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annual progress report

Vehicle and Systems Simulation and Testing

U.S. Department of Energy
Vehicle Technologies Program
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FY 2010

Annual Progress Report for

Vehicle and Systems Simulation and Testing

Submitted to:
U.S. Department of Energy
Energy Efficiency and Renewable Energy
Vehicle Technologies Program
Vehicle and Systems Simulation and Testing

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I. INTRODUCTION

On behalf of the U.S. Department of Energy's Vehicle Technologies Program (VTP), I am pleased to submit the Annual Progress Report for fiscal year 2010 for the Vehicle and Systems Simulation and Testing (VSST) team activities.

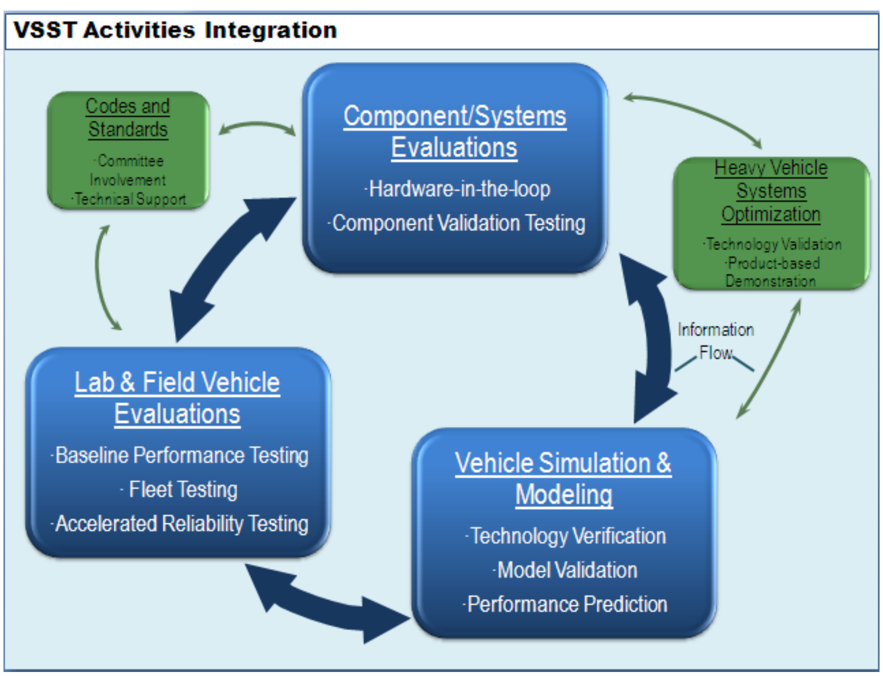
Mission

The VSST team's mission is to evaluate the technologies and performance characteristics of advanced automotive powertrain components and subsystems in an integrated vehicle systems context, covering light to heavy platforms. This work is directed toward evaluating and verifying the targets of the VTP R&D teams and to providing guidance in establishing roadmaps for achievement of these goals.

Objective

The prime objective of the VSST team activities is to evaluate VTP targets and associated data that will enable the VT R&D teams to focus research on specific technology areas. The areas of interest are technologies that will maximize the potential for fuel efficiency improvements, as well as petroleum displacement, and tailpipe emissions reduction. VSST accomplishes this objective through a tight union of computer modeling and simulation, integrated component testing and evaluation, laboratory and field testing of vehicles and systems, heavy vehicle systems optimization, and creation and validation of codes and standards. VSST also supports the VTP goals of fuel consumption reduction by developing and evaluating vehicle system technologies in the area of vehicle ancillary loads reduction.

