VSS141

Powertrain Controls Optimization for Heavy Duty Line Haul Trucks

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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: Sept. 2016

Barriers*

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

**from 2011-2015 VTP MYPP*

Budget (DOE share)

- FY14 funding:
  - DOE VSST - $350k
  - DOE ACE - $100K
- FY15 (current expected) funding: $500k

Partners

- Cummins, Inc.
- Meritor, Inc.
- Argonne National Laboratory
- National Renewable Energy Laboratory
- Oak Ridge National Laboratory

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 greenhouse gases.**
- **The most fuel efficient MD and HD combustion engines are advanced diesels, which require aftertreatment for compliant 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, hybrid energy storage, emissions control, and supervisory control systems in Class 8 trucks.**
- **Evaluate the merits of specific alternative technologies and control strategies under realistic MD and HD drive cycle conditions.**
  - Reactivity Controlled Compression Ignition (RCCI) advanced combustion coupled with series hybrid electric operation
  - Emissions controls to minimize criteria pollutants, with emphasis on challenges of low temperature combustion
  - Actively controlled hybrid energy storage systems (battery plus ultracapacitor) for enhanced regenerative braking energy capture
- **Experimentally verify advanced combustion, hybrid energy storage, and aftertreatment systems utilizing actual hardware and virtual vehicle systems.**

RELEVANCE*

- **Supports 2 major 21st Century Truck Partnership Goals:**
  - Promote research for engine, combustion, exhaust aftertreatment, fuels, and advanced materials to achieve both significantly higher efficiency and emissions compliance with cost effectiveness.
  - Promote research focused on advanced heavy-duty hybrid propulsion systems that will reduce energy consumption and pollutant emissions.
- **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 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

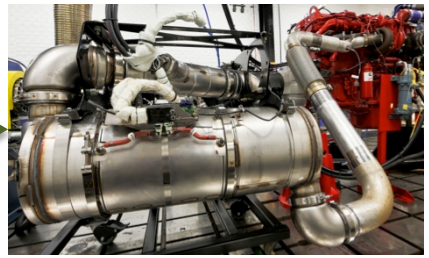
FY2014 MILESTONES

Month /Year	Milestone or Go/No-Go Decision	Description	Status
Dec 2013	Milestone	Completion of baseline hybrid vehicle model supervisory control algorithms for Powertrain Controls Optimization for HD Hybrid Line Haul Trucks	**COMPLETE**
Mar 2014	Milestone	Identification and integration of preliminary hybrid energy storage system component data and baseline control strategy for Powertrain Controls Optimization for HD Hybrid Line Haul Trucks	**COMPLETE**
June 2014	Milestone	Characterize preliminary engine model for RCCI operation for Powertrain Controls Optimization for HD Hybrid Line Haul Trucks	**ON SCHEDULE**
Sept 2014	Milestone	Complete first generation energy management strategy involving hybrid energy storage system ,RCCI operation, and emissions control for Powertrain Controls Optimization for HD Hybrid Line Haul Trucks	**ON SCHEDULE**

APPROACH: HD powertrain optimization – 4 technology focus areas

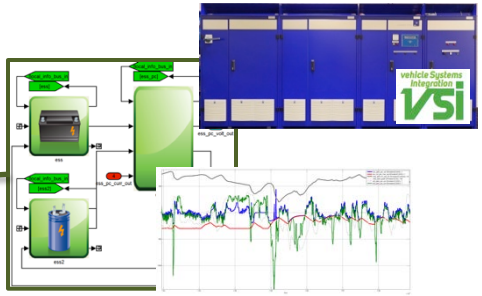
1. Advanced engine control strategies

- Reactivity Controlled Compression Ignition (RCCI) on multi-cylinder engines for improved fuel efficiency and reduced emissions combined with series and parallel HEV operation potential
- Sponsored by DOE VTO ACEC (Singh) through ORNL FEERC



