Autonomous Intelligent Hybrid Propulsion Systems

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Overview

Timeline

- Project start date: December 2011
- Project end date: September 2013
- 70% complete

Budget

- FY12 funding: $200K
- FY13 funding: $200K

Barriers

- Cost
- Lack of sufficient computational models, design and simulation methodologies
- Constant advances in technologies

Partners

- Meritor, Inc.
- CLEERS consortium of suppliers, national labs and universities
- Oak Ridge National Laboratory
  - Fuels, Engines, and Emissions Research Center (FEERC)
  - Power Electronics and Electric Machines Research Center (PEEMRC)
  - Center for Transportation Analysis (CTA)

Objectives:

- Formulate an analytical framework that identifies optimal characteristics for critical subsystems (e.g., traction motor, generator, battery, aftertreatment) in hybrid electric vehicles (HEVs) subject to physical and regulatory constraints.
- Develop stochastic algorithms for *autonomous intelligent control* of HEVs capable of continuous real-time optimization while the driver is driving.
- Develop an online self-sustainability algorithm for the HEV electrical path.

Relevance

Vehicle Technologies Program (VTP) Mission Statement: [1]

- Mission
  - Develop more energy efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum.
  - Develop "leap frog" technologies that will provide Americans with greater freedom of mobility and energy security, with lower costs and lower impacts on the environment.
- Vision
  - Transportation energy security through a U.S. highway vehicle fleet of affordable, full-function cars and trucks that are free from petroleum dependence and harmful emissions without sacrificing mobility, safety, and vehicle choice.
- Goal
  - Develop technologies that enable cars and trucks to become highly efficient, through improved power technologies and cleaner domestic fuels, and to be cost and performance competitive.
  - Reduce both energy use and greenhouse gas emissions, thus improving energy security by dramatically reducing dependence on foreign oil.
  - Save 4-6 million barrels of oil per day, reducing greenhouse gas emissions by 50% and enabling U.S. manufacturers to be competitive in the global market.

This project directly supports VTP mission, vision and goals by accounting for how driver behavior and vehicle controls impact HEV fuel efficiency and emissions.

[1] http://www1.eere.energy.gov/vehiclesandfuels/about/fcvt_mission.html

Relevance (Cont.)

Vehicle and Systems Simulation and Testing (VSST) - Multi-Year Program Plan [2]

- Key activity areas: 1) modeling and simulation; 2) component and systems evaluations; 3) laboratory and field vehicle evaluations; 4) electric drive vehicle codes and standards; and 5) heavy vehicle systems optimization.
- Includes all of VTP's efforts directly related to the planning and modeling, development, and evaluation of advanced hybrid, electric, and plug-in hybrid drive systems for passenger and commercial vehicles.
- Conducts simulation studies, component evaluations, and testing to establish needs, goals, and component/vehicle performance validation.

This project addresses the following specific MYPP Barriers:

- Identifies and clarifies unique control-based opportunities for further improvements in fuel economy and emissions.
- Provides a framework for design optimization codes that more accurately predict the potential benefits of different control strategies.
- Develops a unique class of computational tools (stochastic control algorithms) that can be used for real-time optimization such that both hardware and human factors are accounted for.

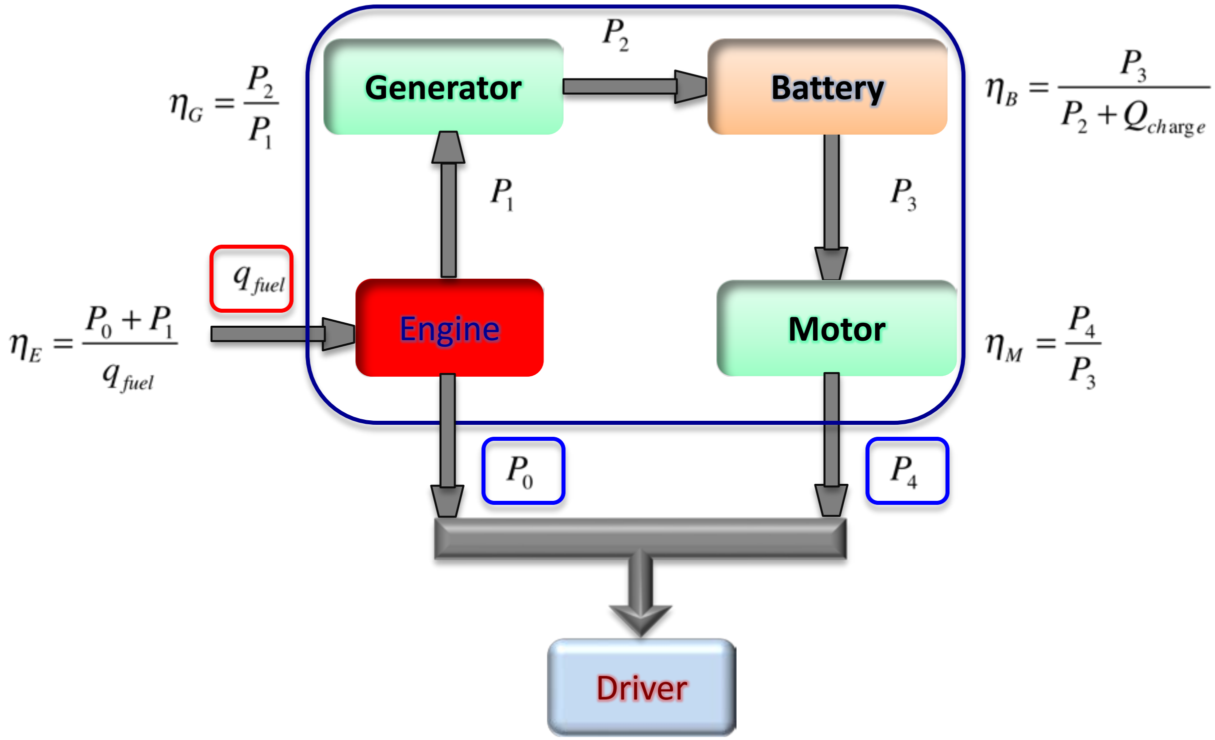
[2] http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