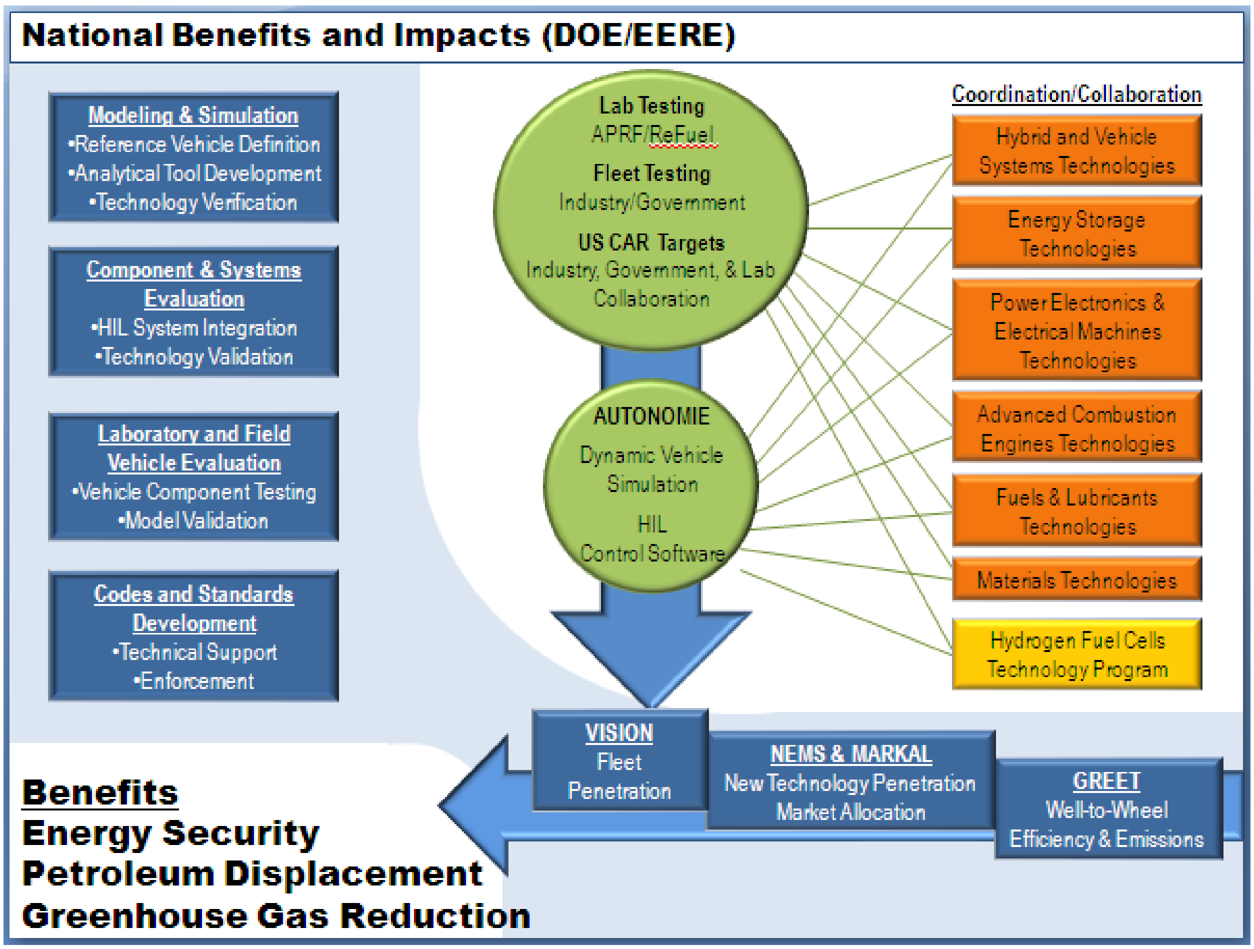
The integration of computer modeling and simulation, component and systems evaluations, laboratory and field vehicle evaluations, and development and validation of codes and standards for vehicle classes from light to heavy is critical to the success of the VSST team. Each respective area feeds important information back to the other, strengthening each aspect of the team. A graphical representation of this is shown in the figure below.