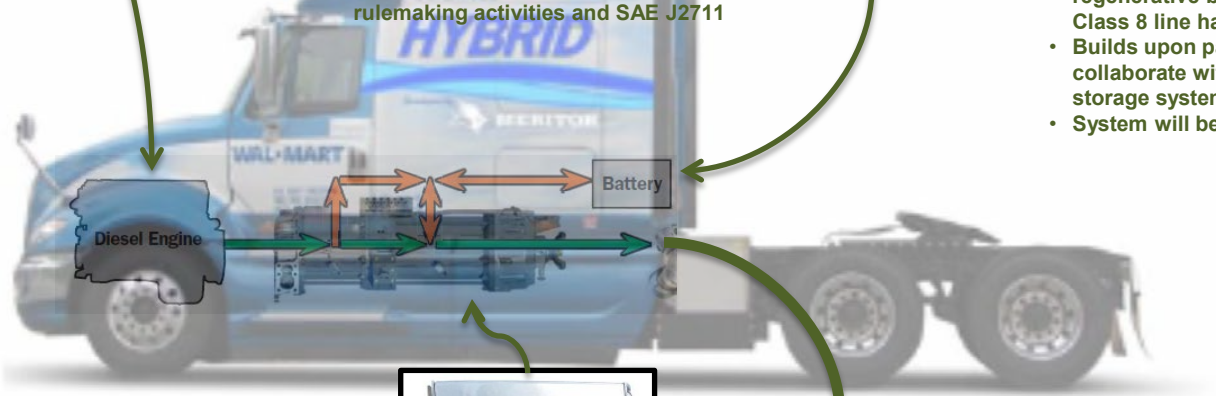
2. Emissions control technologies

- Emissions control essential for success of RCCI due to lower exhaust temperatures coupled with engine start/stop (hybrid) operation
- Ties into test standard development in cooperation with EPA Phase 2 GHG rulemaking activities and SAE J2711

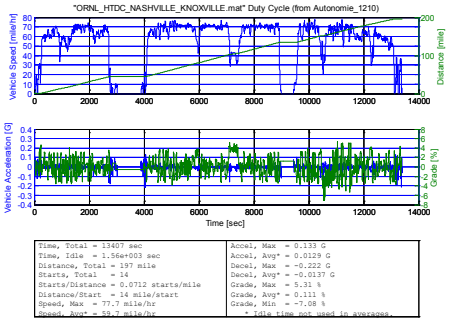


3. Pulse energy storage systems

- Explore the opportunity for increased regenerative braking energy collection for Class 8 line haul hybrid trucks
- Builds upon past research from and collaborate with ANL for hybrid energy storage systems (battery plus ultra-caps)
- System will be emulated in ORNL VSI Lab