Milestones

- **Demonstrate the effectiveness of the efficiency of this approach through simulation (September 30, 2013):**
  - Develop the stochastic HEV control algorithms that achieve online equilibrium operation for series and parallel configurations.
  - Demonstrate that online HEV equilibrium control is equivalent to computationally rigorous offline control.
  - Implement a specific optimal control algorithm for the Meritor dual mode hybrid powertrain (DMHP).
  - Develop an online control algorithm that achieves self-sustainability of the HEV electrical path.

Technical Approach (1)

- Identify in real time the *HEV instantaneous equilibrium operating point* among each subsystem (e.g., engine, motor, generator, and battery) that maximizes overall fuel efficiency in a generic HEV configuration.



$$\eta_{hybrid} = \frac{P_0 + P_4}{q_{fuel}} = \frac{P_0 + \eta_M \cdot P_3}{q_{fuel}} = \frac{P_0 + \eta_M \cdot \eta_B \cdot (P_2 + Q_{charge})}{q_{fuel}} = \frac{P_0 + \eta_M \cdot \eta_B \cdot Q_{charge} + \eta_M \cdot \eta_B \cdot \eta_G \cdot P_1}{q_{fuel}}$$

$$= \frac{P_0 \cdot (1 - \boxed{\eta_M \cdot \eta_B \cdot \eta_G}) + \eta_M \cdot \eta_B \cdot Q_{charge} + \boxed{\eta_M \cdot \eta_B \cdot \eta_G} \boxed{\eta_E} q_{fuel}}{q_{fuel}}$$

Technical Approach (2)

- Utilize a theoretical framework developed earlier [1-3] in which the hybrid propulsion system is modeled as a controlled Markov chain.

[1] Malikopoulos, A.A., "Equilibrium Control Policies for Markov Chains," *Proceedings of the 50th IEEE Conference on Decision and Control and European Control Conference*, Orlando, Florida, December 12-15, 2011.

[2] Malikopoulos, A.A., Papalambros, P.Y. and Assanis, D.N., "A Real-Time Computational Learning Model for Sequential Decision-Making Problems Under Uncertainty," *ASME J. Dyn. Sys., Meas., Control,* Vol. **131**, No. 4, 2009, 041010(8).

[3] Malikopoulos, A.A., "Convergence Properties of a Computational Learning Model for Unknown Markov Chains," *ASME J. Dyn. Sys., Meas., Control,* Vol. **131**, No. 4, 2009, 041011(7).

- Treat the problem of optimizing the power management control in HEVs as sequential decision-making problem under uncertainty.

