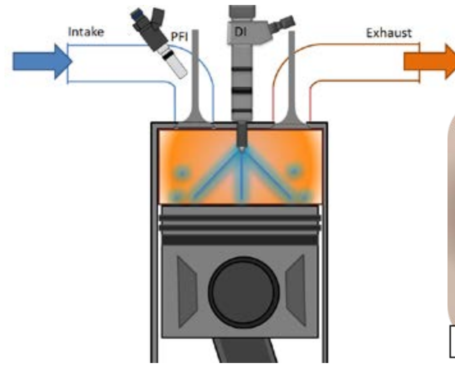


BACKGROUND : ACE developed advanced combustion mode - RCCI

- **Reactivity controlled compression ignition (RCCI) allows precise reaction and heat-release control**
  - A low-reactivity fuel is introduced early and premixed with air.
  - A high-reactivity fuel is injected into the premixed charge before ignition.

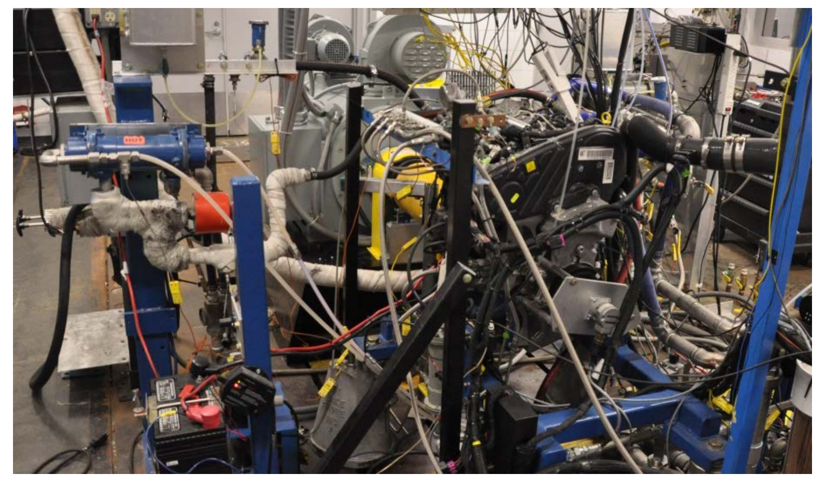
- **RCCI increases engine operating range for premixed combustion**
  - Global fuel reactivity (phasing)
  - Fuel reactivity gradients (pressure rise)
  - Equivalence ratio and temperature stratification

- **RCCI offers both benefits and challenges to implementation of LTC**
  - Diesel-like efficiency or better
  - Low NOx and soot

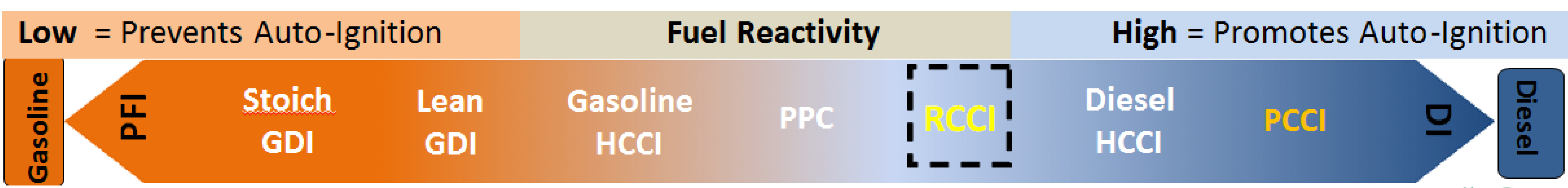


RCCI Concept

RCCI Piston designed for premixed LTC

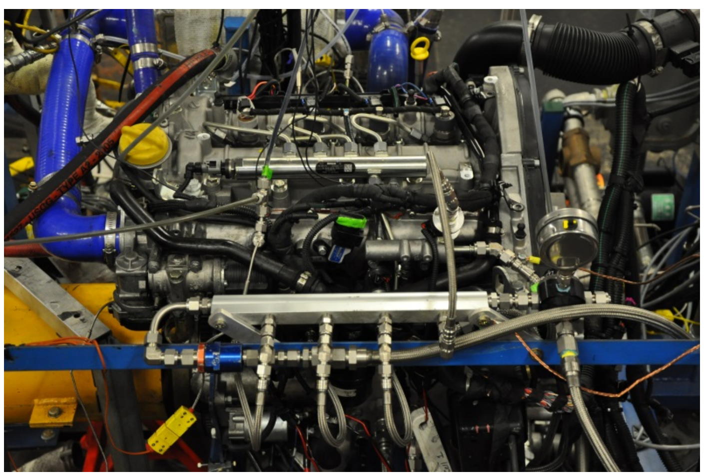


ORNL Multi-cylinder LTC Engine



Technical Accomplishments - Summary

	Tasks
1	Update and refine multimode CDC/RCCI engine maps in collaboration with ACE
2	Conduct fuel economy simulations of RCCI-enabled HEVs in city and highway cycles
3	Evaluate the impact of after-treatment trains on CO/HC/NOx/PM emissions control in RCCI-enabled HEVs/PHEVs beginning at cold start (On track)
4	Compare and evaluate fuel economy and emissions control among RCCI and other HECC engines in HEVs/PHEVs
5	Assess potential benefits of using passive sorbent traps to reduce NOx and HC emissions in RCCI-enabled LD hybrids (On track)



Detailed tracking of critical RCCI steady states

- **Fuel consumption**
- **Engine-out NOx, PM, HC, CO, CO_2, O_2**
- **Exhaust temperature , exhaust flow, equivalence ratio, EGR**

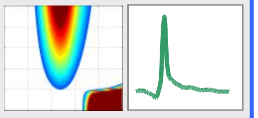
Model of vehicle power by RCCI-enabled engine

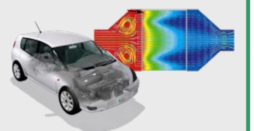
- **Sensitivity analysis for NO and PM control**
- **HC Adsorber impact**
- **Comparative conventional vehicle, HEV and PHEV simulations**

FY 14 Supporting Accomplishments

This project supports other VTO programs leveraging activities in meeting VTO goals