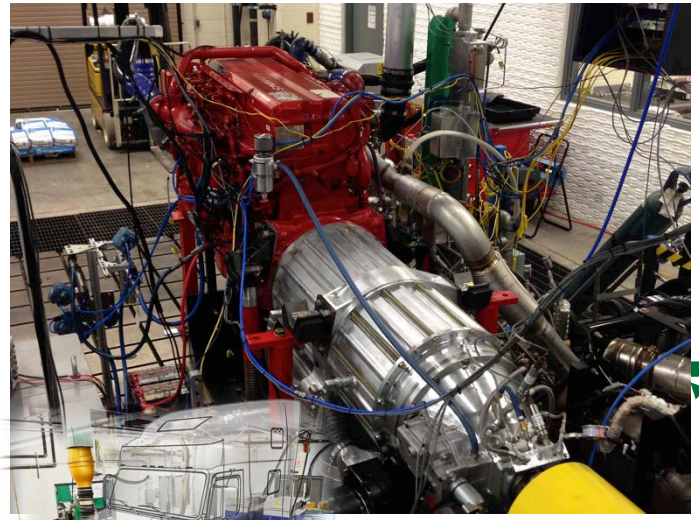
ORNL HTDC / NREL Fleet DNA



4. Advanced energy management/supervisory control

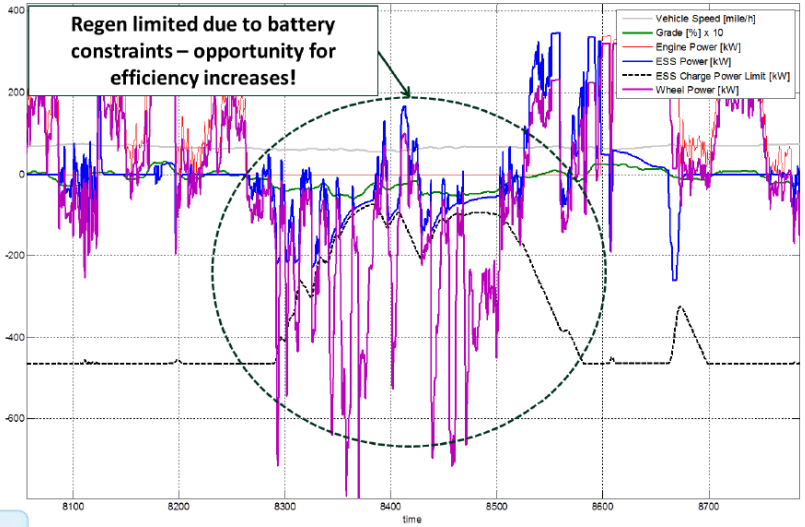
- Energy management strategies must be developed to fully realize compound benefits of technologies listed above
- Opportunity to tie into other existing projects (accessory hybridization CRADA with Cummins)

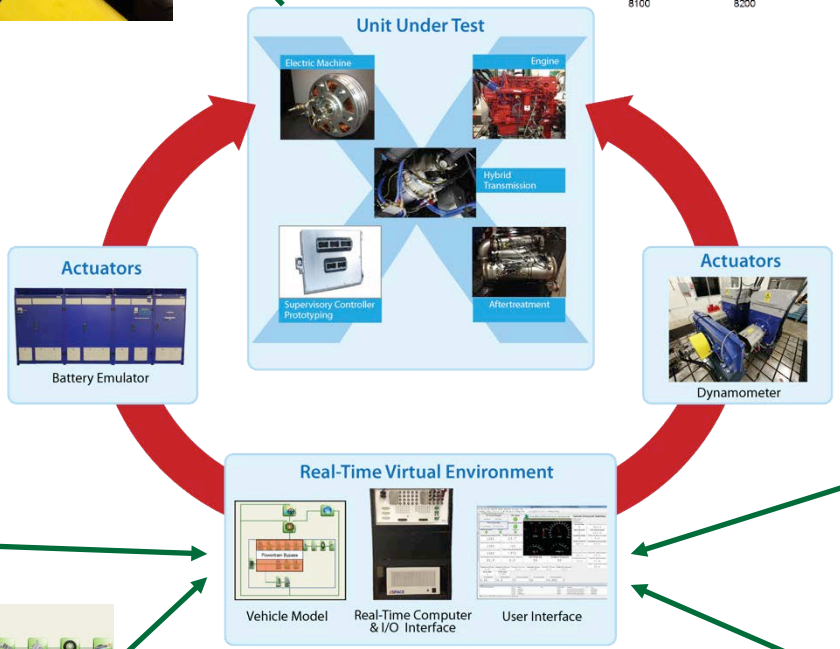
ACCOMPLISHMENT (1): Supervisory controls baseline established



Leveraged powertrain hardware:

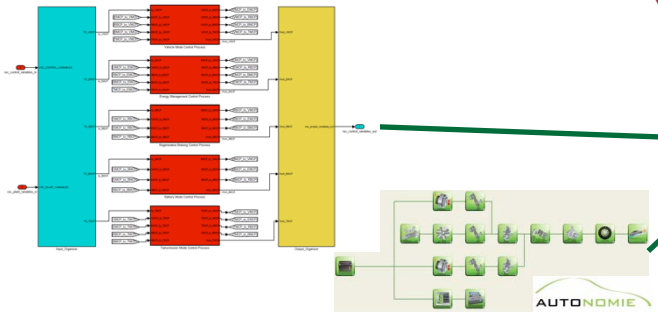
- Verification of vehicle and powertrain models
- Ability to develop precise supervisory control based on actual subsystem interactions
- Benefit of evaluating actual emissions control effects and benefits





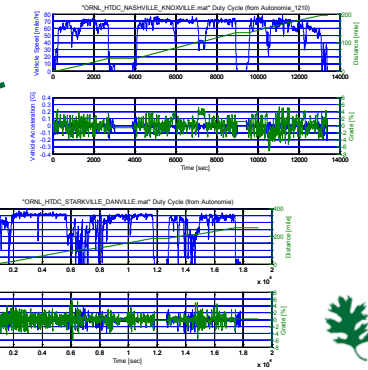
Supervisory control system completed:

- Complete hybrid powertrain model developed in Autonomie
- Baseline supervisory control software developed (single ESS)



"Real world" drive cycle evaluations:

- Data mined from the ORNL Heavy Truck Duty Cycle/NREL Fleet DNA were used to develop custom real world drive cycles
- All drive cycles include grade, a key parameter in evaluating hybrid benefits of line haul trucks



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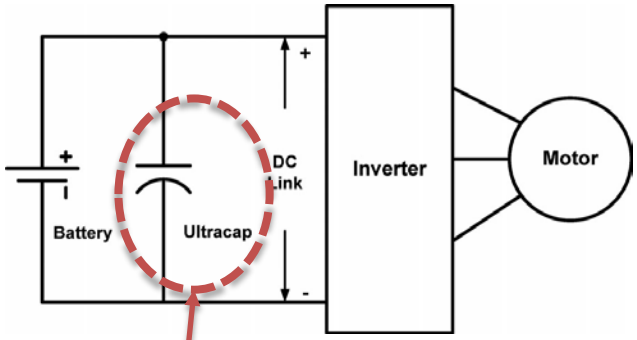
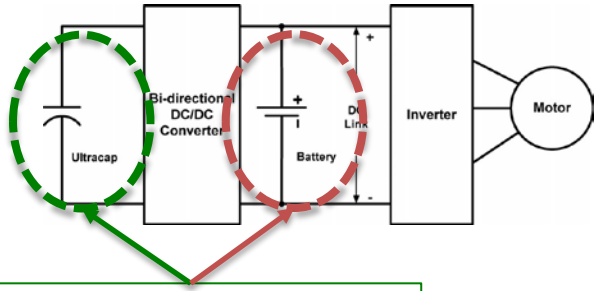
ACCOMPLISHMENT (2): Review of hybrid energy storage approaches

Passive Hybrid Energy Storage System

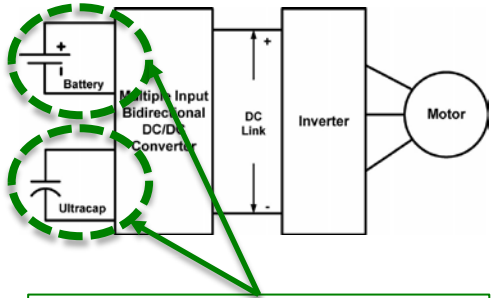


Essentially the UC is a low pass filter, and its stored energy is not used

Active Hybrid Energy Storage Systems



DC/DC converter allows wide voltage range for UC, but requires battery to always operate at DC link voltage



Multi-DC/DC converter allows wide voltage range for UC and lower voltage for both, also reducing balancing difficulties of the system. Focus of ANL study for LD PHEVs