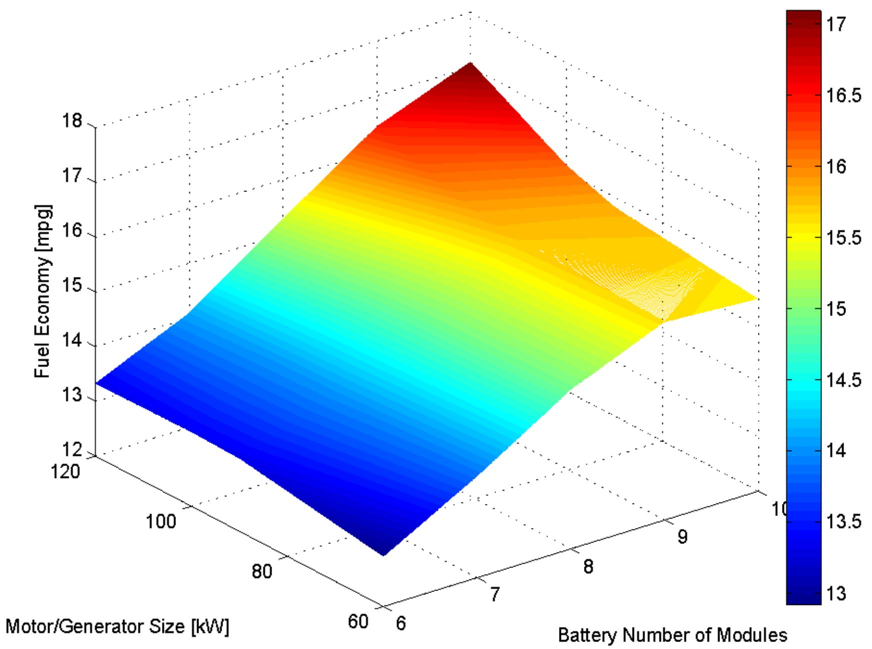
- Construct an intelligent controller that selects optimal control actions (i.e., split power demanded from the driver between the engine and motor, operation mode) in several time steps to achieve maximum fuel efficiency.

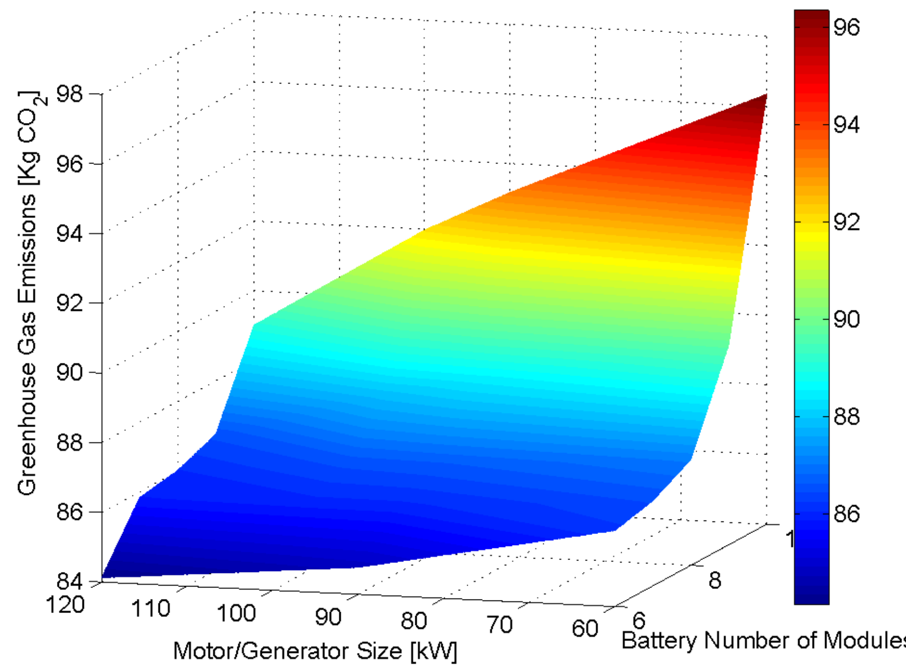
- Use the least-squares method to identify online the parameters of a model aiming at estimating the amount of power required for maintaining self-sustainability of the electrical path in HEVs.

2012 Technical Accomplishments – 1

- Created an optimization framework[6] that provides the optimal size of critical HEV subsystems (e.g., traction motor, generator, battery) subject to physical constrains.

Example of simulated responses of fuel economy and greenhouse gas (GHG) emissions with respect to motor/generator and battery size in a medium duty <u>pre-transmission parallel HEV configuration</u>.

