VSS141

Powertrain Controls Optimization for Heavy Duty Line Haul Trucks

Principal Investigator(s):

David Smith, Presenter

Scott Curran

Zhiming Gao

2015 U.S. DOE Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting

June 8-12, 2015

ORNL is managed by UT-Battelle
for the US Department of Energy

OAK RIDGE
National Laboratory

OVERVIEW

Timeline	**Barriers***
• Project start date: Oct. 2013 • Project end date: Sept. 2016	• Risk aversion • Cost • Constant advances in technology • Computational models, design, and simulation methodologies **from 2011-2015 VTP MYPP*
Budget (DOE share)	**Partners**

• FY15 funding:
    • DOE VSST - $300k
    • DOE ACE - $100K
• FY16 (current expected) funding: $500k
	• 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*

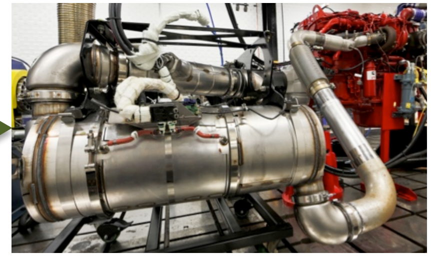
- **Supports 2 major 21st Century Truck Partnership Goals:**
  - Promote research for engine, combustion, exhaust aftertreatment, fuels, and advanced materials to achieve both significantly higher efficiency and emissions compliance with cost effectiveness.
  - Promote research focused on advanced heavy-duty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