Integration of VSST computer modeling and testing activities

FY 2010 VSST Activities

VSST provides an overarching vehicle systems perspective in support of the technology R&D activities of DOE's VTP and Hydrogen Fuel Cells Technologies Program (HFCTP). VSST uses analytical and empirical tools to model and simulate potential vehicle systems, validate component performance in a systems context, verify and benchmark emerging technologies, and validate computer models. Hardware-in-the-loop testing allows components to be controlled in an emulated vehicle environment. Laboratory testing then provides measurement of progress toward VTP technical goals and eventual validation of DOE-sponsored technologies at the Advanced Powertrain Research Facility for light- and medium-duty vehicles and at the ReFUEL Facility for heavy-duty vehicles. For this sub-program to be successful, extensive collaboration with the technology development activities within the VTP and HFCITP is required for both analysis and testing. Analytical results of this sub-program are used to estimate national benefits and/or impacts of DOE-sponsored technology development, as illustrated in the figure below.



VSST activities providing estimates of national benefits and impacts of advanced technologies

VSST is comprised of the following five (5) main focus areas, each of which is described in detail in this report:

1. *Modeling and Simulation*

   DOE has developed and maintains software tools that support VTP research. VISION, NEMS, MARKAL, and GREET are used to forecast national-level energy, environmental, and economic parameters including oil use, market impacts, and greenhouse gas contributions of new technologies. These forecasts are based on VTP vehicle-level simulations that predict fuel economy and emissions using VSST's Autonomie modeling tool. Autonomie's simulation capabilities allow for accelerated development and introduction of advanced technologies through computer modeling rather than through expensive and time-consuming hardware building. Modeling and laboratory and field testing are closely coordinated to enhance and validate models as well as ensure that laboratory and field test procedures and protocols comprehend the needs of new technologies that may eventually be commercialized.

Autonomie is a MATLAB-based software environment and framework for automotive control system design, simulation and analysis. This platform enables dynamic analysis of vehicle performance and efficiency to support detailed design, hardware development, and validation. Autonomie was developed under a Cooperative Research and Development Agreement (CRADA) with General Motors and included substantial input from other original equipment manufacturers (OEMs), and replaces its predecessor, the Powertrain Systems Analysis Toolkit (PSAT). One of the primary benefits of Autonomie is its Plug-and-Play foundation which allows integration of models of various degrees of fidelity and abstraction from multiple engineering software environments, including GT-Power©, AMESim©, CarSim©, and AVL-DRIVE©. Autonomie enables the development, sharing, and rapid application of models, control algorithms and processes from the entire automotive community. Autonomie uses a unique Graphical User Interface (GUI) to simplify the integration and configuration process and accelerate the selection of models to be evaluated. This single powerful tool can be used throughout all the phases of Model Based Design of the Vehicle Development Process (VDP)

2. *Component and Systems Evaluation*

Hardware-in-the-loop (HIL) simulation provides a novel and cost effective approach to isolate and evaluate advanced automotive component and subsystem technologies while maintaining the rest of the system as a control. HIL allows actual hardware components to be tested in the laboratory at a full vehicle level without the extensive cost and lead time of building a complete prototype vehicle. This task integrates modeling and simulation with hardware in the laboratory to develop and evaluate propulsion subsystems in a full vehicle level context. The propulsion system hardware components: batteries, inverters, electric motors and controllers are further validated in simulated vehicle environments to ensure that they meet the vehicle performance targets established by the government-industry technical teams.

The versatile Mobile Automotive Technology Testbed (MATT) was developed in FY 2008. MATT serves as a unique HIL platform for advanced powertrain technology evaluation in an emulated vehicle environment. The flexible chassis testbed allows researchers to easily replace advanced components or change the architecture of the powertrain in various hybrid configurations. MATT was developed to assist DOE in validating advanced technology. MATT was utilized in FY 2010 in a collaborative effort between Argonne National Laboratory (ANL), Oak Ridge National Laboratory (ORNL), and the University of Tennessee to evaluate the impact of Hybrid control strategies on fuel economy and emissions, as detailed in the report entitled "PHEV Engine Control and Energy Management Strategy". As the need for oil independence intensifies, more pressure will be placed on the VTP to produce new technologies. As such, the need to evaluate newly developed technology in a vehicle system context will become critical. Through the FreedomCAR and Fuels Partnership Vehicle System Analysis Technical Team (VSATT), MATT facilitates interactions between each of the other technical teams by providing a common platform for component integration and testing. Each specific set of technical targets and their impacts on the vehicle and systems can easily be studied using the MATT platform.