- **Support FLT –**
  - **Drive Cycle Expansion Enabled by Biofuels – Completed**
  - Simulations used to determine drive cycle coverage
- **Support ACE–**
  - **High Efficiency RCCI Mapping - Underway**
  - Leading to multi-mode engine map
  - **RCCI Vehicle Systems Modeling** - Underway
  - Demonstrate improved modeled fuel economy of **25%** for passenger vehicles solely from improvements in powertrain efficiency relative to a 2009 PFI gasoline baseline


Advanced (HECC) Combustion


Component and System Modeling

Accomplishment (1): Update and refine RCCI multi-mode engine maps

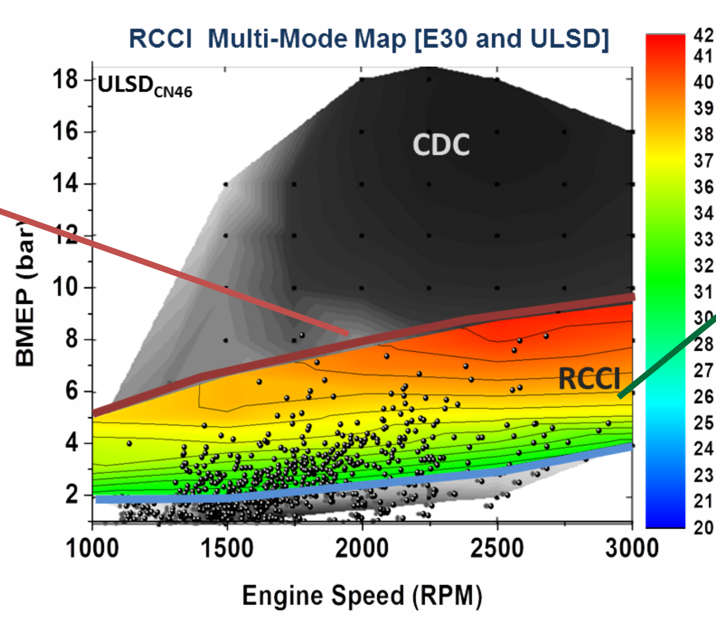
- **Update and refine RCCI engine maps for ORNL advanced combustion engines**
- **Construct transient combustion model for dual-mode combustion engine**
  - Appropriate parameters need to account for combustion mode switches between CDC and RCCI as well as between low and high RCCI loads
  - Accurate dynamic component model accounting for transient effect and hysteresis in engine emissions and exhaust temperature

High load opportunities

Multi-mode strategy for high load transition

Constraint on MPRR and combustion noise

High load increased compared to previous maps resulting in possible fuel efficiency gains



Low load opportunities

Multi-mode strategy for low-load transition
Emissions concerns
•Not able to achieve lower NOx than CDC without sacrificing BTE
•Sub 200°C exhaust temps with high HC and CO represents clear challenges with current oxidation catalysts

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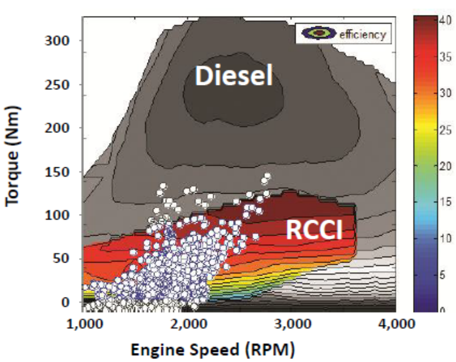
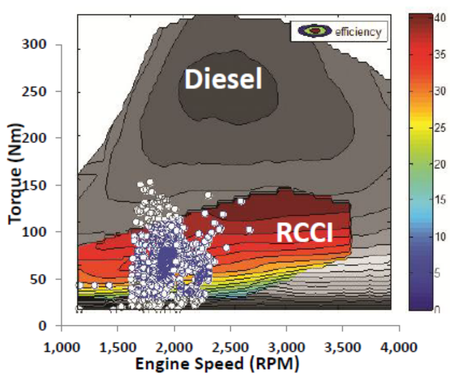
Accomplishment (2.1): Expanded range Enabled by Biofuel Blends Enabling Improved Fuel Economy Relative to Gasoline or Diesel Baselines

- **RCCI mapped with focus on efficiency and lowest possible emissions**
- **Current RCCI map requires mode-switching to cover light-duty drive cycles**
  - 100% coverage of low temperature combustion is necessary to avoid mode-switching (RCCI to Diesel) and additional emissions controls which would have negative impacts on fuel economy and costs

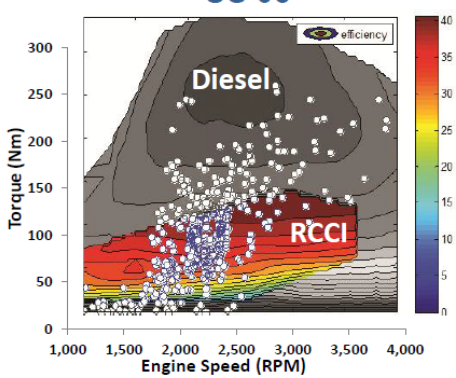
UDDS



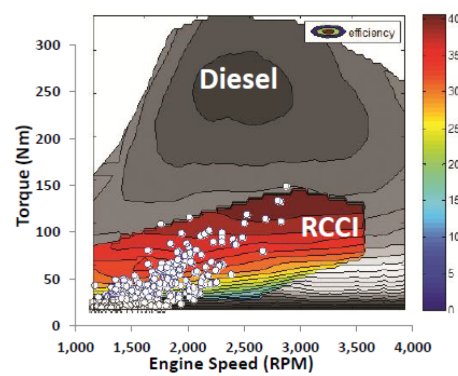
HWFET

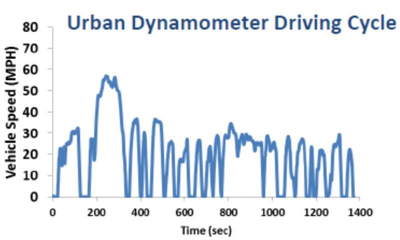


US 06

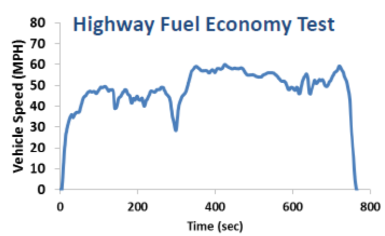


NYCC

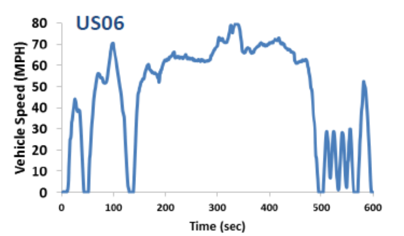




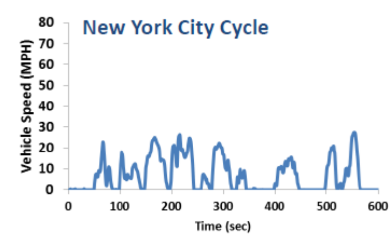
Commonly called the "LA4" or "the city test" and represents city driving conditions