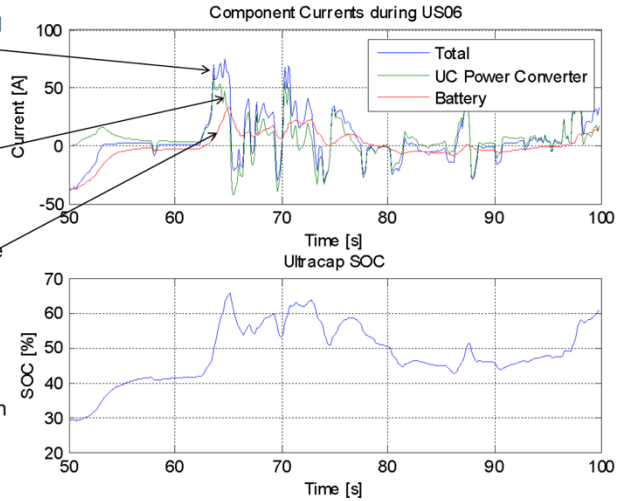
Currents vs Time, Net Change in Battery Current

Blue line is road load (battery current w/o ultracaps)

Green line is U-cap current (dynamic)

Red line is new battery current- more averaged.

SOC is maintained over this 'real world' Prius current trace, on US06 segment

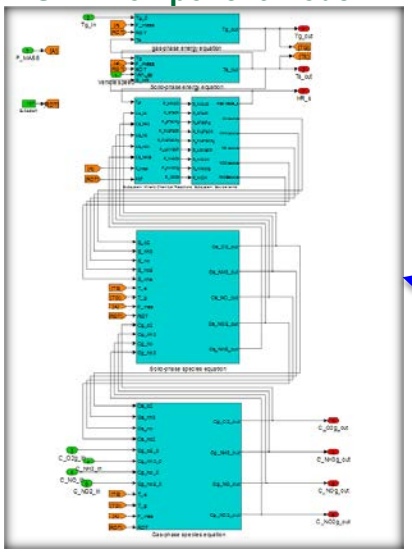


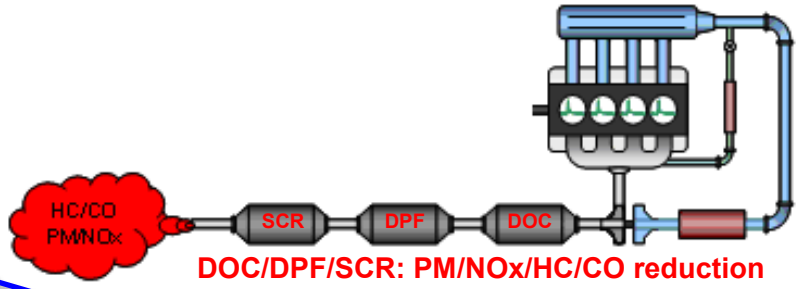
- **ANL Study Objectives***
  - "Create a high power and high energy electrical storage system that has equal or better system efficiency and net cost/density as current conventional batteries.
  - Demonstrate, via long term testing of sub-pack assemblies, that reducing the stress on lithium polymer batteries via actively coupled ultracapacitors can achieve the benefits indicated by simulation results.
  - Develop new SOC control strategies for ultracapacitor bank power blending.
  - Identify component costs for net energy storage system hardware and opportunities to explore technologies that will reduce that cost (such as higher frequency DC-DC converters)
  - Demonstrate that limiting peak power delivered by the li-ion battery, especially in cold weather operation where the li-ion battery may be damaged at high loads, will remove the need to oversize the energy storage system, thus saving battery costs."
- **Research will be leveraged to serve as basis for higher power system focused on increasing regenerative braking for HD line haul trucks**

**Courtesy: Ted Bohn (ANL), "Active Combination of Ultracapacitors and Batteries for PHEV ESS"DOE Annual Merit Review, May, 2009*