High energy traction battery technology is important to the successful development of plug-in hybrid electric vehicles. In support of plug-in hybrid electrical vehicle (PHEV) research, Argonne National Laboratory (ANL) has developed and implemented a battery hardware-in-the-loop simulator to test potential battery packs in vehicle level operating conditions. Research continued in this area in FY 2010 as ANL used Autonomie and Battery Hardware in the loop (BHIL) to investigate energy management for fast battery temperature rise and engine efficiency improvement at very cold conditions.

3. *Laboratory and Field Vehicle Evaluation*

This section describes the activities related to laboratory validation and fleet testing of advanced propulsion subsystem technologies and advanced vehicles. In laboratory benchmarking, the objective is to extensively test production vehicle and component technology to ensure that VTP-developed technologies represent significant advances over technologies that have been developed by industry. Technology validation involves the testing of DOE-developed components or subsystems to evaluate the technology in the proper systems context. Validation helps to guide future VTP research and facilitates the setting of performance targets.

To date, over 130 PHEVs, HEVs, fuel cell vehicles, and propulsion subsystem components have been benchmarked or validated by the VSST team. The results of these evaluations have been used to identify needed areas of improvement for these advanced vehicles and technologies that will help bring them to market faster. They have also been used to identify the most promising new opportunities to achieve greater overall vehicle efficiencies at the lowest possible cost.

The major facility that supports these activities is the Advanced Powertrain Research Facility (APRF), a state-of-the-art automotive testing laboratory operated by ANL. The APRF is a multi-dynamometer facility for testing components (such as engines and electric motors) and a four-wheel vehicle dynamometer that allows accurate testing of all types of powertrain topologies. ANL utilizes its own correlation vehicle for test repeatability. This facility underwent an extensive upgrade in FY2010 to accommodate testing of BEVs, HEVs and PHEVs in temperatures as low as 20°F, up through 95°F. This upgrade also included installation of a solar load array system.

The Advanced Vehicle Testing Activity (AVTA), working with industry partners, conducts field and fleet testing to accurately measure real-world performance of advanced technology vehicles via a testing regime based on test procedures developed with input from industry and other stakeholders. The performance and capabilities of advanced technologies are benchmarked to support the development of industry and DOE technology targets. The testing results provide data for validating component, subsystem, and vehicle simulation models and hardware-in-the-loop testing. Fleet managers and the public use the test results for advanced technology vehicle acquisition decisions. Idaho National Laboratory (INL) conducts light-duty testing activities. In FY 2010, INL partnered with an industry group led by ECOtality North America. Accelerated reliability testing provides reliable benchmark data of the fuel economy, operations and maintenance requirements, general vehicle performance, engine and component (such as energy storage system) life, and life-cycle costs. These tests are described below.

<u>Baseline Performance Testing</u>

The objective of baseline performance testing is to provide a highly accurate snapshot of a vehicle's performance in a controlled testing environment. The testing is designed to be highly repeatable. Hence it is conducted on closed tracks and dynamometers, providing comparative testing results that allow "apples-to-apples" comparisons within respective vehicle technology classes. The APRF at ANL is utilized for the dynamometer testing of the vehicles.

<u>Fleet Testing</u>

Fleet testing provides a real-world balance to highly controlled baseline performance testing.

Some fleet managers prefer fleet testing results to the more controlled baseline performance or the accelerated reliability testing.

During fleet testing, a vehicle or group of vehicles is operated in normal fleet applications. Operating parameters such as fuel-use, operations and maintenance, costs/expenses, and all vehicle problems are documented. Fleet testing usually lasts one to three years and, depending on the vehicle technology, between 3,000 and 25,000 miles are accumulated on each vehicle.