Represents highway driving conditions under 60 mph



High acceleration aggressive driving schedule – also called the "Supplemental FTP"

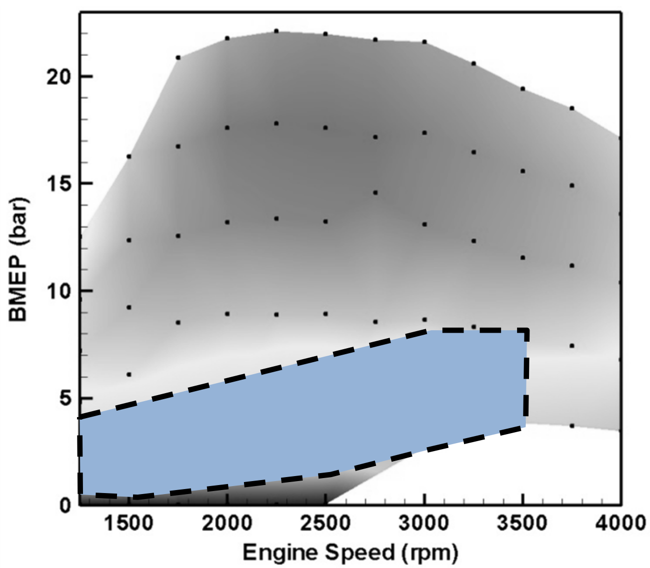


Features low speed stop-and-go traffic conditions

Accomplishment (2.2): RCCI drive cycle coverage over city and highway cycles

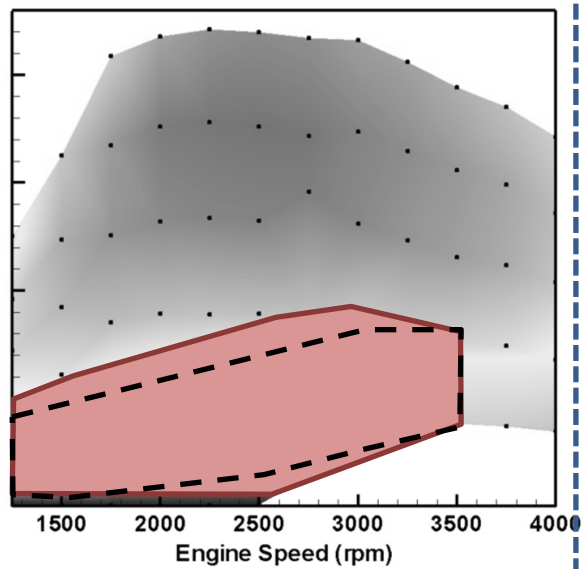
- **Conventional diesel combustion modes used for speed/load demands outside of RCCI range**
- **Multi-mode engine maps and controls integrated into model**
- **Vehicle systems simulations used to model drive cycle coverage and fuel economy**

Diesel / Gasoline



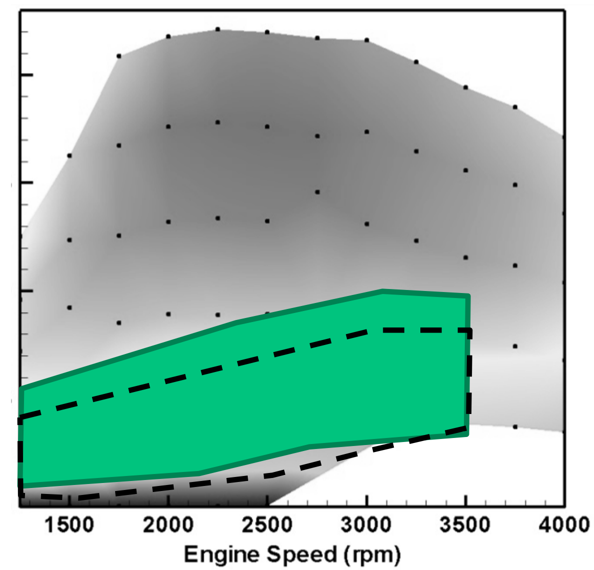
RCCI operational space with conventional fuels