APPROACH: HD powertrain optimization – 4 technology focus areas

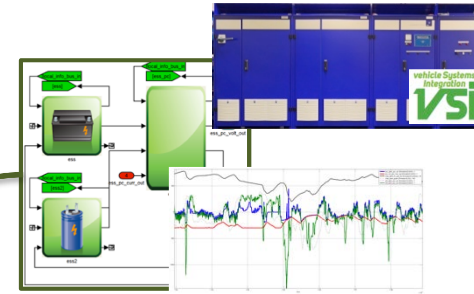
1. Advanced engine control strategies

- 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



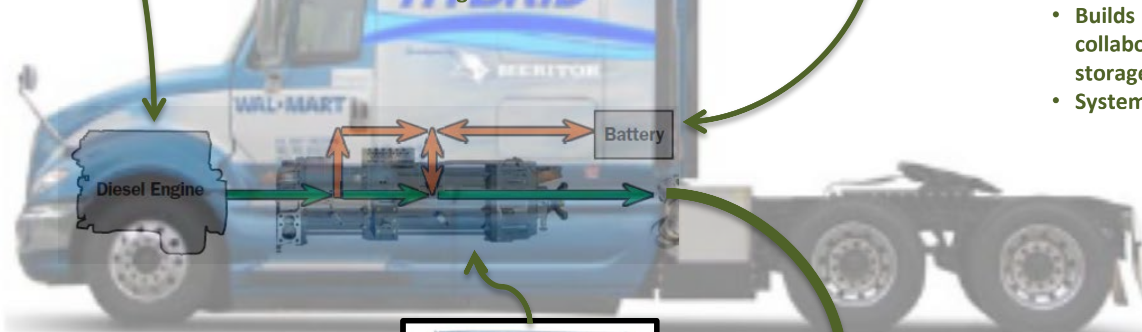
2. Emissions control technologies

- 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

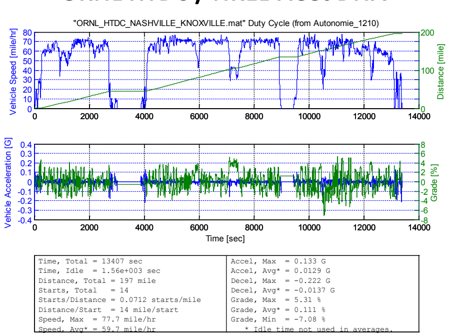


3. Hybrid energy storage systems

- 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

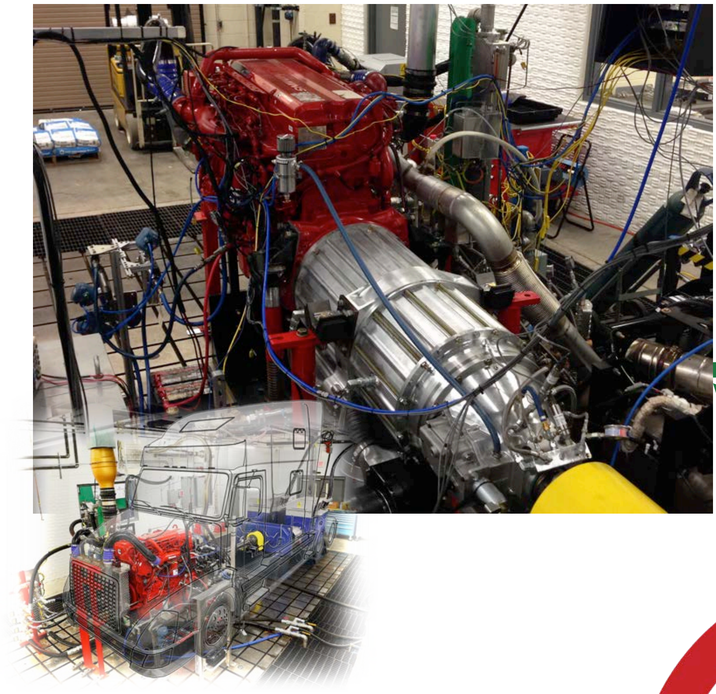


4. Advanced energy management/supervisory control

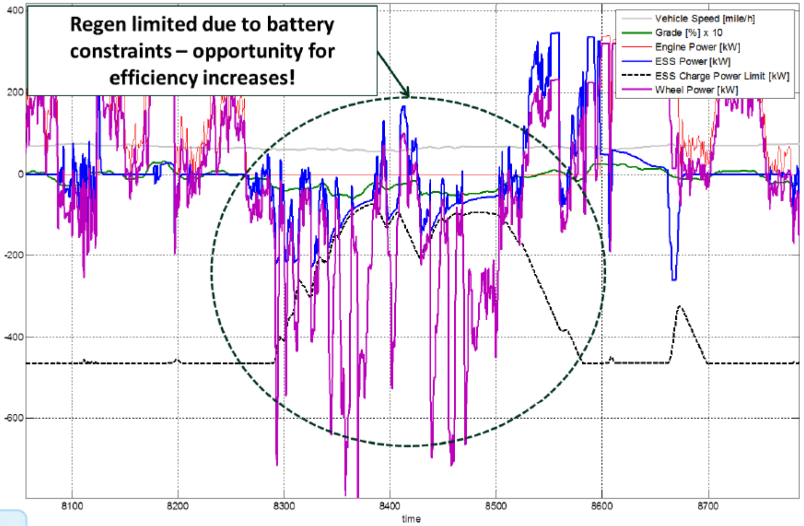
- Energy management strategies must be developed to fully realize compound benefits of technologies listed above
- Optimization of overall supervisory control strategy to minimize fuel consumption while maintaining emissions

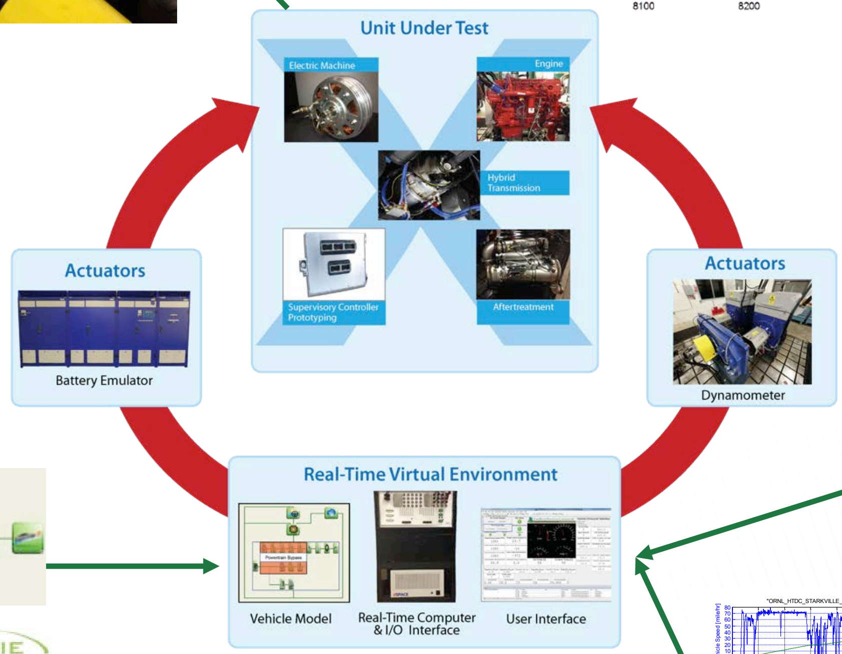
MERITOR Argonne NATIONAL LABORATORY Cummins NREL OAK RIDGE National Laboratory

APPROACH: Model Based Controls to Experimental Verification



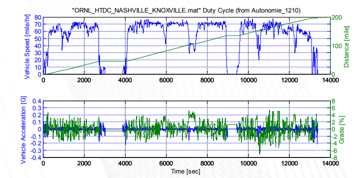
Leveraged powertrain hardware:
- Verification of vehicle and powertrain models
- Ability to develop precise supervisory control based on actual subsystem interactions
- Benefit of evaluating actual emissions control effects and benefits

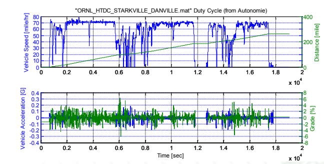




"Real world" drive cycle evaluations:
- Data mined from the ORNL Heavy Truck Duty Cycle/NREL Fleet DNA were used to develop custom real world drive cycles
- All drive cycles include grade, a key parameter in evaluating hybrid benefits of line haul trucks

Supervisory control system completed:
- Complete hybrid powertrain model developed in Autonomie
- ORNL developed supervisory control software (single and hybrid ESS)