For some vehicle technologies, fleet testing may be the only viable test method. Neighborhood electric vehicles (NEVs) are a good example. Their manufacturer-recommended charging practices often require up to 10 hours per charge cycle, while they operate at low speeds (<26 mph). This makes it nearly impossible to perform accelerated reliability testing on such vehicles.

<u>Accelerated Reliability Testing</u>
The objective of accelerated reliability testing is to quickly accumulate several years or an entire vehicle-life's worth of mileage on each test vehicle. The tests are generally conducted on public roads and highways, and testing usually lasts for up to 36 months per vehicle. The miles to be accumulated and time required depend heavily on the vehicle technology being tested. For instance, the accelerated reliability testing goal for PHEVs is to accumulate 5,400 miles per vehicle in 6 months. The testing goal for HEVs is to accumulate 160,000 miles per vehicle within three years, and for EVs is 12,000 miles within one year. This is several times greater than most HEVs will be driven in three years, but it is required to provide meaningful vehicle-life data within a useful time frame. Generally, two vehicles of each model are tested to ensure accuracy. Ideally, a larger sample size would be tested, but funding tradeoffs necessitate only testing two of each model to ensure accuracy.

Depending on the vehicle technology, a vehicle report is completed for each vehicle model for both fleet and accelerated reliability testing. However, because of the significant volume of data collected for the HEVs, fleet testing fact sheets (including accelerated reliability testing) and maintenance sheets are provided for the HEVs.

4. *Codes and Standards Development*

A comprehensive and consistent set of codes and standards addressing grid-connected vehicles and infrastructure is essential for the successful market introduction of electric-drive vehicles. The VTP is active in driving the development of these standards through committee involvement and technical support by the National Laboratories. The VTP also supports activities of the FreedomCAR and Fuels Partnership's Grid Interaction Tech Team (GITT), a government/industry partnership aimed at ensuring a smooth transition for vehicle electrification by closing technology gaps that exist in connecting vehicles to the electric grid. In FY2010, GITT worked with PNNL and ANL to participate in SAE and NIST standard development for connectivity and communication for grid-connected vehicles. The VTP also addressed the codes and standards for grid-connected vehicle charger permitting and installation process, electric drive vehicle components, and submetering communication devices for EVSE. Electric vehicles reach beyond national boundaries, so ANL was employed in international cooperative initiatives to adopt international electric drive vehicle standards and promote market penetration of grid-connected vehicles. Many new technologies require adaptations and more careful attention to specific procedures. VSST engineers have contributed to the development of many new standards and protocols, which have been presented to a wide audience such as FreedomCAR partners, other government agencies, and the European Commission, and are being adopted as industry standard.

Component modeling and simulation also require the use of internationally accepted test procedures and measurement methods. These testing standards must be applicable throughout the industry; therefore it is imperative that component/system interoperability be validated. In FY 2010, ANL provided technical data support and leadership to rewrite SAE J1711, the standard for measuring exhaust emissions and fuel economy for hybrid electric vehicle (HEC), which specifically addressed PHEVs. Codes and standards were also developed for sanctioned sporting regulations to stimulate rapid vehicle technology development and to educate consumers about the benefits of fuel efficient technologies. The Green Racing Initiative worked with the American Le Mans Series (ALMS) to strengthen and improve the visibility of the green racing program through the development of scoring protocols to support technology advancement through motorsports competition, promoting market acceptance of advanced vehicle technologies.

5. *Heavy Vehicle Systems Optimization*

This focus area involves research and development on a variety of mechanisms to improve the energy efficiency of heavy vehicles. Projects in this focus area involve reducing the aerodynamic drag of heavy vehicles by controlling the tractor-trailer flow field and tractor-trailer integration, thermal management approaches to increase the engine thermal efficiency and reduce parasitic energy uses and losses, and the development of advanced technologies to improve the fuel efficiency of critical engine and driveline components by characterizing the fundamental friction and wear mechanisms.

