# Autonomous Intelligent Plug-In Hybrid Electric Vehicles (PHEVs)

**Project ID: VSS092**


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*Office of Vehicle Technologies*
*US Department of Energy*



U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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# Overview

## Timeline

- Project start date: December 2011
- Project end date: September 2013
- 20% complete

## Barriers

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

## Budget

New project, no FY11 funding

- FY12 (current) funding: $200K
- FY13 (projected) funding: $250K

## 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)

# Motivation

- Widespread use of alternative hybrid powertrains appears inevitable and many opportunities for substantial progress remain.
- Concerns about environmental impact, foreign oil dependence, and climate change have led to significant enhancement of the propulsion technology portfolio.
- Plug-in hybrid electric vehicles (PHEVs) have considerable potential to reduce petroleum consumption and greenhouse gas (GHG) emissions.

# Objectives:

- Conduct extensive literature review to identify state-of-the-art power management control algorithms in hybrid electric vehicles (HEVs) and PHEVs.
- Develop stochastic control algorithms for making a PHEV into an *Autonomous Intelligent System* capable of realizing its optimal operation while the driver is driving the vehicle.
- Use the above algorithms to operate a PHEV at an *instantaneous equilibrium operating point,* which assures maximization of the efficiency of the PHEV at each instant of time.

# 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 the VTP mission, vision and goal because it provides a mechanism to reduce petroleum use and environmental impact by achieving maximum PHEV efficiency and minimum emissions possible for each individual driver.

[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 VTP Multi-Year Program Plan Barriers for VSST:**

- The literature review identifies and clarifies opportunities for substantial progress towards achieving further fuel economy improvements and emissions reductions.
- The stochastic control framework aims to develop codes for optimizing future designs, and for accurately predicting fuel economy of advanced commercial vehicles.
- The simulation framework established to evaluate the effectiveness of the efficiency of the stochastic control algorithms augments current efforts towards ensuring the accuracy of simulation results.

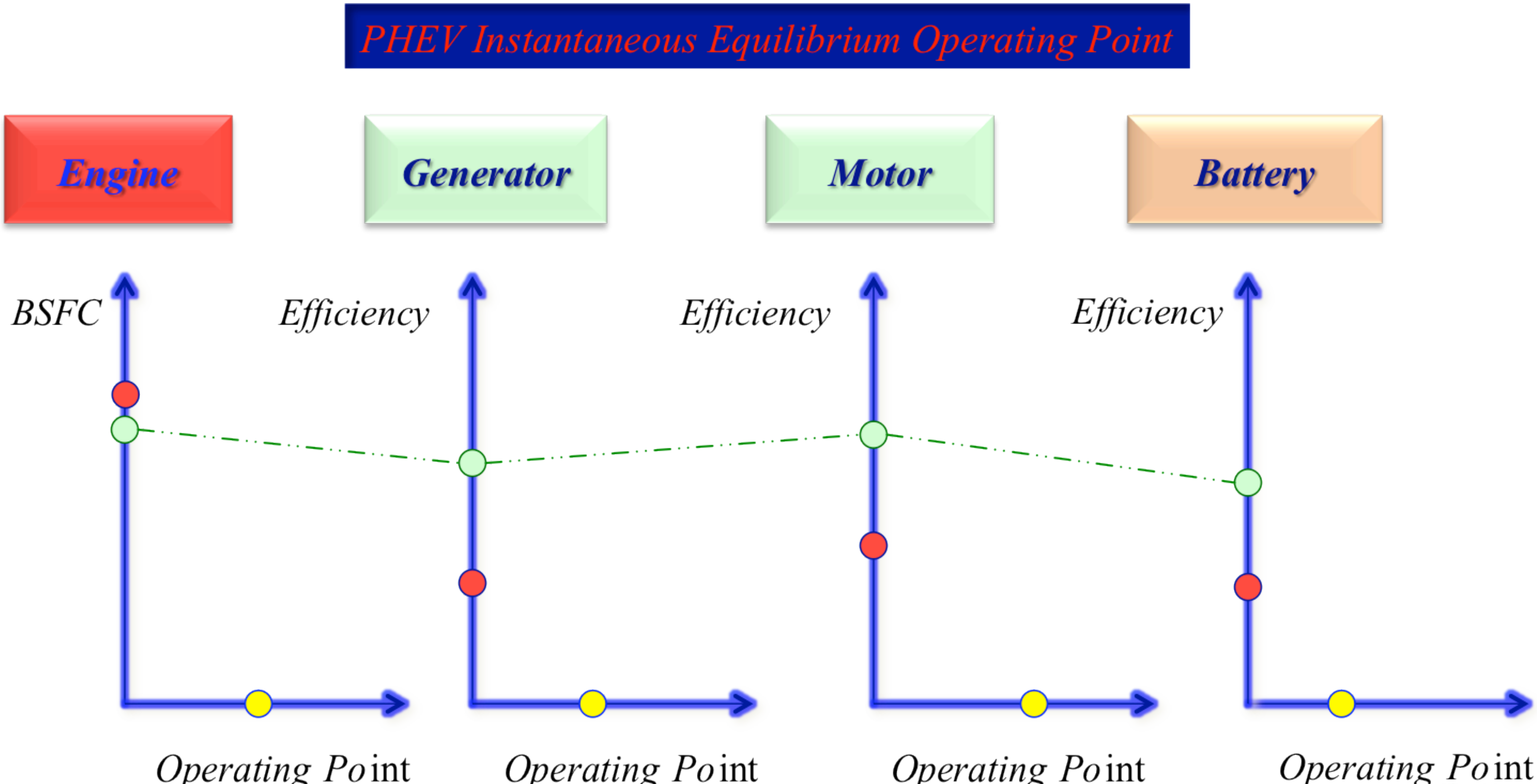
[2] http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/vt_mypp_2011-2015.pdf