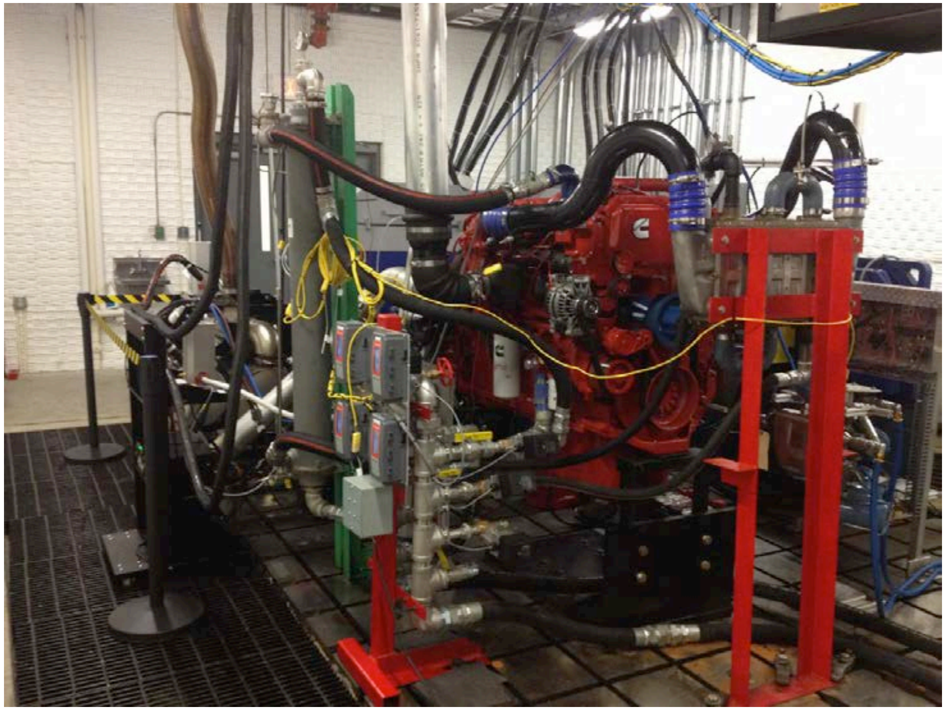
Oak Ridge National Laboratory

FY2015 MILESTONES

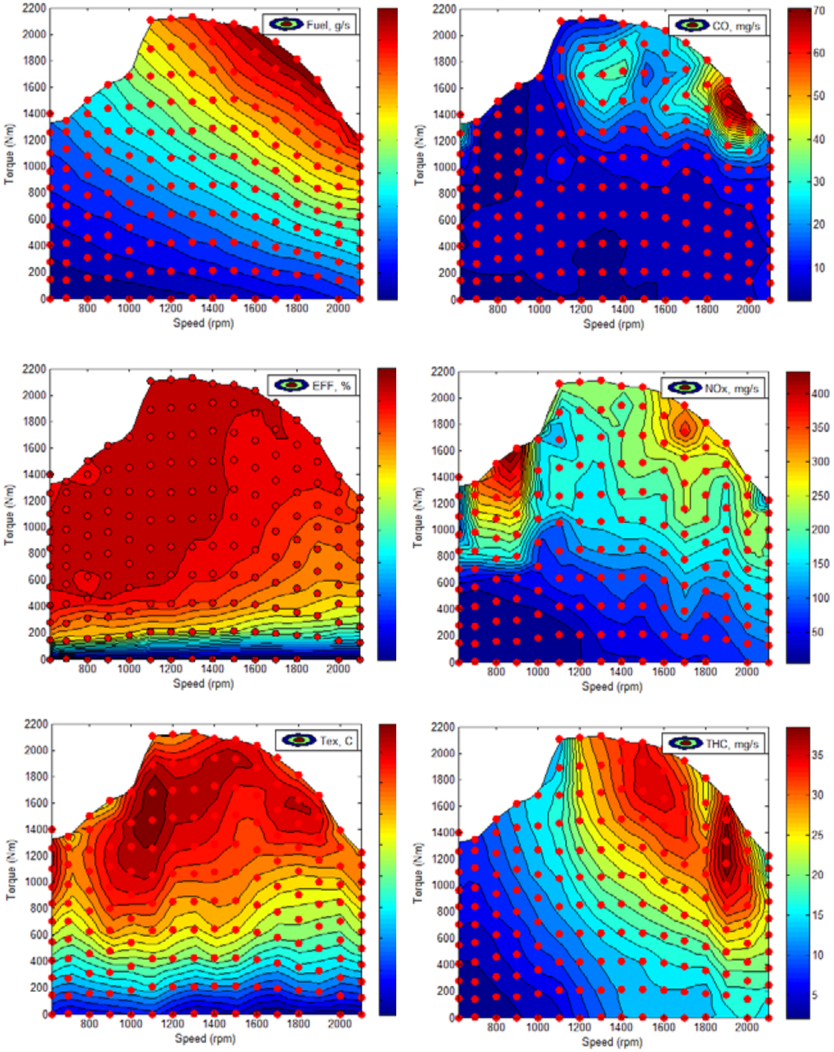
Month /Year	Milestone or Go/No-Go Decision	Description	Status
Dec 2014	Milestone	Update engine and aftertreatment models with experimental data from ORNL VSI Laboratory	COMPLETE
Dec 2014	Milestone	Properly size energy storage system for cases of larger Li-ion battery, hybrid Li-ion and ultra-capacitor system for HD powertrain optimization project	COMPLETE
June 2015	Milestone	Perform supervisory controls optimization (hybrid ESS, RCCI operation, emissions constraints)	ON TRACK
Oct 2015	Milestone	Implement RCCI operation in the Cummins ISX 15L engine	ON TRACK