Aerodynamic Drag Reduction

The primary goal of this focus area is improving the freight-efficiency of heavy vehicles. Aerodynamic drag reduction, thermal management, and friction and wear are the main focuses of this area. Reduction of aerodynamic drag in Class 8 tractor-trailers can result in a significant improvement on fuel economy while satisfying regulatory and industry operational constraints. An important part of this effort is to expand and coordinate industry collaborations with DOE and establish buy-in through CRADAs and to accelerate the introduction of proven aerodynamic drag reduction devices into new vehicle offerings.

The primary approach in drag reduction is through the control of the tractor-trailer flow field and tractor-trailer integration. This will be achieved with geometry modifications, integration, and flow conditioning. These are essential components to develop and design the next generation of aerodynamically integrated tractor-trailer.

To accomplish this goal, Lawrence Livermore National Laboratory (LLNL) has established a unique team of experts from industry, university, and government laboratory and performed over 140 runs in a full-scale (80'x120') wind tunnel test at NFAC/NASA Ames research facility. A number of drag reducing aerodynamic devices/concepts are analyzed, including research and development of fairings to reduce the aerodynamic drag of tanker trailers in collaboration with Praxair. Three flow regions around the heavy vehicle are explored: trailer base, underbody, and tractor-trailer gap for application of drag reducing add-on devices. Many add-on devices are tested, with two different tractors (standard and long sleeper) and three different trailers (28', 53', and 53' drop frame) for their individual performance and in combination with other devices.

Thermal Management for Heavy Duty Vehicles

Thermal management of heavy vehicle engines and support systems is a technology area that addresses reduction in energy usage through improvements in engine thermal efficiency and reductions in parasitic energy uses and losses. Fuel consumption is directly related to the thermal efficiency of engines and support systems. New methods to reduce heat related losses are investigated and developed under this program. These technologies include, but are not limited to more efficient coolant materials, smaller radiators, and reduction of underhood thermal loads through more efficient auxiliary engine systems.

Thermal Management projects for FY 2010 were significantly reduced from previous years. FY 2010 focused on nucleated boiling in engine coolant for heavy duty trucks. It is well known that boiling heat transfer coefficients are much higher than the convective heat transfer coefficient of the same fluid. However, in order to use boiling for cooling a truck radiator, the critical heat flux (CHF) must be avoided or severe damage would occur. Hence, this program is designed to measure the heat transfer coefficient and CHF of several possible coolants, compare the results to theories, and transfer the data to industry. ANL investigated coolant boiling in a CRADA with PACCAR to design engines to take advantage of operation just below the CHF under realistic conditions.

Friction and Wear for Heavy Duty Vehicles

Parasitic engine and driveline energy losses arising from boundary friction and viscous losses consume 10 to 15 percent of fuel used in transportation, and thus engines and driveline components are being redesigned to incorporate low-friction technologies to increase fuel efficiency of passenger and heavy-duty vehicles. The Friction and Wear Project, within the Heavy Vehicle Systems Optimization Program, supports research agreements/projects that focus on the development of advanced technologies required to improve the fuel efficiency and reliability of critical engine and driveline components, notably:

- Activities to experimentally investigate fundamental friction and wear mechanisms to provide the understanding required for developing advanced low-friction, fuel-efficient technologies.
- Activities to model and validate, component-by-component, the impact of friction on overall vehicle efficiency.

Activities to develop advanced low friction technologies (materials, coatings, engineered surfaces, and advanced lubricants) required to improve engine and driveline efficiency and reliability/durability.

Boundary Layer Lubrication

Researchers at ANL have made significant progress on the development of tools to model the scuffing phenomena and the formation of protective tribofilms. In the first task, material pairs with a high CSI (contact severity index – a measure of resistance to scuffing) were evaluated. The mechanisms for scuffing in these material pairs were elucidated, providing a pathway for further improvement in scuffing resistance. The development of materials with enhanced scuffing resistance will facilitate the development of high-power-density components and systems. The second task involved characterization of low-friction boundary films produced from a model lubricant and fully formulated lubricant. Post-test analysis of the films by SEM, EDX, and FIB is ongoing. These analyses will provide information on the thickness, composition, and structure of highly desirable low-friction boundary films.