20% Biodiesel Blend / Gasoline



Expanded low and high load due to higher PFI to DI ratio

Diesel / 30% Ethanol Blend

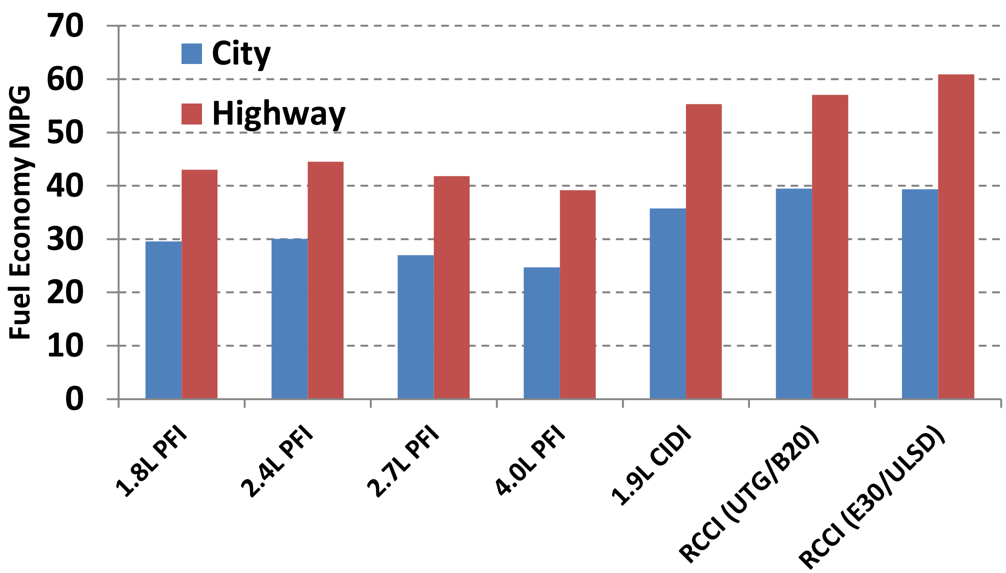


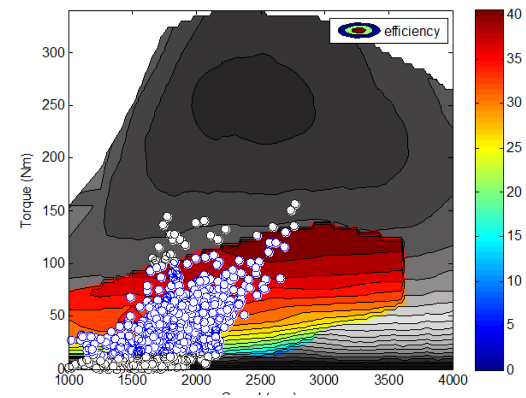
Expanded high load due to higher octane and charge cooling, reduced low load due to stability issues

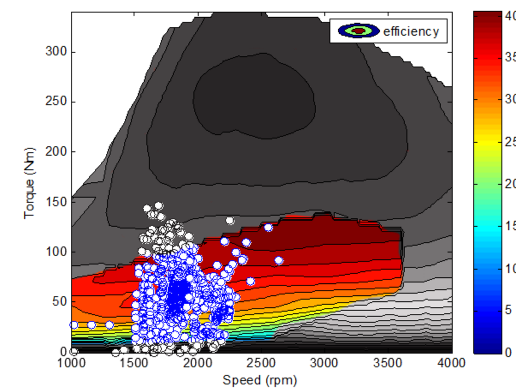
Accomplishment (3): Vehicle systems simulations enable drive cycle coverage comparisons of renewable fuels

- **Modeling results show greater than 75% drive cycle coverage with RCCI over UDDS (city) and HWFET (highway) with B20 and gasoline**
  - **Hot start with conventional powertrain**
  - **Increased coverage compared to other RCCI fuel combinations**

RCCI	Fuel Economy	RCCI distance	cycle distance	Cycle Coverage
UNIT	MPG	MILE	MILE	%
UDDS	39.50	5.87	7.45	79
HWFET	53.55	9.49	10.25	93







- **41% improvement in combined city/hwy MPG compared to PFI baseline**
- **6% improvement in combined compared to CDC**

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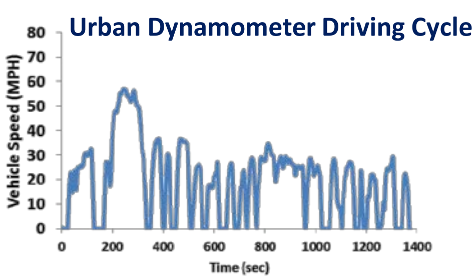
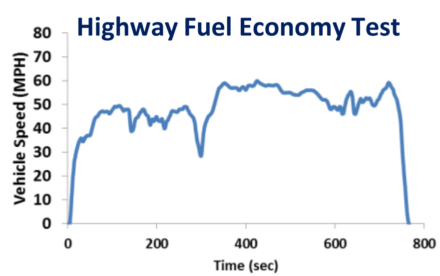
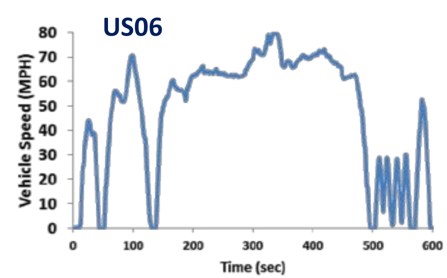
Accomplishment (4.1) Fuel economy simulations of RCCI-enabled HEVs modeled

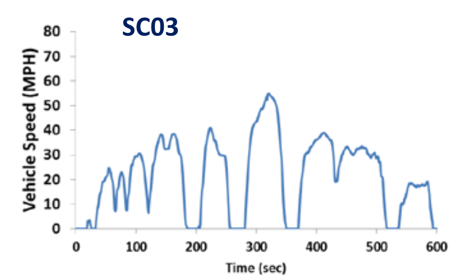
- **Simulated hybrid powertrain configuration**
  - Power-split hybrid electrical vehicle similar to 2010 Ford Fusion Configuration
  - Plug-in hybrid electrical vehicle similar to 2010 Ford Fusion Configuration
  - Parallel and series hybrid electrical vehicles
  - ANL Downloadable Dynamometer Database (D3)
- **Simulated driving cycles: EPA 5-cycle method**
  - UDDS: Urban Dynamometer Driving Schedule, also called LA-4 or FTP72
  - HWFET: Highway Fuel Economy Test
  - US06 Supplemental Federal Test Procedure
  - SC03 Supplemental Federal Test Procedure

	Time (s)	Distance (mile)	Max Speed (mph)	Avg Speed (mph)
UDDS	1370	7.50	56.7	19.6
HWFET	765	10.26	59.9	48.3
US06	600	8.01	80.3	48.4
SC03	596	3.60	54.8	21.6