ACCOMPLISHMENT (1): Engine and emissions data enhanced

Engine Dynamometer Installation at ORNL VSI Laboratory



Detailed Data for Component Models

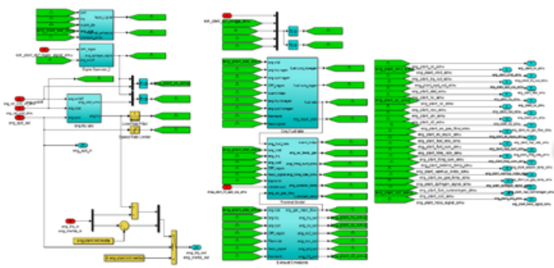


Engine testing and data development:

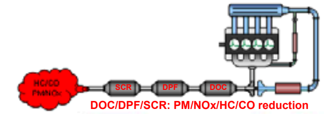
- **Complete test matrix executed (and repeated for accuracy) for developing detailed engine and emissions data**
- **Leveraged against on-going work for another ORNL project**
- **Fuel consumption data verified through comparison of actual fuel measurement, J1939 data, and emission/air fuel calculation**

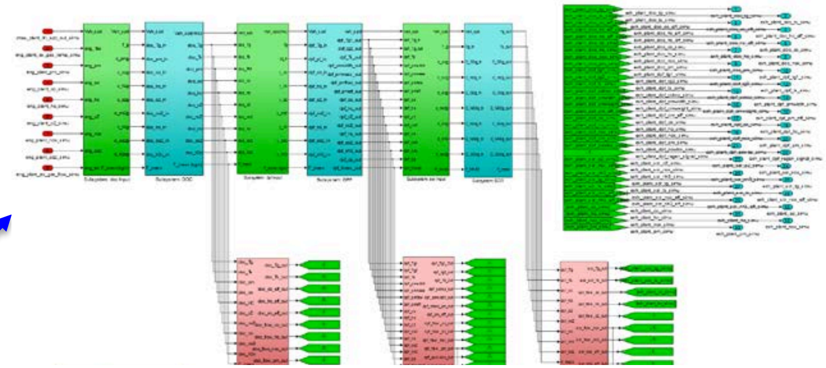
ACCOMPLISHMENT (2): Engine system models updated & validated

Transient Engine Model

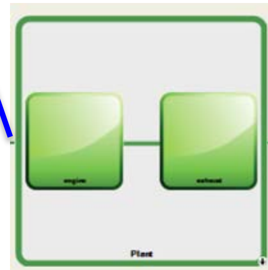


Aftertreatment Package Model



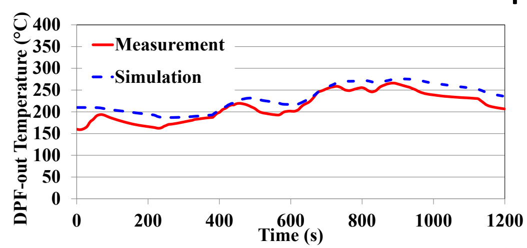


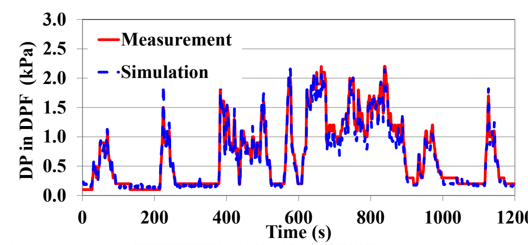
Engine system model:
- Engine and aftertreatment system models created by ORNL
- Component models are being validated against ORNL VSI Lab data

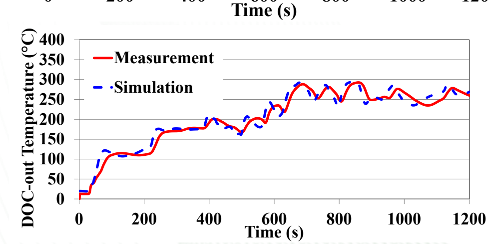


Transient engine and emissions models:
- **ORNL has implemented past transient engine modeling experience to develop transient version of Cummins ISX model**
- **Complete engine mapping exercise leveraged from other ORNL projects to develop detailed engine component model**
- **Provides sound basis for baseline comparison and future RCCI mapping exercise**
- **Model includes capability to simulate engine cold start conditions, and associated exhaust after-treatment**

Exhaust aftertreatment models:
- **ORNL has established expertise in developing exhaust aftertreatment models for a variety of relevant components**
- **Complete engine mapping exercise leveraged from other ORNL projects to develop validated**
- **Provides sound basis for baseline comparison and supervisory emissions control development**