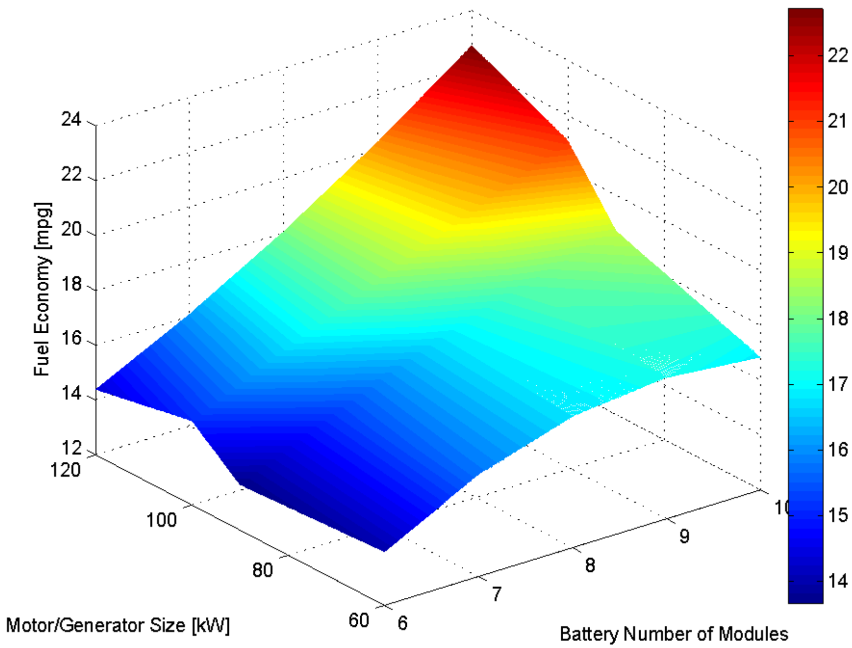


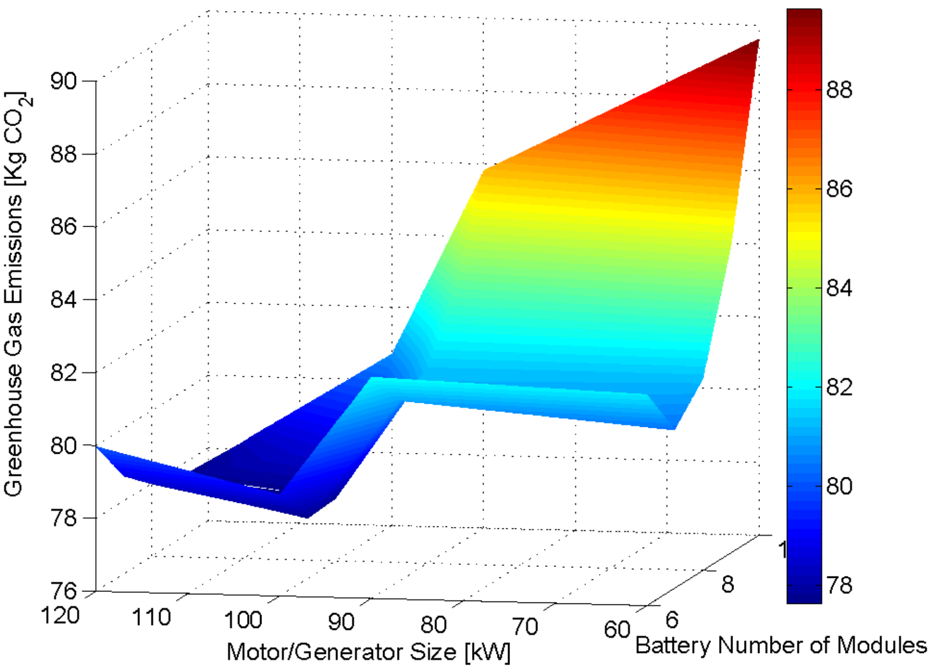


[6] Malikopoulos, A.A. "Impact of Component Sizing in Plug-In Hybrid Electric Vehicles for Energy Resource and Greenhouse Emissions Reduction," *ASME J. Energy Resour. Technol. (in press)*

2012 Technical Accomplishments – 1 (Cont.)

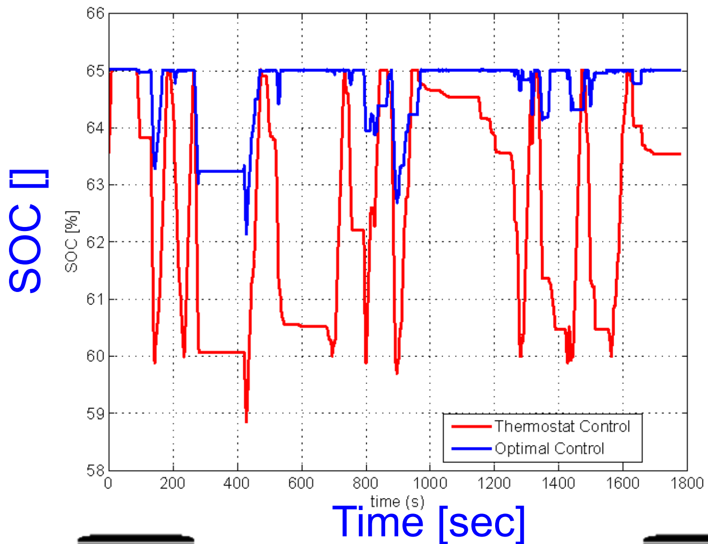
Example of simulated fuel economy and greenhouse gas (GHG) emissions with respect to motor/generator and battery size in a medium duty post-transmission parallel HEV configuration.

