The Meritor Dual Mode Hybrid Powertrain (DMHP): Opportunities and Potential for Systems Optimization

Cooperative Research and Development Agreement with Meritor, Inc.

Project ID: VSS072

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Lee Slezak
Lead, Vehicle and Systems Simulation and Testing
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: April 2011
- Project end date: Sept. 2014
- 15% complete

Barriers*

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

from 2011-2015 VTP MYPP

Budget (DOE share)

- New project, no FY10 funding
- FY11 (current) funding: $350k
- FY12 (projected) funding: $500k
- FY13 (projected) funding: $500k

Partners

- Meritor, Inc.
- 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

Hybrid electric powertrain configurations have attracted considerable attention due to their potential to reduce petroleum consumption and greenhouse gas (GHG) emissions in the transportation sector.

The objectives of this project is to:

o Develop an advanced modeling and simulation framework of a Class 8, dual mode hybrid powertrain (DMHP), conceived by Meritor, with the aim of accurately predicting the response of the vehicle to all anticipated inputs.

o Formulate an optimization framework analytically with the objective to minimize fuel consumption with respect to the size of various critical subsystems (e.g., traction motor, generator, battery) subject to the vehicle's physical constrains.

o Implement a power management control algorithm with the aim of optimizing DMHP operation by making each subsystem (e.g., engine, traction motor, generator) to operate continuously at its most fuel economy efficient operating point.

o Conduct a sensitivity parametric analysis to identify future opportunities to improve overall system efficiency.

o Evaluate the effectiveness of the efficiency of this powertrain technology through extensive dynamometer and on-road testing.

Relevance

Vehicle Technologies Program (VTP): The mission, the vision and the goal [1]

"The mission of the Vehicle Technologies Program is to develop more energy efficient and environmentally friendly highway transportation technologies that enable America to use less petroleum. The long-term aim is to 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. The vision is transportation energy security will be achieved 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. The general goal is to 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. Manufacturers and consumers will then use these technologies to help the nation reduce both energy use and greenhouse gas emissions, thus improving energy security by dramatically reducing dependence on foreign oil. The benefits will include saving 4 to 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."

The Meritor DMHP CRADA directly supports the VTP mission, vision and goal:

o   The DMHP system enables a new paradigm in powertrain operational efficiency, particularly in the Class 8 truck segment.

o   The DMHP in conjunction with the power management controller allows the engine to operate in a narrow range, thus providing the opportunity for maximum fuel economy and minimum emissions.

o   The DMHP operation choices include running in full series, full parallel and engine-off modes allowing elimination of overnight hoteling and idling at stops, and thus further fuel economy savings and elimination of emissions.

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

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Relevance (Cont.)

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

"…The VSST activity comprises work in five 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. This subprogram 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. The subprogram also conducts simulation studies, component evaluations, and testing to establish needs, goals, and component/vehicle performance validation…"
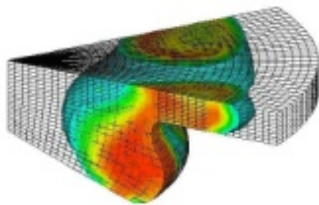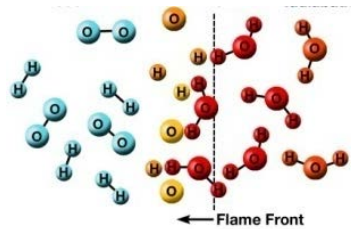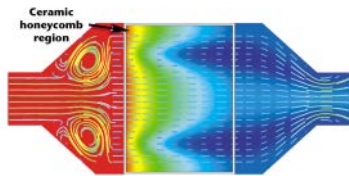

The Meritor DMHP CRADA contributes to the following VTP Multi-Year Program Plan Goals for VSST:

o The modeling and simulation framework provides an effective and timely evaluation of the DMHP technology with respect to components and configuration with implications to opportunities for further improvements in fuel economy and emissions reductions.

o The optimization framework aims to develop codes for optimizing future designs, and for accurately predicting fuel economy of advanced heavy-duty commercial vehicles.

o The sensitivity parametric analysis can identify future advances of this technology with the aim of the developed modeling and simulation tool.

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

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Milestones

o Simulation model and control algorithm development (November 30, 2011).