ACCOMPLISHMENT (3): System and component models completed

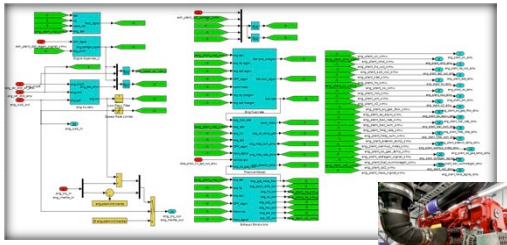
SCR Component Model



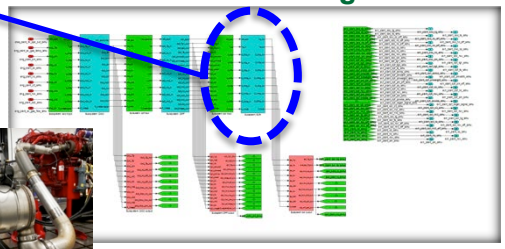


DOC/DPF/SCR: PM/NOx/HC/CO reduction

Transient Engine Model



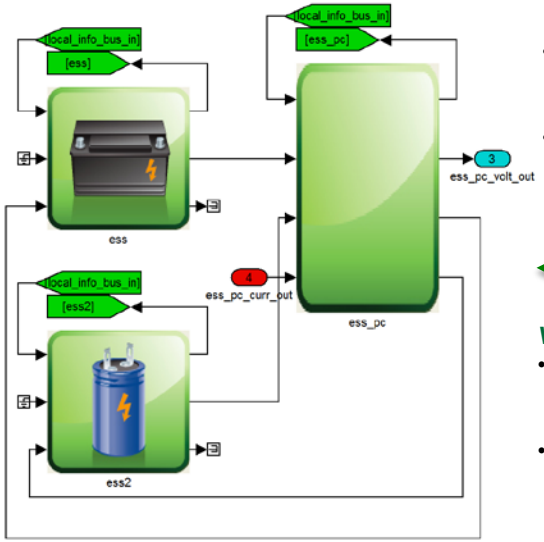
Aftertreatment Package Model



Transient engine and aftertreatment models:

- ORNL has implemented past transient engine modeling experience to develop transient version of Cummins ISX model
- A full aftertreatment suite of models has been "built" and is currently being validated against experimental data

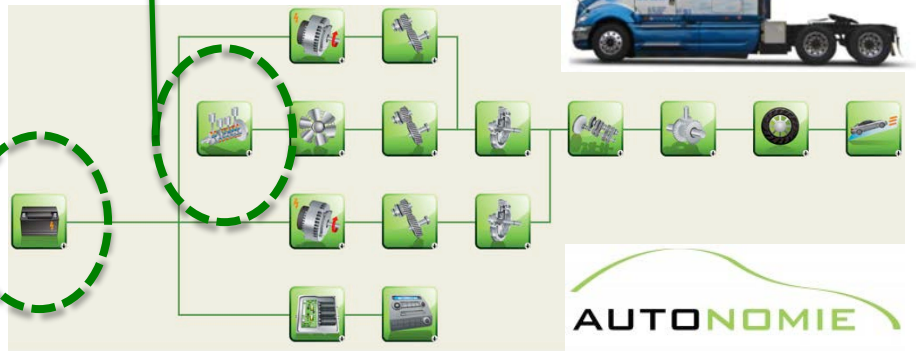
Hybrid Energy Storage Model



Hybrid energy storage model:

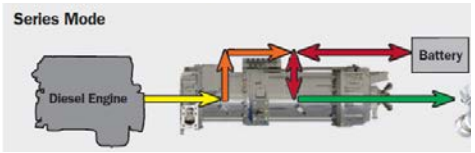
- Based upon past work by ANL in light duty systems
- Baseline active control strategy development and component sizing in process
- Li-ion battery model is based upon proprietary data from Meritor on actual vehicle energy storage system