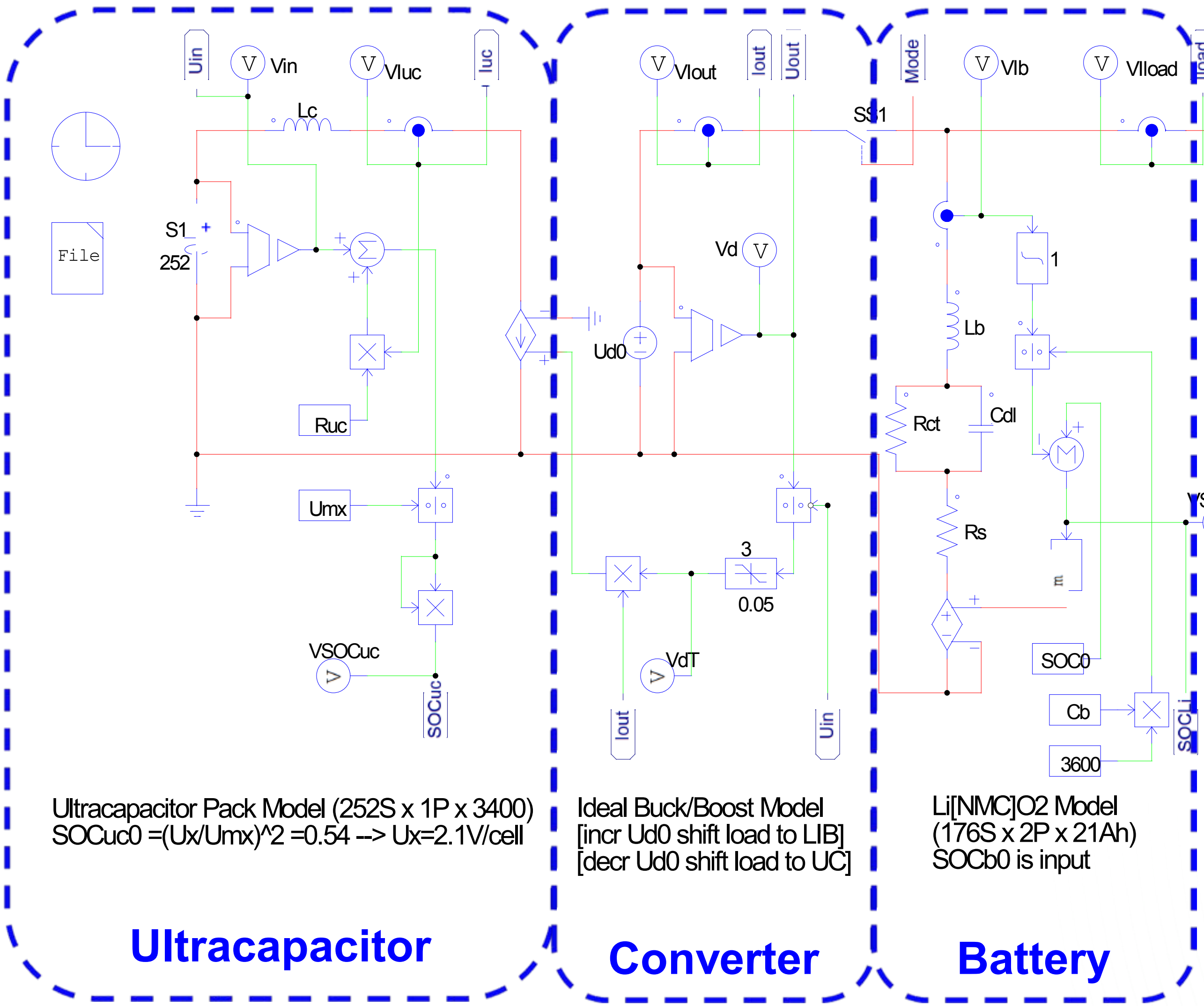


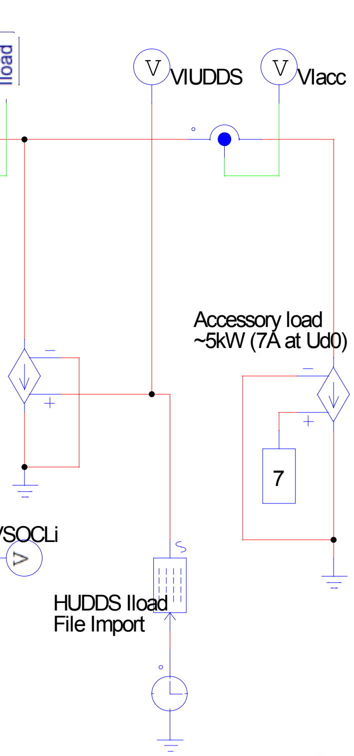


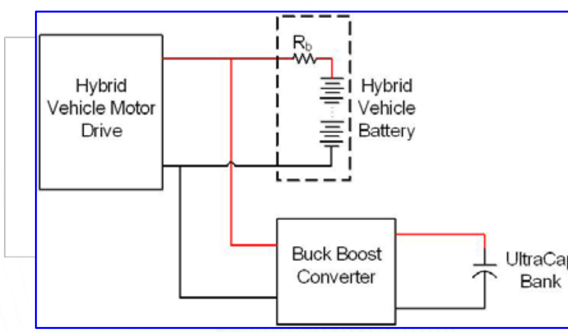


OAK RIDGE National Laboratory

ACCOMPLISHMENT (3): Hybrid energy storage system (HESS) modeling



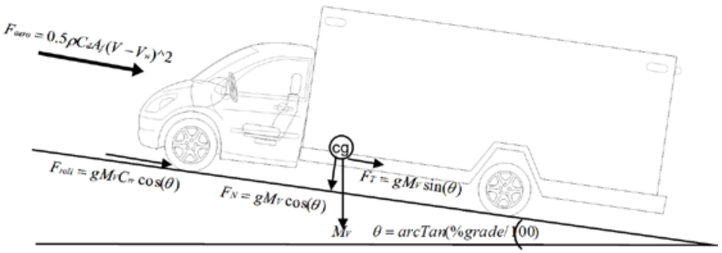




High Level HESS Block Diagram

- **Electrical model created in PSIM for each component and integrated system to allow for proper component sizing and hybrid energy storage system controls development**
- **Actively controlled UC portion of system utilizing ideal DC-DC (buck-boost) converter model**

ACCOMPLISHMENT (4): Hybrid energy storage system sizing



$$P(V) = M_V V dV/dt + F_{roll} V + F_{aero}(V - Vw) + F_T V$$

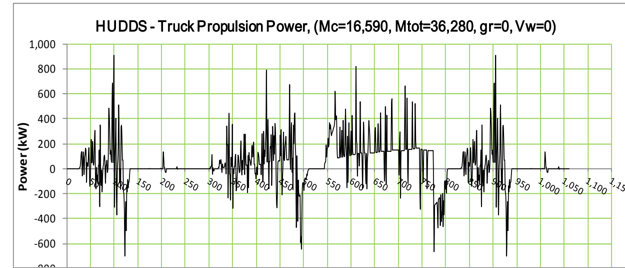
Attribute	Value	Unit	Attribute	Value	Unit
Tractor mass, M_t	12,917	(kg)	Tire rolling resistance, C_{rr}	0.010	(kg/kg)
Semi-trailer mass, M_{tr}	6773	(kg)	Aerodynamic drag, C_d	0.715	(#)
Cargo mass (avg), M_c	16050	(kg)	Frontal area, A_f	9.6	(m^2)
Limit on total mass, M_{v_mx}	36280	(kg)	Tire rolling radius, r_w	0.531	(m)
Vehicle mass in sim., M_v	(M_t+M_{tr}+M_c)	(kg)	Air density, ρ	1.225	(kg/m^3)
Head/tail wind, V_w	0	(m/s)	Grade, θ	0	(rad)