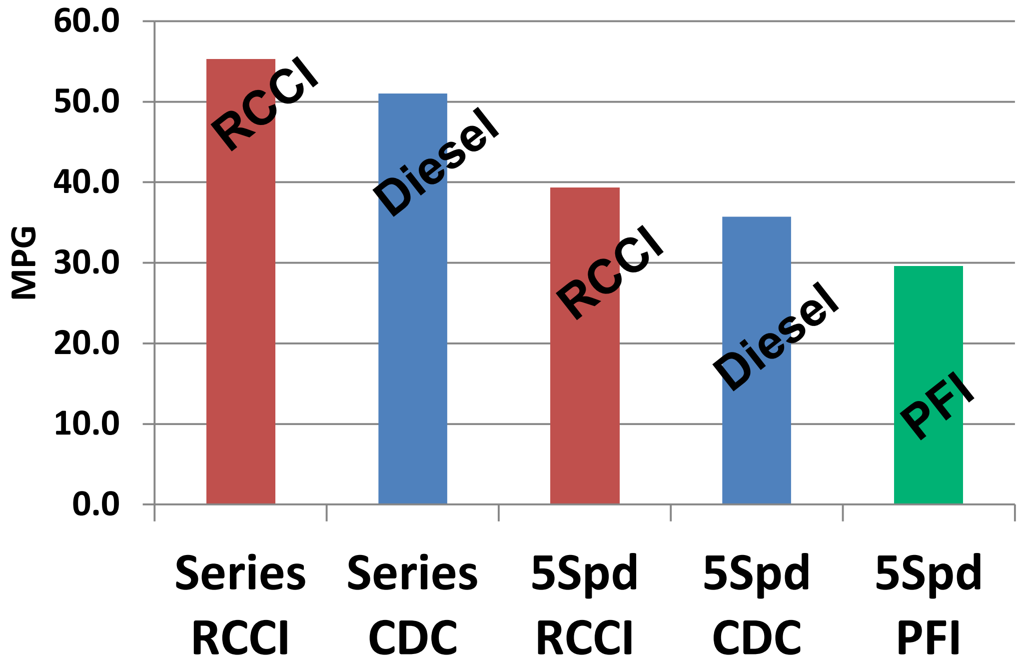


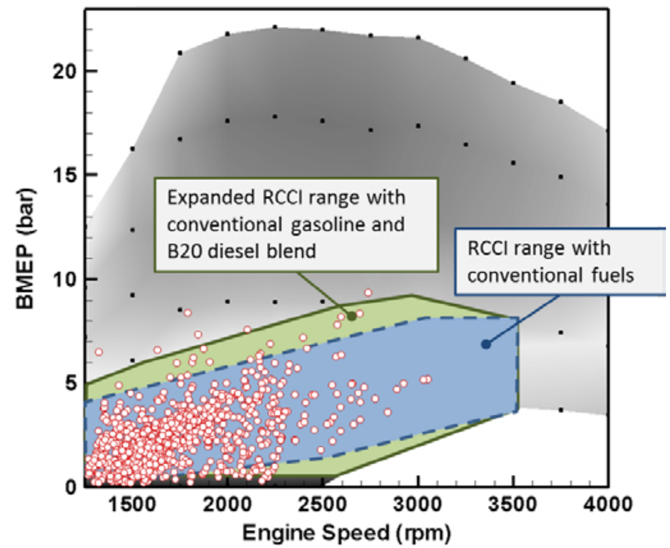




Accomplishment (4.2): Initial modeling shows significant improvement with RCCI-enabled HEV configuration over even diesel HEV

- **UDDS Operation demonstrate 55.3 MPG with RCCI series hybrid in charge sustaining mode compared to 29.6 mpg for PFI baseline**
  - **Similar increase seen with RCCI in both conventional and HEV powertrains**
  - **Further optimization for targeting high efficiency RCCI operation underway**



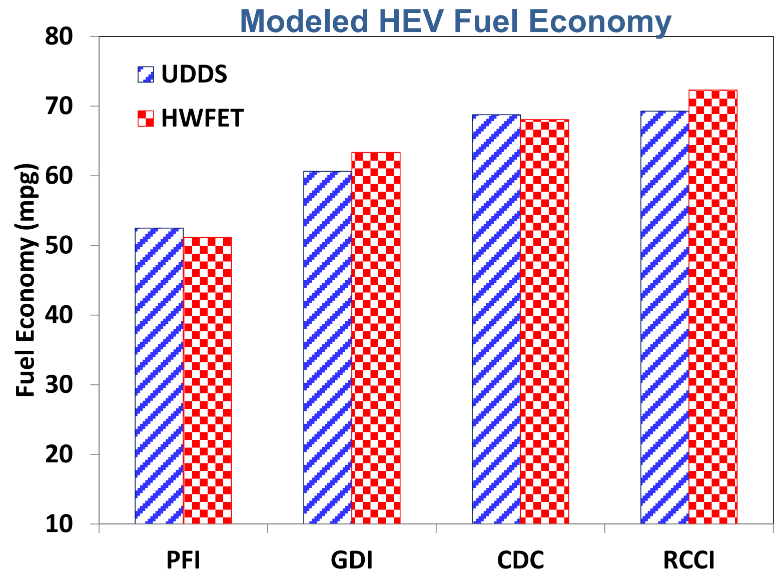


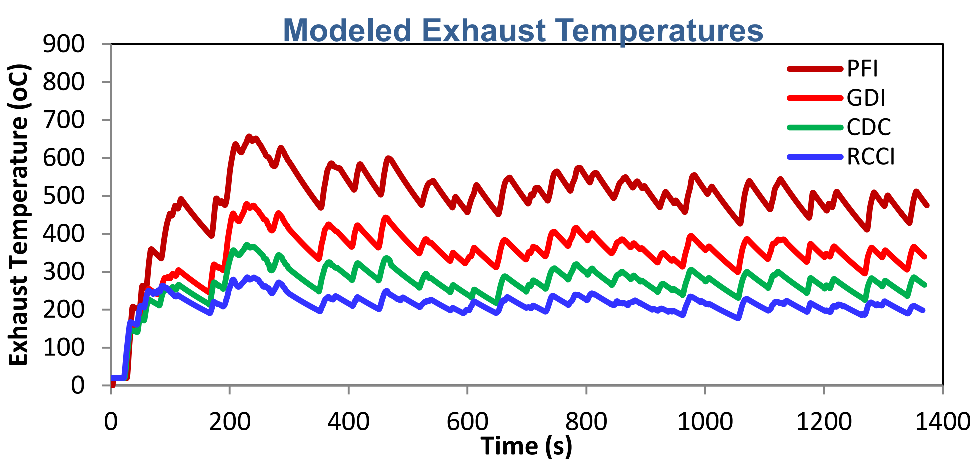
CDC = Conventional Diesel Combustion

Results presented at SAE 2014 Hybrid and Electric Vehicle Technologies Symposium
Curran, et al.,., "Opportunities and Challenges for Integrating Future Engine Concepts into Hybrid Electric Vehicle Powertrains, "