ANL tested lubricated surfaces to determine basic mechanisms of catastrophic failure in material behavior to facilitate the design of higher power density components and systems. This task also investigated the basic mechanisms of chemical boundary lubrication to facilitate lubricant and surface design for minimum frictional properties. These accomplishments allowed ANL to establish methodologies for predicting the performance and failure of lubricated components and systems. Future steps will validate this prediction for integrating into diesel engines and vehicle components and systems.

Parasitic Energy Losses

At ANL, researchers continued to use computer simulations of parasitic energy losses in diesel engines to guide fundamental research on low friction coatings and additive treatments. Work is underway to experimentally validate the models through tests that were developed using prototypic components to evaluate the impact of lubrication additives on the friction between the piston skirt and cylinder liner.

Major projects that were conducted by the national laboratories in support of these areas in FY 2010 are described in this report. A summary of the major activities in each area is given first, followed by detailed reports on the approach, accomplishments and future directions for the projects. For further information, please contact the DOE Project Leader named for each project.

Future Directions for VSST

Near-term solutions for reducing the nation's dependence on imported oil, such as PHEVs, will require the development, integration, and control of vehicle components, subsystems, and support systems. These solutions will require exploration of high capacity energy storage and propulsion system combinations to get the most out of hybrid propulsion. Analysis and testing procedures at the national labs will be enhanced to study these advanced powertrains with simulation tools, component/subsystem integration, and hardware-in-the-loop testing. DOE-sponsored hardware developments will be validated at the vehicle level, using a combination of testing and simulation procedures.

In FY 2011, the VSST will continue to expand activities in the area of PHEV simulation and modeling including further baseline performance testing of conversion and original equipment manufacturer (OEM) PHEVs, and validation of simulation models for PHEVs tested in the newly-upgraded APRF. Field and laboratory testing will continue to be integrated with modeling/simulation tools. Fleet evaluation of PHEV conversion vehicles will continue, with continued emphasis on evaluation fleets of OEM production PHEVs. In FY 2008, DOE VT issued a solicitation for the purpose of establishing a PHEV demonstration fleet consisting of large volume manufacturers and OEMs as participants. This program launched in FY 2009, continued in FY 2010, and is scheduled to conclude in FY 2011.

In addition to the HEV and PHEV activities, a full range of simulation and evaluation activities will be conducted on the Battery Electric Vehicles (EV) as they are brought to market by OEMs. Because EVs are dependent on a robust charging infrastructure for their operation and ultimate consumer acceptance, the VSST will greatly increase efforts to address issues related to codes and standards for EVs, charging infrastructure, and vehicle/grid integration. This will be accomplished by leading and participating in committees that develop standards including SAE J1772 for connector standards, SAE J2847 for communication standards, and SAE J2953 for Electric-Vehicle Supply Equipment-Vehicle Compatibility. Technical support tasks will also continue to validate SAE J1711 for PHEV test procedures, which was submitted in FY 2010.

VSST will also be deeply involved in the collection and analysis of data from the American Recovery and Reinvestment Act of 2009 (ARRA) Transportation Electrification Demonstration projects. These eight demonstrations will place more than 12,000 electric drive vehicles and 25,000 recharging sites in service throughout 2011 and the VSST will direct the collection and analysis of data from these units. In addition to performance, reliability, and petroleum displacement results, VSST will utilize the data to determine the impact of concentrations of electric dive vehicles on the electricity grid, as well as the changes in operators driving and recharging patterns as they become more comfortable with this new technology.