⊙ Develop a robust DMHP vehicle simulation model for the study and discovery of potential operating scenarios of the total system, major components, e.g., engine, traction motor, generator, battery, and synergetic interactions under simulated load cycles.

$$\left. \frac{dS}{dt} \right|_{CV} = \int \frac{\partial \dot{Q}}{T_w} + ...$$

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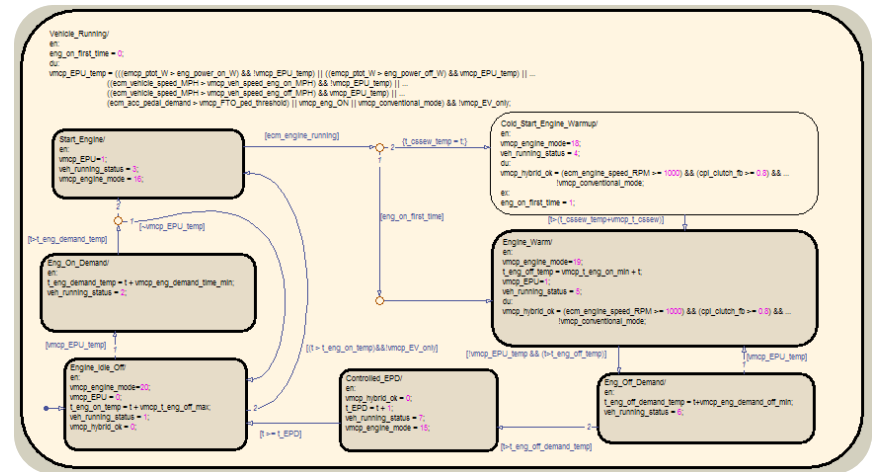
Milestones (Cont.)

o DMHP System optimization studies.

   ◉ Develop a power management control algorithm with the aim of optimizing DMHP operation by making each subsystem (e.g., engine, traction motor, generator) to operate continuously at its most fuel economy efficient operating point (June 30, 2012)

   ◉ Complete sensitivity parametric analysis to identify future opportunities to improve overall system efficiency. (September 30, 2012)

T_{demand}
$Velocity$
SOC
$Gear$

Power Management Controller

T_{engine}
T_{motor}
$T_{generator}$
T_{brake}

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Approach

- Simulation Model and Control Algorithm Development
    - Develop and integrate a detailed engine model with the DMHP for understanding the engine interactions within the hybrid powertrain.
    - Update and further develop a robust DMHP vehicle simulation model for the study and discovery of potential operating scenarios of the total system, major components such as the engine and battery pack, and synergistic interactions under simulated load cycles.
- Identify Further DMHP Improvement Potential
- Alternative Technology Evaluation

*Autonomie® model of Meritor DMHP system*

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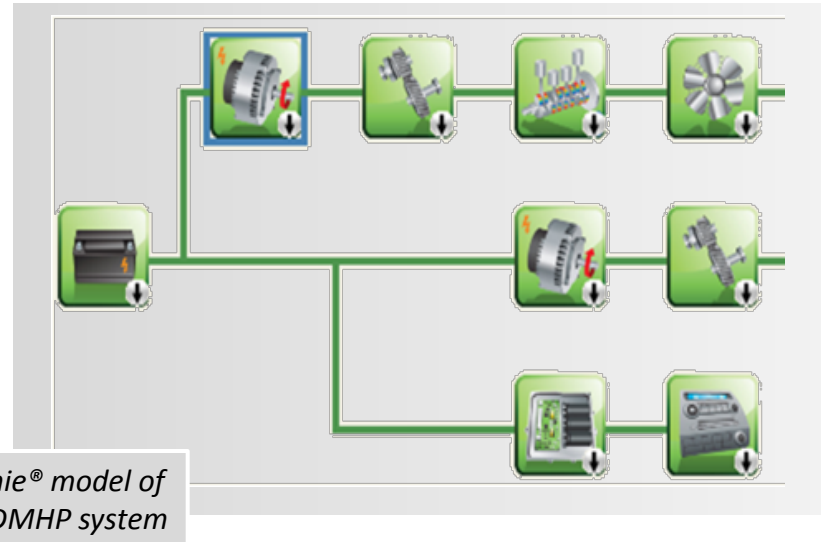
Approach (Cont.)

o The power management control algorithm developed [3] for the DMHP draws from stochastic control theory research in a wide range of areas including reinforcement learning and game theory, and attempts to make the DMHP into realizing continuously its most efficient operating point.

- ⊙ The operation of DMHP is modeled as a controlled Markov chain.