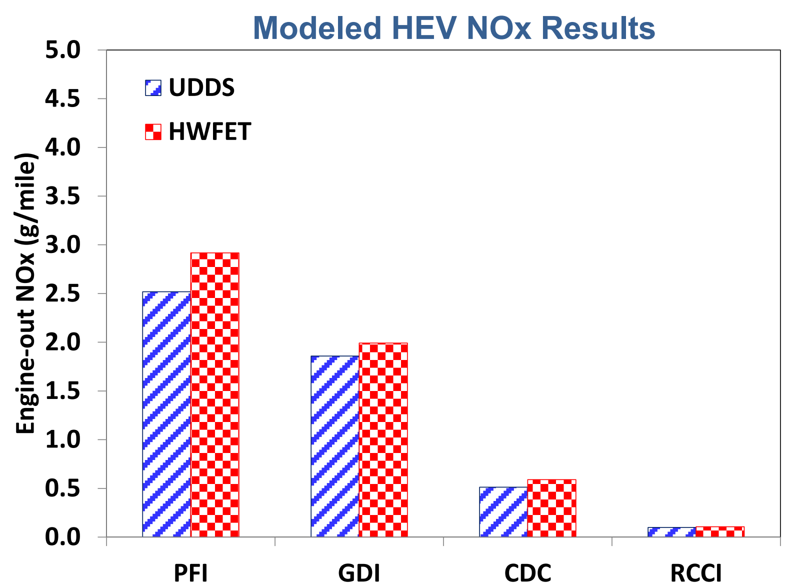
Accomplishment (5): Initial simulation comparison among PFI, GDI, CDC and RCCI in a power-split mid-sized hybrid sedan including cold start cycles

- **Example case study**
  - 1800kg power-split mid-sized charge-sustaining HEV sedan
    - PFI HEV architecture calibration using ANL D3 database
    - Baseline: 5-speed auto transmission (not shown here)
  - Engines: 2.0L PFI (SAAB engine), 2.0L GDI (BMW engine), 1.9L CDC &RCCI (GM engine)
  - UDDS and HWFET with 20°C cold start
    - Correcting factors for steady state and first order lag
    - CDC mode assumed for RCCI cold start
- **Observations**
  - RCCI achieves higher fuel economy than CDC, and GDI
  - Significantly lower NOx with RCCI with higher CO and HC





RCCI exhaust temperature is much lower than other combustion modes



Responses to Previous Year Reviewer Comments

- **Project was not reviewed previously**

COLLABORATION AND COORDINATION

- **VTO ACE**
  - Support task integrates ACE combustion developed maps into multi-mode model
- **VTO FLT**
  - Support task evaluates effect of drive cycle coverage as relates to fuel effects
- **US Drive VSA and ACEC Tech teams**
  - Feedback and presentations to both US Drive tech teams
- **CLEERS Collaboration**
  - **Multiple engine OEMs, suppliers, universities, national labs (ACE022).**
  - **DOE Advanced Engine Crosscut Team.**
  - **USDRIVE Advanced Combustion and Emissions Control Tech Team.**

Discussion of engine research with industry visitors at ORNL.

- **Related ORNL Activities**
  - **Advanced LD Engine Systems and Emissions Control Modeling and Analysis (VSS041)**
  - **High Efficiency Engine Systems Development and Evaluation (ACE016).**
  - **Non-Petroleum-Based Fuels: Effects on Emissions Control Technologies (FT007).**
  - **Gasoline-like Fuel Effects on Advanced Combustion Regimes (FT008).**

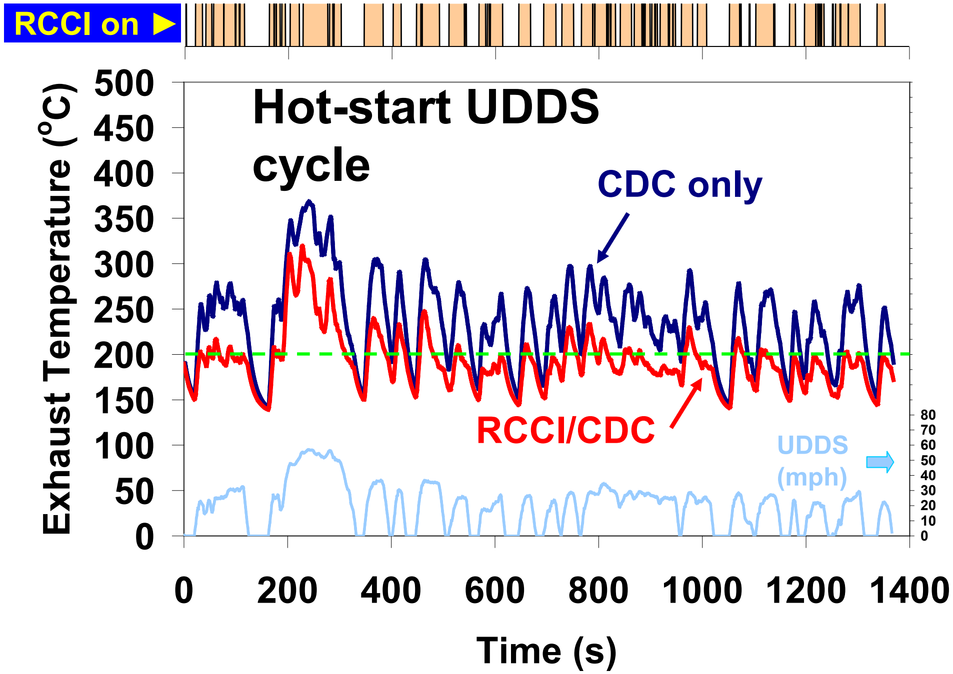
Remaining Challenges and Barriers

Challenges

- **Need for transient LTC validation for approach**
- **Need to validate exhaust emissions against actual transient LTC operation**
  - Current collaboration with the university of Wisconsin RCCI Hybrid team for test validation
- **Applicability of current aftertreatment models to LTC exhaust including PM**
  - Being addressed at ORNL with ACE research on multi-cylinder engines

Barriers

- **Lack of production LTC modes being addressed by this project on a vehicle systems basis first**