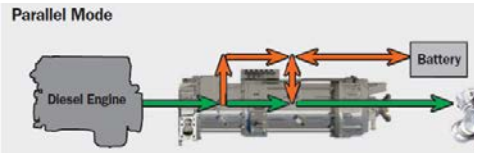
Vehicle Powertrain Model



Vehicle powertrain Model:

- Powertrain model has been leveraged from previous project
- Component models are being validated against ORNL VSI Lab data





Responses to Previous Year Reviewer Comments

- **This project is a new start for FY2014, and was not reviewed last year.**

COLLABORATION AND COORDINATION

- **DOE Advanced Combustion and Engines (ACE)**
  - Collaboration between VSST and ACE to develop and integrate RCCI combustion into the test engine (Cummins ISX 15L).
- **Cummins, Inc.**
  - Instrumented cylinder head for ISX 15L engine (pressure transducer ports)
  - Engine Control Unit (ECU) software access for modifying fuel injection timing, etc.
- **Meritor, Inc.**
  - Exclusive use of prototype Dual-Mode Hybrid Powertrain (DMHP)
  - Data and models for development of optimal DMHP supervisory control, integrating advanced RCCI combustion, hybrid energy storage systems, and emissions control.
- **Argonne National Laboratory**
  - Building upon previous work at ANL for light duty, plug-in hybrid electric vehicles
  - Consulting for baseline approaches for actively controlling integration of batteries and ultra-capacitors
- **National Renewable Energy Laboratory**
  - Collaboration with and use of duty cycle information from Fleet DNA database
- **Related ORNL Activities**
  - ORNL Heavy Truck Duty Cycle "real world" database (including grade).
  - Advanced HD Engine Systems and Emissions Control Modeling and Analysis (VSS048)
  - High Efficiency Clean Combustion in Multi-Cylinder Light-Duty Engines (ACE016)

PROPOSED FUTURE WORK

- **FY2014**
  - **Development and integration of RCCI engine model into vehicle simulation for estimated drive cycle efficiencies**
  - **Baseline powertrain testing of system in ORNL VSI Laboratory to establish reference point**
  - **Completion of baseline active control strategies for hybrid energy storage system**
  - **Integration of baseline emissions control strategies into overall supervisory controls**
- **FY2015**
  - **Conversion of current Cummins ISX 15L engine to RCCI operation (installation of instrumented cylinder head and engine control hooks)**
  - **Baseline engine mapping of the RCCI engine**
    - **Population of new RCCI engine model with engine map for use in supervisory controls development**
    - **Emissions data collected will provide insight into proper emissions control strategy variations due to low temperature combustion**
    - **Revise series hybrid engine operating region to better utilize RCCI**
  - **Powertrain testing of improved system incorporating hybrid energy**

SUMMARY:

- **Relevance**
  - Research is focused on advanced **heavy-duty** powertrain systems that will **reduce energy consumption and criteria emissions**.
- **Approach**
  - **Multi-faceted approach** to optimization of a Class 8 line haul powertrain utilizing **advanced combustion**, **hybridization**, and **dual energy storage systems**.
- **Technical accomplishments and progress**
  - **Established reference supervisory controls** based upon experimental powertrain results for ORNL VSI Laboratory
  - **Completed literature review** of various approaches to **hybrid energy storage systems**
  - **Adapted transient engine** and **aftertreatment modeling "package,"** as well as actively controlled **hybrid energy storage system model**
- **Collaborations:**
  - **Industry**: Cummins, Meritor
  - **Government**: DOE Advanced Combustion Engines, Argonne National Laboratory, and National Renewable Energy Laboratory
- **Proposed Future Work**
  - Complete **baseline advanced technology modeling tasks** (RCCI maps, active control for hybrid energy storage, emissions controls strategies)
  - **Powertrain testing**: establish firm **reference** with current technologies, integrate advanced technology components to **evaluate merits of powertrain optimization**

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Technical Back-Up 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).