Gravity constant, g	9.806	(m/s^2)			

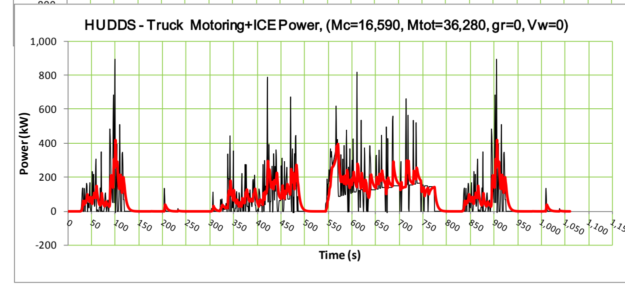
Development of ESS Load Cases:

- **High level vehicle model used to understand overall load demands on traction drive system**
- **Engine dominant overall strategy implemented**
- **ESS load cases used for input into detailed HESS model**

Drive cycle analysis:

- **Propulsion power traces established (idealized)**
- **Engine dominant load following operation**
- **HESS propulsion and regeneration traces used for component sizing**





Battery Parameters (scaled P21 Li[NMC])			Ultracapacitor Parameters (scaled K3400)		
Open circuit voltage, U_{oc}	680	(V_{dc})	Maximum voltage, U_{cmx}	718	(V_{dc})
Capacity, C_b	42	(Ah)	Nominal voltage, U_{cn}	567	(V_{dc})
Li-ion cell voltage, U_{cell}	3.87	(V)	Cell Capacitance, C_{cell}	3400	(Fd)
Number cells, N_{cb}	176	(#)	Cell working voltage, U_{cell}	2.85	(V)
Stored energy, W_b	28.5	(kWh)	Number cells, N_{cu}	252	(#)
Series resistance, R_s	0.149	(Ω)	Maximum pack energy, W_{uc}	966	(Wh)
Electrode resistance, R_{ct}	0.167	(Ω)	Pack series resistance, R_{uc}	0.1033	(Ω)
Electrode capacitance, C_{dl}	113.6	(Fd)	Pack inductance, L_{int}	3	(μH)