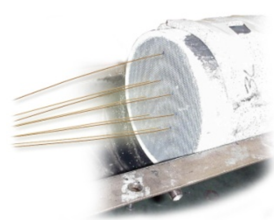
PROPOSED FUTURE WORK

- **FY2014**
  - Generate and integrate new RCCI map into multi-mode (ACE Q3) (backup slide)
  - Vehicle systems simulations of Q3 map for fuel economy (ACE Q4)(backup slide)
  - Complete aftertreatment task (backup slide)
  - Complete passive HC adsorber task (backup slide)
- **FY2015**
  - Expand the current project including collaboration with ANL
    - High Fidelity Engine Models (ANL with IAV)
    - Emissions Aftertreatment and Controls (ORNL)
    - Vehicle Level Simulations (ANL/ORNL)
  - Integration of transient engine data for refinement of multi-mode engine model
  - Utilize experimental data for refinement of aftertreatment component models including low-temperature catalyst in support of ACEC goals

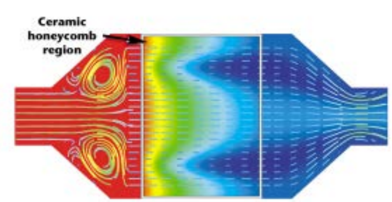
Vehicles

Components

Data



Modeling



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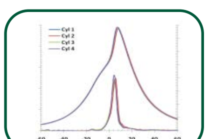
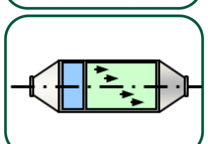
SUMMARY: VSST collaboration with the VTO ACE and FLT programs enhances the U.S. DOE mission of improving vehicle energy efficiency within emissions constraints

- **Significant progress has been made toward simulating fuel consumption and emissions for advanced combustion**
- **Focused on investigating fuel economy potential of LTC using comprehensive engine systems approach**
  - Multi-cylinder advanced combustion experiments
  - Aftertreatment integration
  - Vehicle systems level modeling
- **Collected and integrated 1.9L GM dual-mode CDC/RCCI engine map into transient engine model enabled to switch CDC and RCCI**
- **Simulated LD hybrid vehicle powered by an RCCI-enabled engine over realistic driving cycles**
- **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**



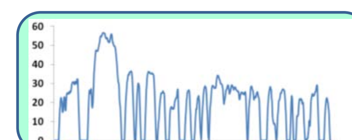
Engine Efficiency



Emissions Aftertreatment

Vehicle System

Fuel Economy



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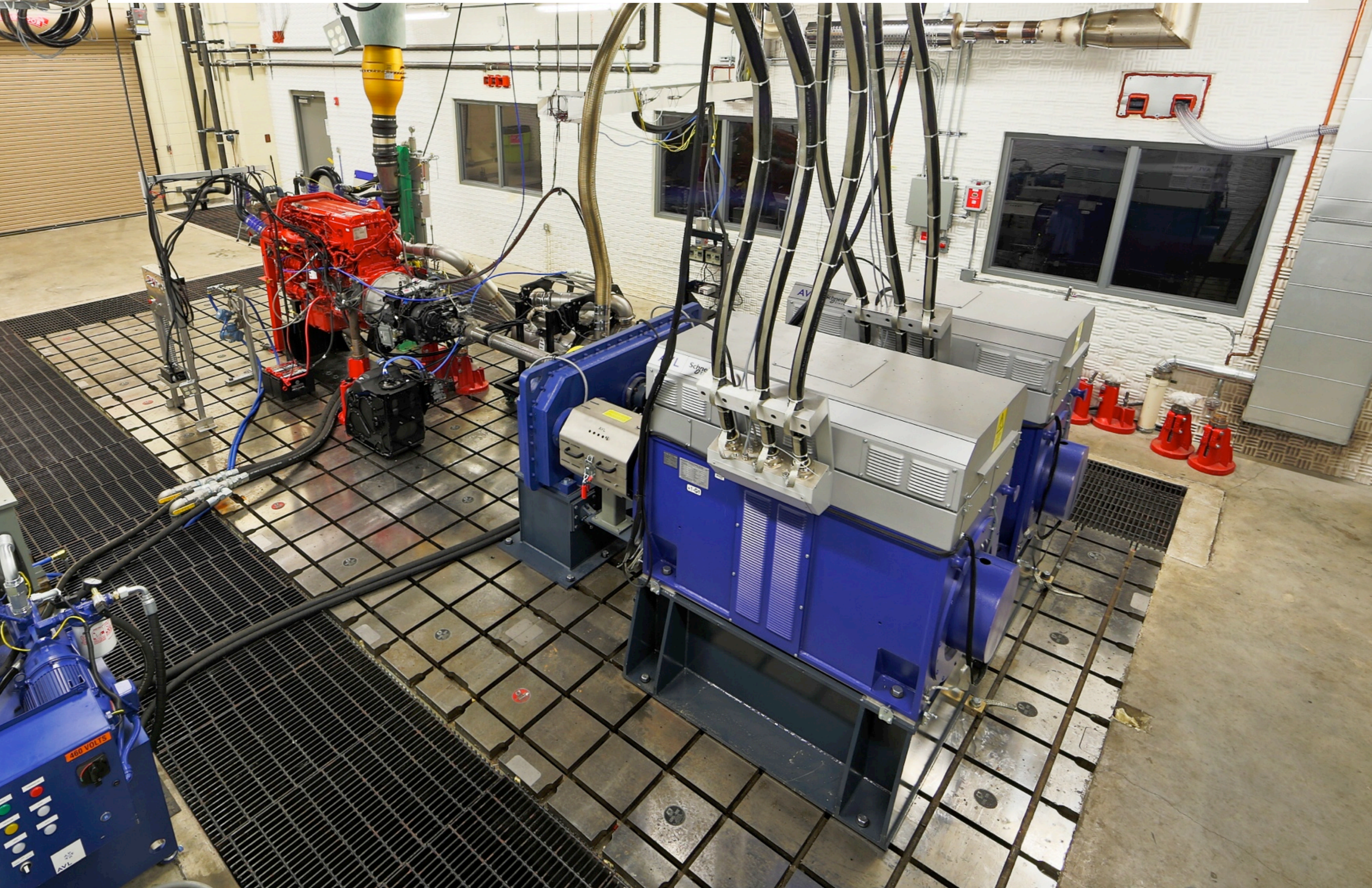
Backup Slides