- ⊙ The problem is formulated as sequential decision-making under uncertainly in which an intelligent system (controller) is faced with the task to select those optimal control actions (i.e., power split between the engine and motor, DMHP operation mode) in several time steps to achieve long-term goals efficiently (minimize 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.

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Approach (Cont.)

- ○ Engine Acquisition, Installation, and Mapping
  - ◉ Acquire a representative HD engine and dynamometer-compatible controller/wiring harness.
  - ◉ Benchmark engine to develop a performance/emissions map to support modeling efforts.
- ○ DMHP Simulated and Full System Dynamometer Testing
  - ◉ Develop and test a simulated DMHP on the HD engine acquired in the previous task utilizing engine hardware-in-the-loop and advanced control methodologies.
  - ◉ Install and test a complete DMHP system (provided by Meritor) on powertrain integration dynamometer for full system hardware developmental testing.
  - ◉ Development and integration of prototype supervisory controller (hardware and software). This controller will be used for dynamometer as well as in vehicle testing
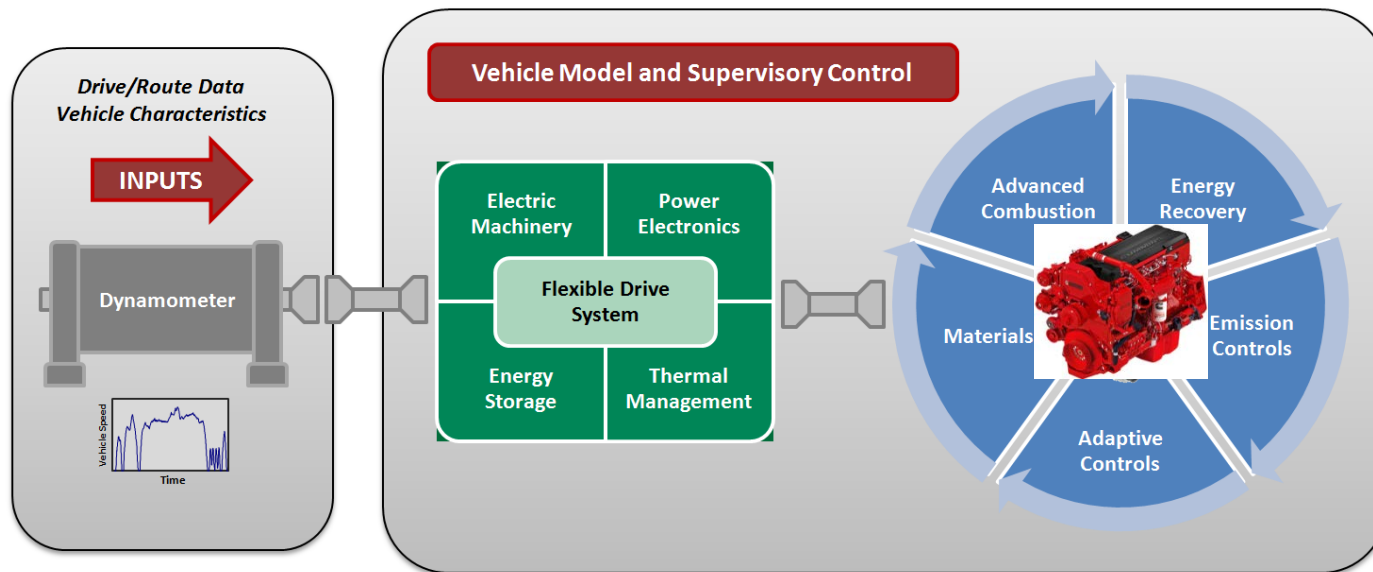
Approach (Cont.)

o DMHP On-Road Testing in a HD Class 8 Truck

  - Develop a test plan and install the necessary data acquisition and instrumentation on a prototype, Class 8 truck equipped with DMHP (vehicle provided by Meritor or a TBD fleet partner).

  - Place test vehicle into service to observe normal fleet operation over the road under real-life conditions. Information, such as vehicle loading, duty cycle, component physical conditions, etc. will be acquired and analyzed.