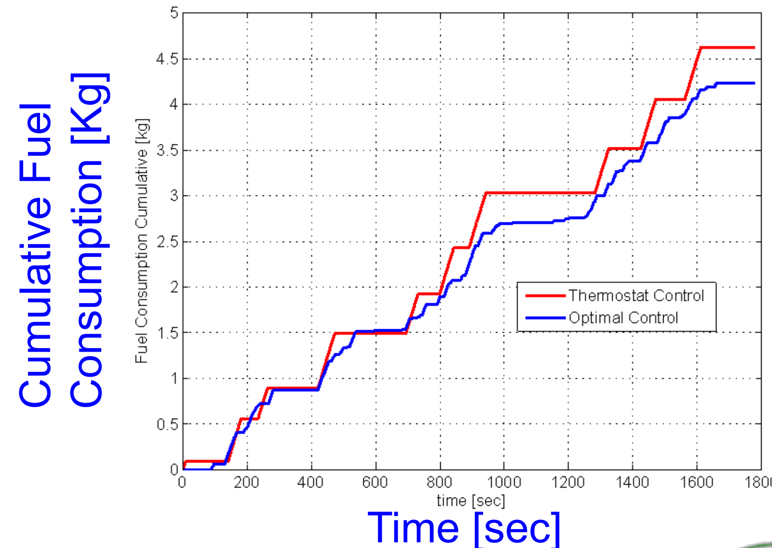


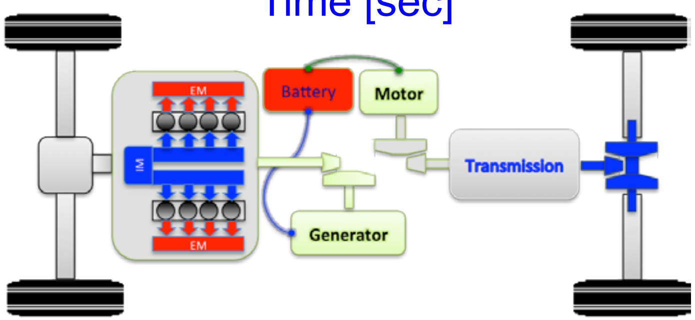


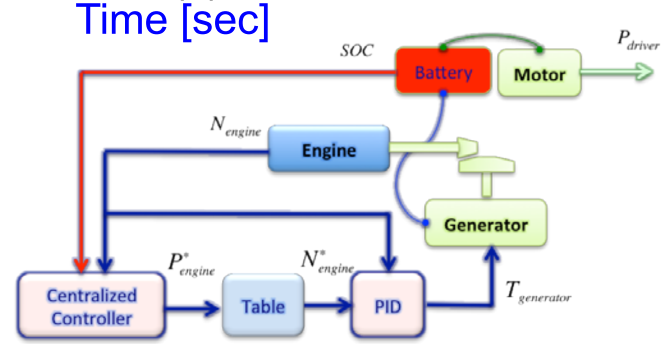
2012 Technical Accomplishments - 2

- A stochastic control algorithm was developed in a series HEV configuration that achieves a 6.6% fuel economy improvement[7] compared to a thermostat-type control algorithm.