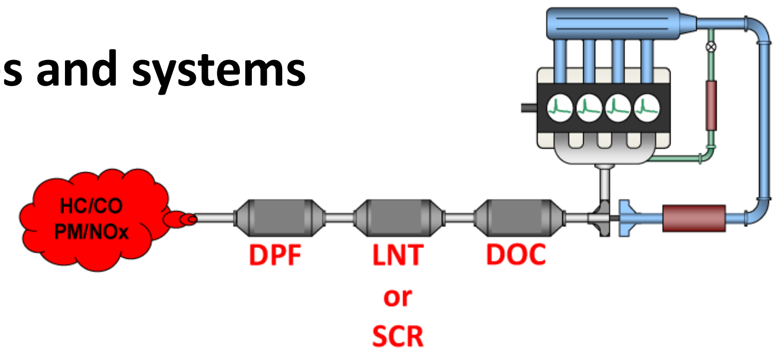


List of References for the VSST models

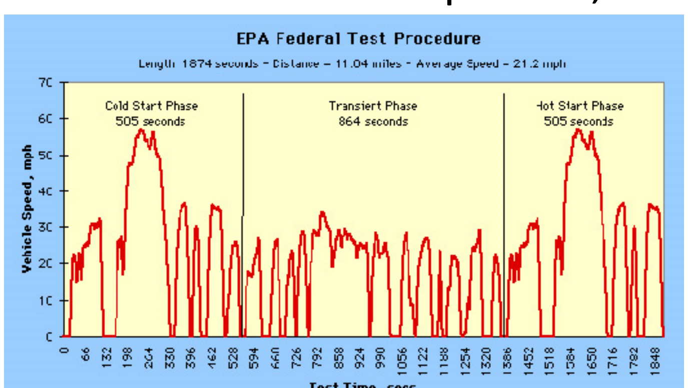
- **Transient Engine Simulation Methodology**
  - **Z. Gao et.al., A Proposed Methodology for Estimating Transient Engine-out Temperature and Emissions from Steady-State Maps, Int. J. Engine Res., 11(2), 2010.**
- **DOC/DPF/SCR Component models**
  - **Z. Gao et.al., Simulation of Catalytic Oxidation and Selective catalytic NOx Reduction in Lean-Exhaust Hybrid Vehicles, SAE paper 2012-01-1304 (DOC and SCR modeling).**
  - **Z. Gao et.al., Simulating the Impact of Premixed Charge Compression Ignition on Light-Duty Diesel Fuel Economy and Emissions of Particulates and NOx, Proc. IMechE - Part D: J. Automobile Engineering, 227(1), 2013 (DPF modeling).**
  - **C.S. Daw et.al., Simulated Fuel Economy and Emissions Performance during City and Interstate Driving For a Heavy-Duty Hybrid Truck, SAE paper 2013-01-1033 (DOC/DPF/SCR and new SCR parameters).**
- **HD Hybrid Truck Simulation**
  - **C.S. Daw et.al., Simulated Fuel Economy and Emissions Performance during City and Interstate Driving For a Heavy-Duty Hybrid Truck, SAE paper 2013-01-1033.**
- **Advanced Diesel Combustion Simulation**
  - **Z. Gao et.al., Using a phenomenological Computer Model to Investigate Advanced Combustion Trajectories in a CIDI Engine, Fuel, 90, 1907–1918, 2011.**

Task (3) Impact of aftertreatment systems on emissions control in RCCI-enabled HEVs/PHEVs (In progress)

- **Simulated ORNL aftertreatment devices and systems**
  - CO and HC oxidation: DOC
  - NOx reduction: LNT or SCR
  - PM trapping and oxidation: DPF
  - Aftertreatment systems: DOC/LNT/DPF or DOC/SCR/DPF



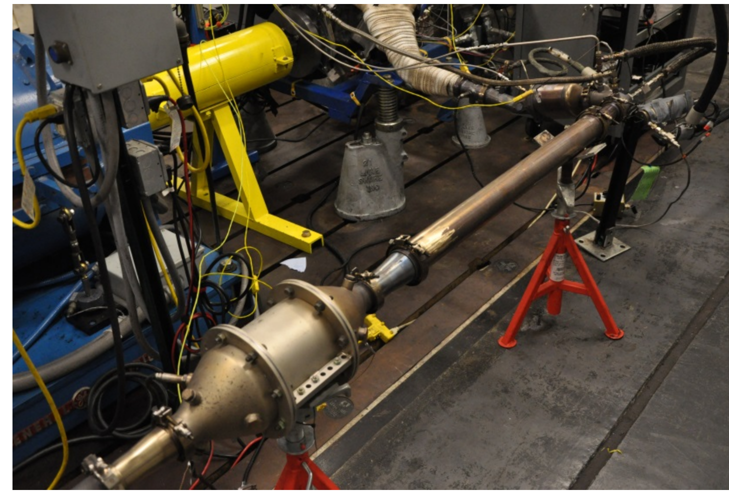
- **Simulated driving cycle for emissions control: FTP75**
  - Cold start transient phase (ambient temperature 20-30°C), 0-505s
  - Stabilized phase, 506-1372s
  - Hot start transient phase*, final 505s **(**Hot soak (min 540 s, max 660 s)**)**



43% of cold start phase + 100% of 'stabilized' phase + 57% of hot start phase = EPA emission

Task (5) Assess benefits of using passive sorbent traps to reduce NOx and HC emissions in RCCI-enabled LD hybrids (in progress)

- **Cold start and repeated engine off delay catalyst heat-up, leading to significant CO, HCs, and NOx emissions**
  - Significant cold start impact in HEVs and PHEVs
  - HEVs and PHEVs engine intermittent operation
- **Significant HCs released from RCCI**
  - Lower-load exhaust temps < 260°C
- **Sorbent trapping is an innovative technology**
- **Our approach and plan for this simulation**
  - Update our previously published passive sorbent trap models
  - Implement and demonstrate adsorber model in Autonomie
  - Simulate the potential benefits of using a passive adsorber device to reduce the NOx and HC tailpipe emissions during initial cold-start and repeated engine restarts



ORNL ACE Aftertreatment Research Setup