  - Findings will be transferred back to both the vehicle simulation model and the experimental full system test facility for an additional cycle of learning.
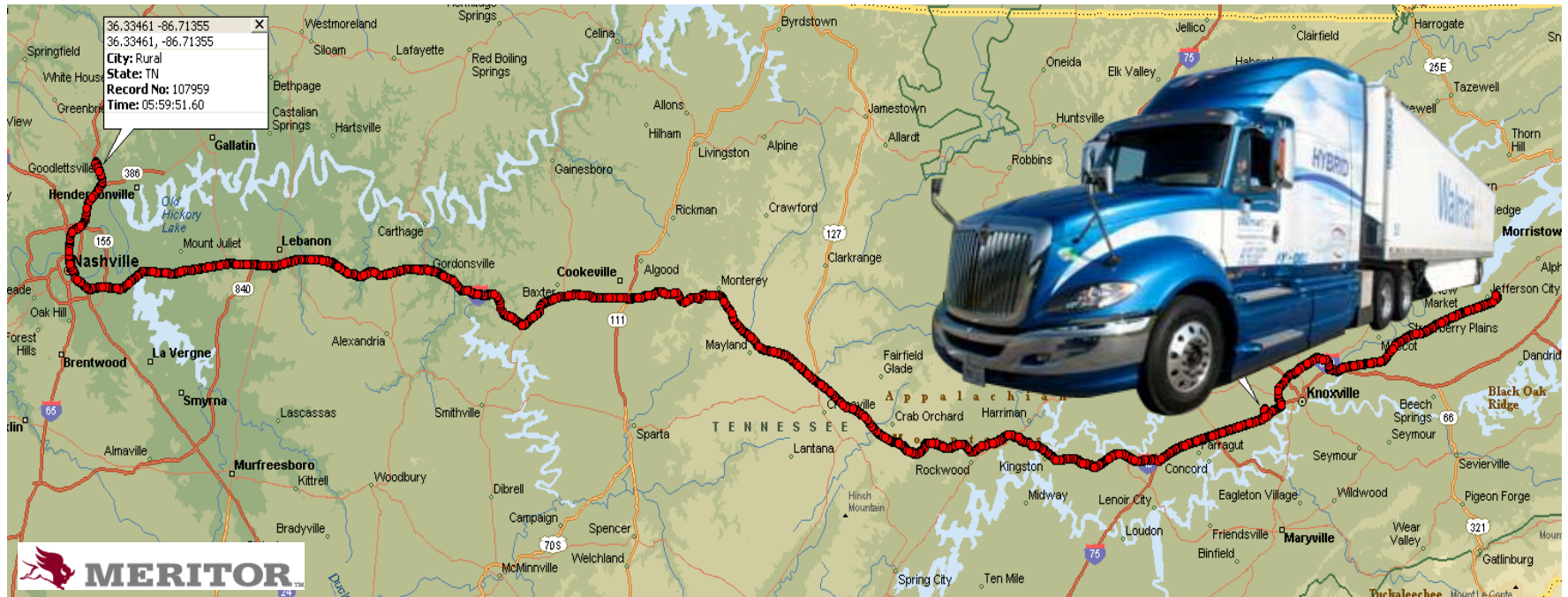
Technical Accomplishments

o Established full vehicle model with DMHP powertrain in Autonomie modeling environment

  ◉ Proprietary engine data used for representative 2007 emissions compliant HD engine

  ◉ Prototype electric machine (traction motor and generator) integrated into overall model

  ◉ Well-structured supervisory control model architecture created and integrated into model

o Vehicle model simulated over standard and "real world" drive cycles

  ◉ Standard heavy vehicle drive cycles were exercised to confirm expected operation of the DMHP, as well as baseline comparison for data found in the literature

  ◉ "Real world" drive cycles were utilized based on the ORNL Heavy Truck Duty Cycle database.

o Results suggested high degree of merit for DMHP → warrants much deeper research and development efforts