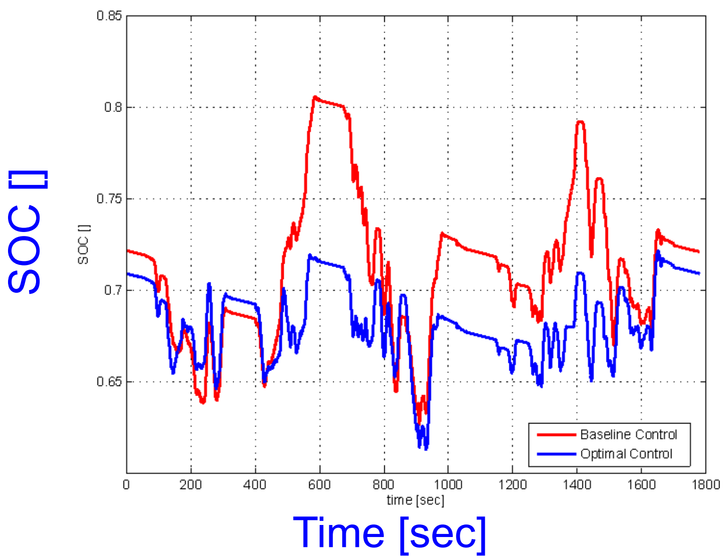


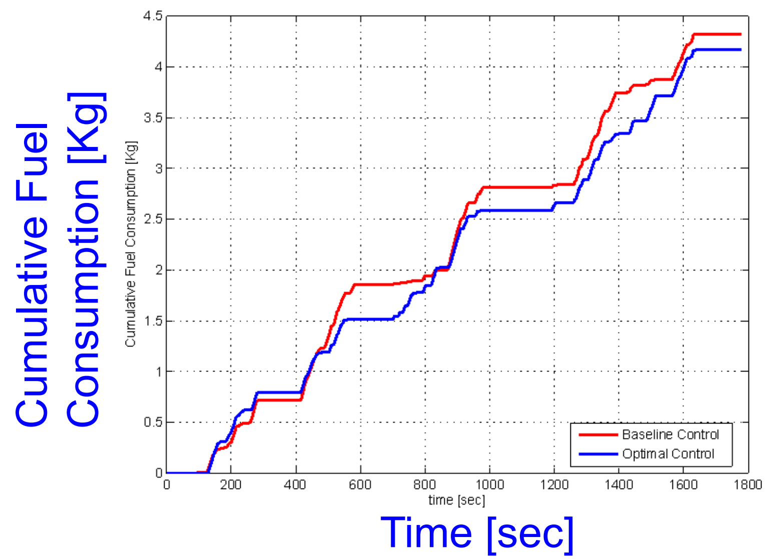


[7] Malikopoulos, A.A., "Stochastic Optimal Control for Series Hybrid Electric Vehicles," *Proceedings of the 2013 American Control Conference, Washington DC, June 17-19, 2013. (to appear)*

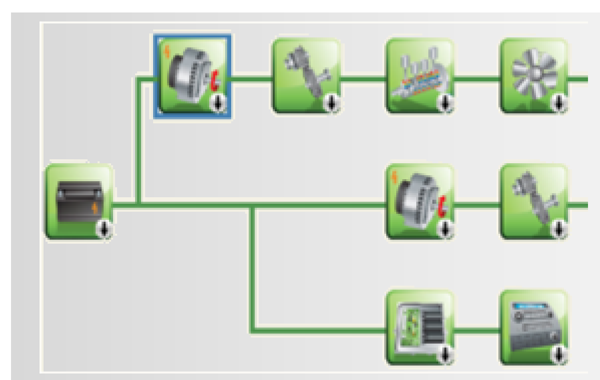
2012 Technical Accomplishments - 3

- The stochastic control algorithm was implemented in the Meritor DMHP and achieved a 5% fuel economy improvement compared to the baseline control algorithm.