# Milestones

- **Demonstrate the effectiveness of the efficiency of this approach through simulation (September 30, 2012).**
    - Conduct an extensive literature review to identify the state-of-the-art power management control algorithms in HEVs and PHEVs.
    - Develop a robust PHEV simulation model in Autonomie for the study and discovery of potential operating scenarios of the total system, major components, e.g., engine, motor, generator, battery, and synergetic interactions under different driving cycles.
    - Implement the stochastic control algorithms for making a PHEV capable of realizing its optimal operation in real time while the driver is driving the vehicle by achieving the *PHEV instantaneous equilibrium operating point*.

# Technical Approach

- In an ideal world the electrical path would have efficiency of 100%.
- Running the engine at the best BSFC is not equivalent to operating a hybrid powertrain most efficiently.



# Technical Approach (Cont.)

- Draws from control theory research in a wide range of areas including discrete-time control Markov processes.
- Algorithms make PHEV operate at its instantaneous equilibrium point [3], which assures maximum efficiency for the entire PHEV at each instant of time.
- The power management controller employs a theoretical framework developed earlier [4,5] in which the PHEV is modeled as a controlled Markov chain.
  - Formulated as sequential decision-making problem under uncertainly
  - Intelligent system (controller) selects optimal control actions (i.e., split power demanded from the driver between the engine and motor, PHEV operation mode) in several time steps to achieve minimal fuel consumption and emissions.

[3] 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.

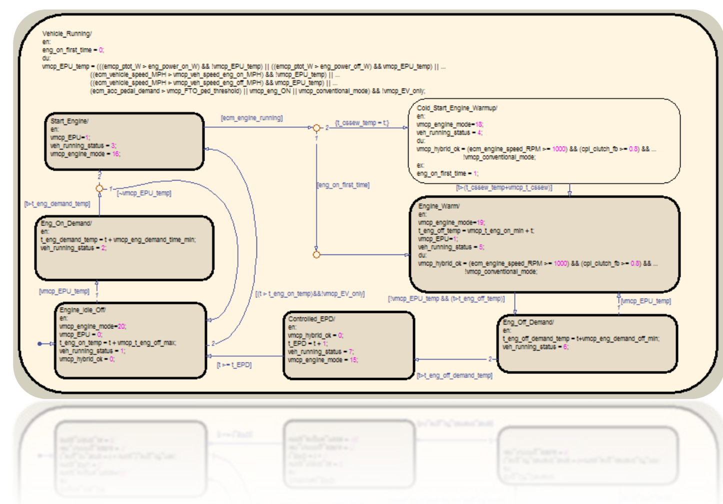
[4] Malikopoulos, A.A., Papalambros, P.Y. and Assanis, D.N., "A Real-Time Computational Learning Model for Sequential Decision-Making Problems Under Uncertainty," ASME J. Dyn. Sys., Meas., Control, **Vol.131**, No. 4, 2009, 041010(8).

[5] 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).