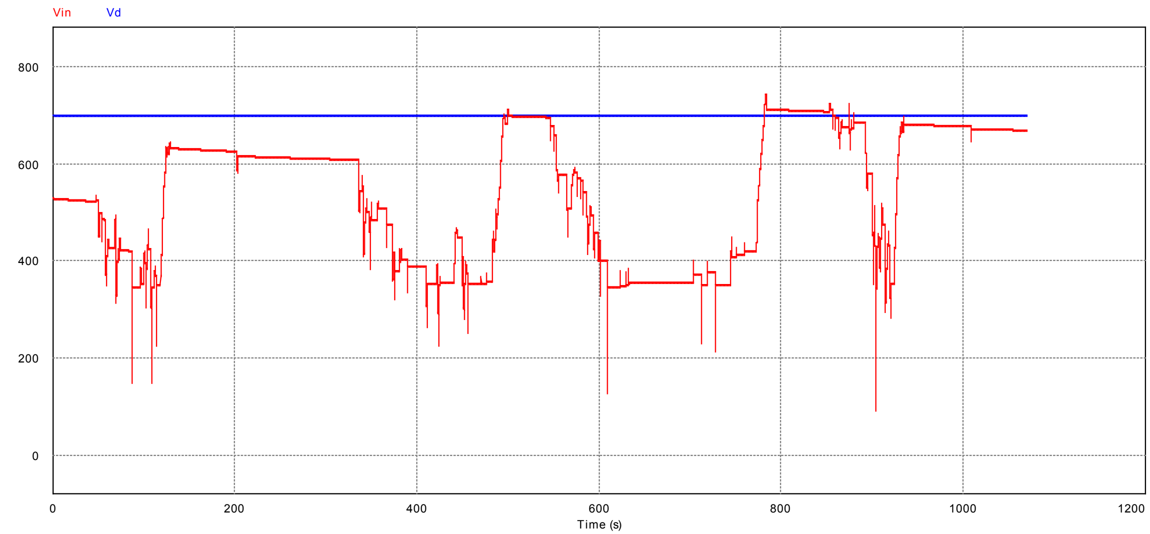
Note: The ultracapacitor data is based on Maxwell Technologies new K2 cell (2.85V, 3400F, 0.27mOhm).

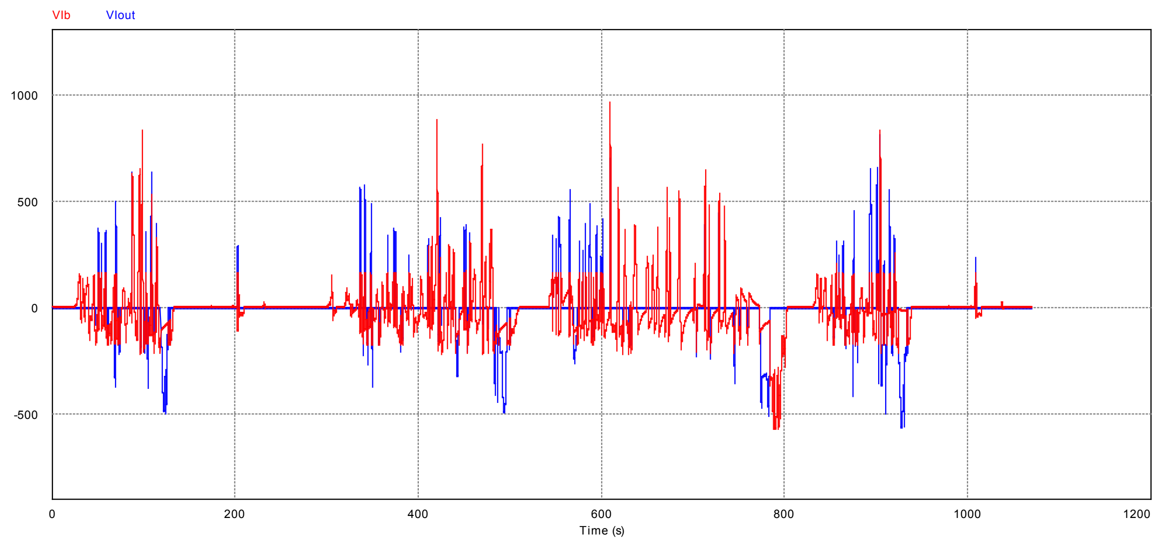
Baseline HESS sizing:

- **~700 VDC bus for traction drive**
- **Battery capacity sized for power demand as well as nominal hotel loads**
- **UC based upon new Maxwell K2 cells, with ~1 kWhr capacity (single series strand)**

OAK RIDGE National Laboratory

ACCOMPLISHMENT (5): Hybrid energy storage baseline control





- The Li-ion battery model exhibits the same behavior as a real battery, its terminal voltage rises or sags depending on power level in or out.
- HESS control: voltage-mode control
  - Effectively determines the energy sharing between the two storage elements.
  - The stiffer link voltage is a plus for the traction inverter (higher efficiency due to less DC-link voltage droop under load)
- The presence of the UC storage means most of the dynamics are passed to the UC so that Li-ion cycling (throughput) is minimized