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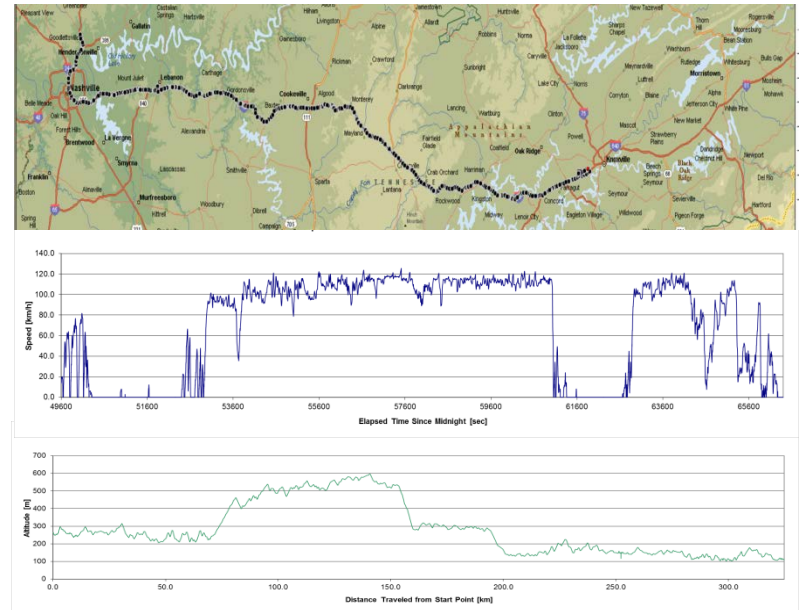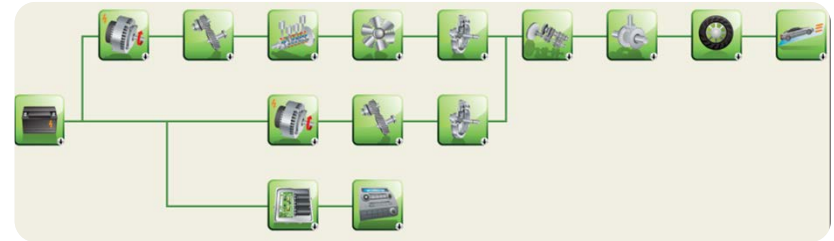
Technical Accomplishments (Cont.)

o Representative engine acquired, currently being installed in NTRC test cell for preliminary performance mapping. Data will be used to update vehicle system model.

o The stochastic control algorithm was derived and documented in the following paper:

  ⊙ 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

o **Meritor**

  ⊙ Development and delivery of Dual Mode Hybrid Powertrain, including prototype electric machines, integrated two-speed transmission, and respective control systems.

  ⊙ Modification and delivery of full Class 8 test vehicle with prototype DMHP.

  ⊙ DMHP system and component data sharing for optimization efforts.

  ⊙ Vehicle performance constraints sharing for optimization effort.

o **Oak Ridge National Laboratory**

  ⊙ Fuels, Engines, and Emissions Research Center (FEERC)

  • Development of detailed engine model 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)

  • Provide access and use of ORNL Heavy Truck Duty Cycle (HTDC) database for developing "real world" drive cycles, **including grade**, to assess benefits of DMHP in simulation.

  • Instrumentation of full vehicle to understand in-use operating patterns and opportunities for improvement to component sizing, control strategy, etc.

Proposed Future Work

○ Remainder of FY2012

- ◉ Complete Alternative Technology evaluation

- ◉ Engine installation and dynamometer testing

  - Steady state and transient engine mapping for integration into component/vehicle models

  - Transient engine component-in-the-loop testing with DMHP and vehicle emulated in software

- ◉ Implement the stochastic learning power management control algorithm into the DMHP model in Autonomie.

  - Key milestone to be addressed: the algorithm needs to be executed in real time.

○ FY2013 and beyond

- ◉ Preliminary DMHP system benchmarking

  - Receive complete DMHP system and install on test stand at ORNL VSI lab

  - Commission powertrain dynamometer system and complete baseline testing

- ◉ Class 8 vehicle instrumentation and deployment

  - Install appropriate instrumentation and data acquisition equipment into prototype vehicle

  - Deploy vehicle into fleet service and initiate data monitoring

- ◉ Detailed DMHP system testing at ORNL VSI

- ◉ Complete data monitoring of in use vehicle data

- ◉ Provide assessment for refined vehicle powertrain optimization and proposed future work

Summary

o The successful implementation of DMHP requires a system level understanding of the complex interactions between various energy sources and consumption components.

o The DMHP system enables a new paradigm in powertrain operational efficiency, particularly in the Class 8 truck segment.

o The modeling and simulation framework developed here provides an effective and timely evaluation of the DMHP technology with respect to components and configuration with implications to opportunities for further improvements in fuel economy and emissions reductions.

o The optimization framework and sensitivity parametric analysis can identify future advances of this technology with the aim of the developed modeling and simulation tool.

o The DMHP in conjunction with the power management controller allows the engine to operate in a narrow range, thus providing the opportunity for maximum fuel economy and minimum emissions.

o The DMHP operation choices include running in full series, full parallel and engine-off modes allowing elimination of overnight hoteling and idling at stops, and thus further fuel economy savings and elimination of emissions.

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