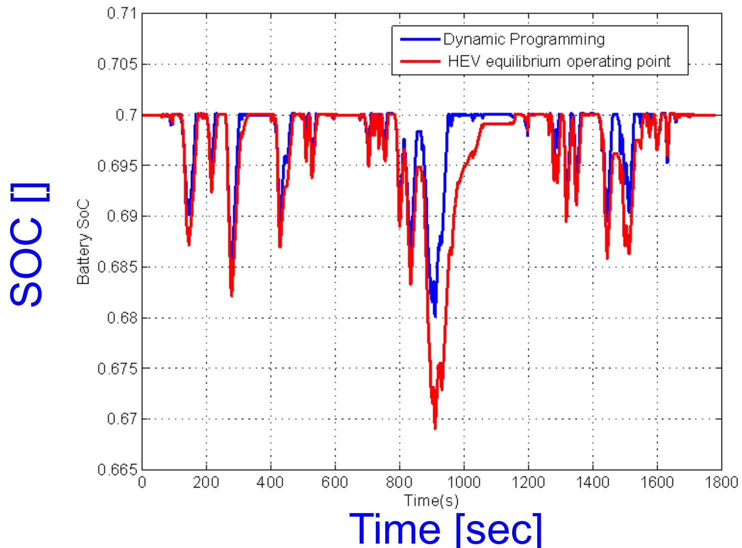


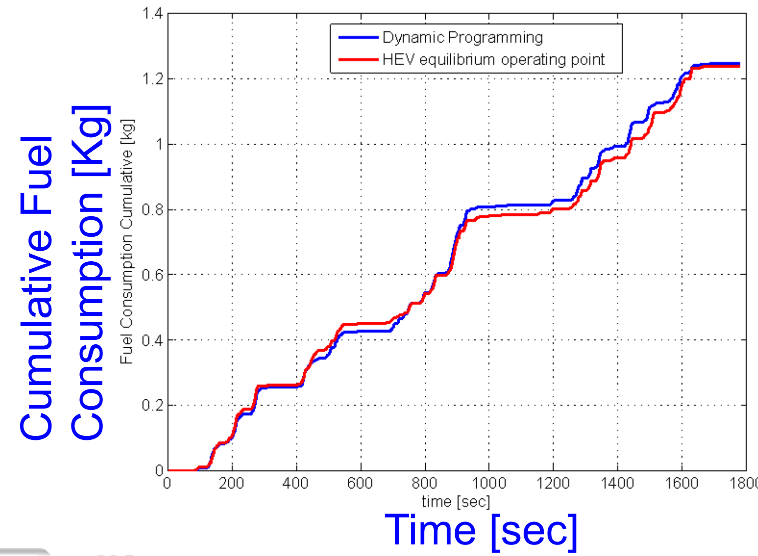
Autonomie model of Meritor DMHP system

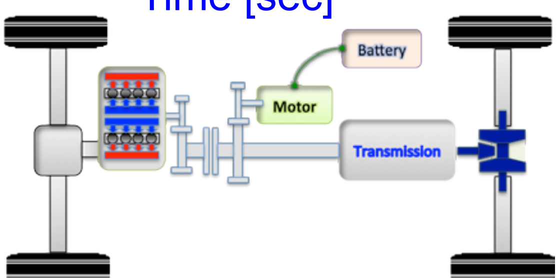


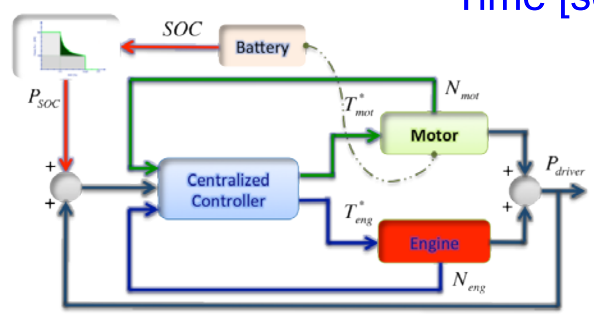
2012 Technical Accomplishments - 4

- Operating a parallel HEV at the *HEV equilibrium operating point* achieves equivalent performance to offline Dynamic Programming[8,9], thus demonstrating that the new algorithm provides a truly optimal solution online.