Responses to Previous Year Reviewer Comments

- **Question 1: Approach to performing the work -the degree to which technical barriers are addressed, the project is well-designed, feasible, and integrated with other efforts.**
  - ***COMMENT*: The reviewer described that they support the approach of RCCI with the engine; however, they cautioned that series hybrid electric powertrains are very expensive and their adoption versus a parallel system is going to be highly-challenged because of the cost versus additional benefit (if any) is not justified. The project evaluator suggested the researchers look for a hybrid concept that has a higher likelihood of being relevant.**
  - ***RESPONSE:* The series hybrid powertrain offers the benefits of tighter engine control that could benefit overall efficiency in this operating region due to RCCI operating "limitations." The project will also investigate RCCI operation during parallel hybrid operating conditions as required by the nature of the series-parallel powertrain. The hybrid concept in this case provides substantial flexibility in determining potential efficiency improvements from RCCI, HESS, and emissions considerations that can easily be transferred to other powertrains (parallel) that might be considered more relevant and/or cost effective.**
- **Question 4: Proposed future research – the degree to which the project has effectively planned its future work in a logical manner by incorporating appropriate decision points, considering barriers to the realization of the proposed technology, and, when sensible, mitigating risk by providing alternate development pathways.**
  - ***COMMENT*: The reviewer criticized that the hybrid energy storage approach is flawed because it is too heavy and too big. The reviewer explained that Li-ion batteries alone are a better value per pound, cost, performance, and size.**
  - ***RESPONSE:* The HESS was sized such that in addition to maintaining acceptable levels of performance, required hotel load requirements could also be met. The HESS provides benefits to overall durability of the system due to reduced throughput of the battery (offset by the UC). In addition, the HESS provides further possibilities for increased efficiency through increased regenerative braking capture and stiff DC link voltages (a plus for the traction inverter efficiency).**

Responses to Previous Year Reviewer Comments (2)

- **Question 6: Resources: How sufficient are the resources for the project to achieve the stated milestones in a timely fashion?**
  - ***COMMENT*: The reviewer commented that this project needs more resources to ensure that experimental equipment can be maintained and rebuilt to enable validation of optimization strategies.**
  - ***RESPONSE*: The use of prototype powertrain equipment was a concern at the outset of the project. However, this contingency was considered early on (ref. Critical Assumptions from 2014 AMR). ORNL has developed a very detailed model of the powertrain utilizing data collected from a past collaboration with Meritor. In the event of a catastrophic failure, the hybrid drive unit will be removed, and tests will proceed using the engine in a component-in-the-loop configuration. Emissions data will still be actual and impacts on expected results will be minimized.**

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.**
  - Previous use of prototype Dual-Mode Hybrid Powertrain (DMHP) to support model development and validation
  - 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).
  - Research in High Efficiency Clean Combustion in Multi-Cylinder Light-Duty Engines

PROPOSED FUTURE WORK

- **FY2015**
  - Development and integration of RCCI engine model into vehicle simulation for estimated drive cycle efficiencies
  - Investigation of hybrid energy storage system variants
    - Increased UC capacity and effects on overall powertrain efficiency and reduced battery throughput
    - High power battery only system (mentioned during 2014 AMR) compared to HESS
  - Integration of baseline emissions control strategies into overall supervisory controls
  - Preliminary supervisory controls optimization for minimal fuel consumption
  - Baseline powertrain (engine-in-the-loop) testing of system in ORNL VSI Laboratory to establish reference point

- **FY2016**
  - Conversion of current Cummins ISX 15L engine (or other) 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
  - HIL testing of improved system incorporating hybrid energy storage system (emulated)

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**
  - **Updated engine and aftertreatment models** based upon experimental powertrain results from ORNL VSI Laboratory in preparation for developing **RCCI engine maps**
  - **Completed** detailed **hybrid energy storage systems models** and associated sizing
  - **Supervisory controls optimization** and **experimental RCCI implementation** is on track
- **Collaborations**
  - **Industry**: Cummins, Meritor
  - **Government**: DOE Advanced Combustion Engines, Argonne National Laboratory, and National Renewable Energy Laboratory
- **Proposed Future Work**
  - Complete **supervisory controls optimization task** (considering RCCI maps, active control for hybrid energy storage, emissions controls strategies)
  - **Engine-in-the-loop testing**: establish firm **reference** with current technologies, integrate advanced technology components to **evaluate merits of powertrain optimization**

ACKOWLEDGEMENTS

Lee Slezak
Lead, Vehicle and Systems Simulation and Testing
Office of Vehicle Technologies
US Department of Energy

David Anderson
Vehicle and Systems Simulation and Testing
Office of Vehicle Technologies
US Department of Energy

Contacts

David Smith
Principle Investigator
Center for Transportation Analysis (CTA)
(865) 946-1324
smithde@ornl.gov

Scott Curran
Project Co-Investigator
Fuels, Engines, and Emissions Research Center (FEERC)
(865) 946-1522
curransj@ornl.gov

Zhiming Gao
Project Co-Investigator
Fuels, Engines, and Emissions Research Center (FEERC)
(865) 946-1339
gaoz@ornl.gov

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).