# 2012 Technical Accomplishments

## In the past four months (December 2011-March 2012):

- **Completed extensive literature review of > 120 archival publications covering key state-of-the-art power management control algorithms:**
  - Rule-based control
  - Fuzzy logic/Artificial neural networks (ANNs)
  - Dynamic Programming (deterministic and stochastic formulation)
  - Analytic optimal control (*Pontryagin's* minimum principle)
  - Equivalent consumption minimization strategies (ECMS)
  - Model predictive control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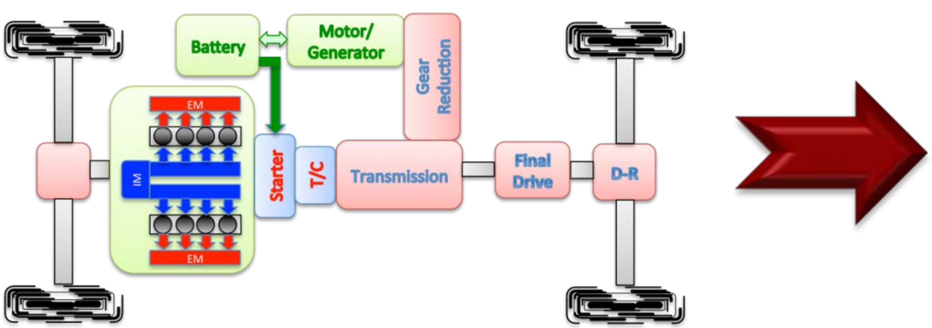
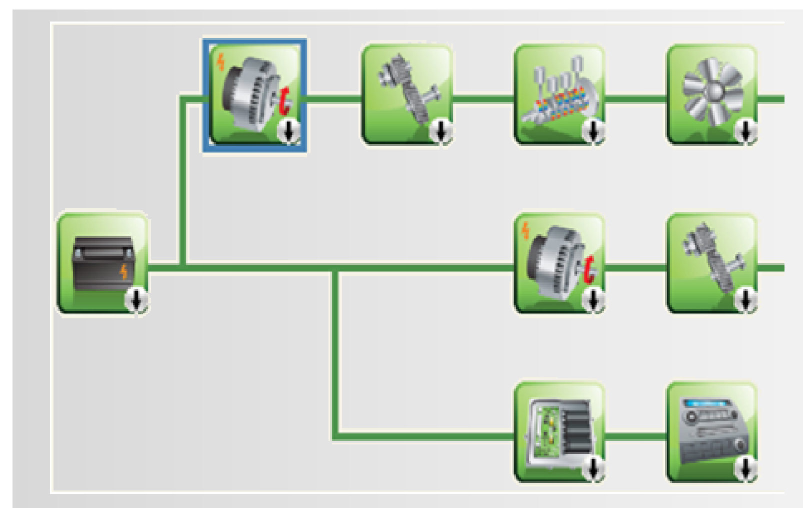
# 2012 Technical Accomplishments (Cont.)

- **Established a series/parallel PHEV model in Autonomie modeling environment.**
  - Prototype electric machine (motor and generator) integrated into overall model.
  - Well-structured supervisory control model architecture created as a baseline and integrated into model.
  - Vehicle model simulated over standard driving cycles.
- **Derived and submitted the stochastic control algorithm for publication:**
  - Malikopoulos, A.A., Charalambous, C.D. and Tzortzis, I., “Dual Constrained Optimization of Markov Chains Subject to Total Variation Distance Uncertainty,” *Proceedings of the 51th IEEE Conference on Decision and Control and European Control Conference*, Maui, Hawaii, December 10-13, 2012. (*in review*)



# Collaborations

- **Meritor, Inc. (CRADA)**
  - The power management control algorithms and knowledge developed in this project will be implemented to the Meritor heavy-duty, Dual Mode Hybrid Powertrain (DMHP) (Class 8 truck) to optimize overall operation.
- **Crosscut Lean Exhaust Emissions Reduction Simulation (CLEERS) consortium (ACE022)**
  - Shared emissions control data and models.
  - Strong collaboration towards optimizing engine warm-up process in HEVs and PHEVs.
- **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.
    - Assessment of interfacial relationships within high voltage traction drive system.
  - 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 algorithm in Autonomie.
  - Key milestone: Execute the algorithm in a real-time PHEV simulation.
- Modify the algorithm to allow optimizing engine warm-up process in HEVs and PHEVs (collaborative task with Stuart Daw and Zhiming Gao).
- Conduct simulations of different driving cycles with the control algorithms included to evaluate the potential benefits.
  - Compare with other existing power management control algorithms in the literature.
  - Implement in the Meritor heavy-duty, Dual Mode Hybrid Powertrain (DMHP).
  - Key milestone: Assess the impact of DMHP complexity on the effective control problem dimensionality.
  - Evaluate the controller efficiency under "real world" light-duty and heavy-duty driving cycles (data provided by the Center for Transportation Analysis (CTA) at ORNL).

# Proposed Future Work (Cont.)

- FY 2013
  - Implement the power management controller in the powertrain-in-the-loop (PIL) at ORNL Vehicle Systems Integration (VSI) Laboratory and demonstrate the efficiency in fuel economy and emissions.

# Summary

- Overall objective: Develop stochastic control algorithms for making a PHEV into an Autonomous Intelligent System capable of realizing optimal operation in real time while the driver is driving the vehicle.*
- Technical Approach: Target the PHEV instantaneous equilibrium operating point, which assures maximization of the efficiency of the entire PHEV at each instant of time.
- Collaborators include Meritor, CLEERS, ORNL/FEERC/PEEMRC/CTA
- Technical Accomplishments since project start (December 2011):
  - Established series/parallel PHEV model in Autonomie.
  - Completed extensive literature review of state-of-the-art power management control algorithms.
  - Derived the stochastic control algorithm and submitted paper for publication.
- Future plans for current FY:
  - Execute the algorithm in a real-time PHEV simulation
  - Assess the complexity of using the algorithm for DMHP

* Aligns directly with VTP Mission and VSST MYPP

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