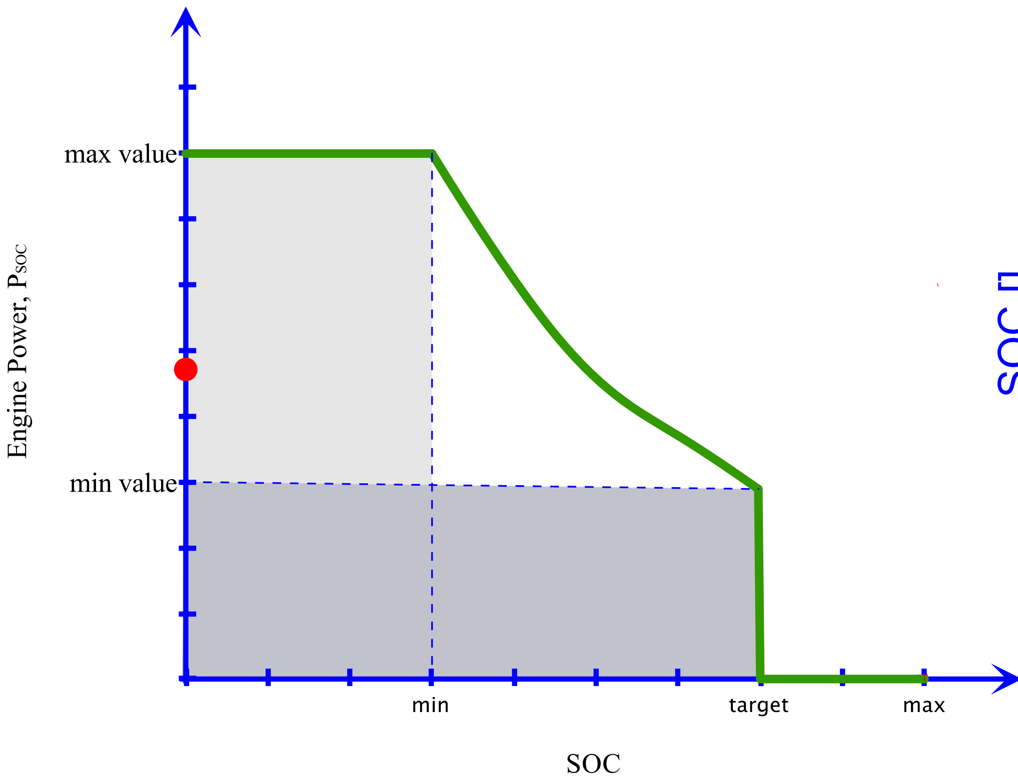


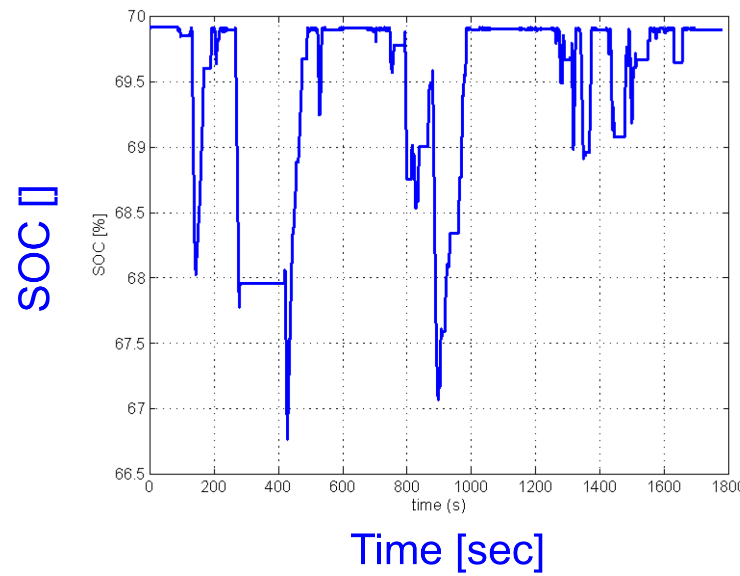
[8] Malikopoulos, A.A., "Pareto Efficient Power Management Control in Parallel Hybrid Electric Vehicles," *Proceedings of the 52nd IEEE Conference on Decision and Control,* Florence, Italy, December 10-13, 2013 (*in review*).

[9] Malikopoulos, A.A., Maroulas, V., "A Multiobjective Optimization Analysis for Stochastic Control of Complex Systems," *Proceedings of the 52nd IEEE Conference on Decision and Control,* Florence, Italy, December 10-13, 2013 (*in review*).

2012 Technical Accomplishments - 5

- An online self-sustainability algorithm[10] was developed to maintain the battery state of charge within a range of a target value.





[10] Malikopoulos, A.A., "Online Identification of Power Required for Self-Sustainability of the Electrical Path in Hybrid Electric Vehicles," *Proceedings of the 2013 ASME Dynamic Systems and Control Conference, Palo Alto, October 21-23, 2013 (in review).*

Collaborations

- **Meritor, Inc. (CRADA)**
  - Power management knowledge and controls developed in this project are being implemented in the Meritor heavy-duty, DMHP (Class 8 truck).
- **Crosscut Lean Exhaust Emissions Reduction Simulation (CLEERS) consortium (ACE022)**
  - Developing basis for including adaptive online models of aftertreatment components and engine emissions that can account for emissions constraints as part of intelligent controls. (Stuart Daw and CLEERS partners).
- **Oak Ridge National Laboratory**
  - Fuels, Engines, and Emissions Research Center (FEERC).
    - Detailed engine models for use within Autonomie.
    - Engine dynamometer commissioning and mapping of emissions and fuel economy.
  - Power Electronics and Electric Machines Research Center (PEEMRC).
    - Power electronics and electric machine analysis and support.
  - Center for Transportation Analysis (CTA).
    - Access to ORNL database of "real world" driving cycles to assess benefits of DMHP.
    - Fully instrumented vehicle data on in-use operating patterns and opportunities for improvement to component sizing, control strategy, etc.

Proposed Future Work

For the remainder of the fiscal year:

- Implement the power management control algorithms developed in other powertrain configurations and evaluate the effectiveness under different driving cycles.
- Compare the proposed control algorithms with other existing algorithms in the literature.
- Document an extensive review of the state-of-the-art of power management controls in *IEEE Transactions on Intelligent Transportation Systems*.
- Seek OEM collaborator to further develop the proposed stochastic control algorithms in a production passenger vehicle of interest.

Summary

- **Overall objective:** Develop HEV control algorithms capable of achieving optimal operation in real time while the driver is driving the vehicle.*
- **Technical Approach:** Implement instantaneous equilibrium vehicle operation with online stochastic controls.
- **Technical Accomplishments:**
  - Created an optimization framework that provides the optimal size of critical subsystems.
  - Developed stochastic control algorithms that achieve online equilibrium operation with performance equal to offline Dynamic Programming.
  - Implemented stochastic online control in the Meritor DMHP.
  - Developed an online identification algorithm that aims to maintain self-sustainability of the electrical path in HEVs.
- **Collaborators:** Meritor, CLEERS, ORNL/FEERC/PEEMRC/CTA
- **Future plans for current FY:**
  - Assess the feasibility of using above algorithms in other powertrain configurations and driving cycles.
  - Seek OEM collaboration for implementation in a production passenger vehicle.

* Aligns directly with VTP Mission and VSST MYPP

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Thank you for your Attention!

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