Heavy vehicle systems optimization work in the areas of aerodynamics, thermal management, and friction and wear will continue with several new projects in thermal control and friction and wear. The focus of these activities will continue to revolve around cooperative projects with industry partners in an attempt to bring developed technologies to market quickly. New efforts to conduct evaluations of methods to improve thermal heat transfer efficiencies through the use of active radiator airside cooling techniques and varying locations will attempt to partner with truck and/or radiator manufacturers. VSST will also add projects to develop high power density drivelines to improve overall vehicle efficiencies in collaboration with a testing company to bridge tribology and application.

In order to develop an accurate vehicle cost model for passenger vehicles, VSST identified market costs for technology combinations for new, emerging, and existing light vehicle fuel economy-improving technologies in FY 2010, which will continue and be validated in FY 2011. VSST technologies for advanced power electronics, energy storage, and combustion engines will continue to be validated as each technology closes in on energy efficiency targets.

Inquiries regarding the VSST activities may be directed to the undersigned.

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II. AMERICAN RECOVERY and REINVESTMENT ACT PROJECTS

The economic stimulus packaged enacted as a result of the American Recovery and Reinvestment Act of 2009 (ARRA) provided $400M to fund projects under the Transportation Electrification initiative, aimed at accelerating the development and deployment of advanced electric-drive vehicles and the necessary infrastructure to support them. The Vehicle and Systems Simulation and Testing team was heavily involved in the management and execution of the transportation electrification demonstration activities in 2010 under this initiative. DOE has teamed up with eight OEMs as a result of this funding to deploy these electrification demonstration projects. A brief summary of each project can be found below.

A. ECOtality North America

Objective

Ecotality North America is a leader in research, development, and testing of advanced transportation. It has teamed up with DOE to establish a charging infrastructure and collect comprehensive operational data to evaluate the influences on vehicle and charging infrastructure use, performance, and location suitability.

Description

- Deployment of 14,850 Level 2 Charging Stations, plus 320 DC "Fast Chargers", in 8 major metropolitan areas (Phoenix/Tucson, Portland, Seattle, San Diego, Los Angeles, Houston/Dallas, Nashville/Chattanooga/Knoxville, Washington DC)
- Demonstration of 5,700 Nissan Leaf EVs and 2,600 Chevy Volt E-REVs
- Full instrumentation of vehicles and infrastructure for comprehensive data-collection and analysis effort
- Charger / vehicle deployment begins mid-December 2010, scheduled to be complete in December 2011

Impact

Upon implementation, this project will aid in accelerating the deployment of electric vehicles, which will result in mitigation of green house gases as a result of reduction in gasoline usage. The US would also reap energy and security benefits from lessening our current dependence on foreign oil. Other benefits also include the creation of green jobs in manufacturing, data analysis, and infrastructure development and deployment.

B. Coulomb Technologies

Objective

The objective of this project is to collect data on vehicle use and charging patterns for analysis by Idaho National Laboratory.

Description

- Deployment of approximately 4,600 public and private charging stations in 9 U.S. Cities (Bellevue/Redmond WA, San Francisco, Sacramento, Los Angeles, Austin, Orlando, New York, Detroit, Washington DC)
- Locations will be coordinated with deployment of 2,600 grid connected vehicles from GM (Chevrolet Volt), Ford (Transit Connect EV), and smart USA
- Approximately 30 EVSEs have been deployed, and full deployment is scheduled to complete in June 2011

Impact

Results from this partnership between DOE and Coulomb Technologies will allow for insight into communications between the grid and the electric vehicle supply equipment, as well as among the charging stations themselves. This will provide greater knowledge in effective energy usage and storage during peak and off-peak times. This allows for the development of an optimized charging infrastructure to use the energy resources in the most efficient manner possible.

C. Chrysler, LLC

Objective

Chrysler will develop, validate, and deploy 110 advanced plug-in hybrid electric Dodge Ram pickup trucks manufactured in Warren, MI. These vehicles will be deployed through eleven partner fleets representing a range of geographic, climatic, and operating environments.

Description

- Development, validation, and deployment of 153 PHEV Dodge Ram pickups
- Deployment of vehicles and charging infrastructure through 11 partner fleets across a wide range of geographic, climatic, and operating environments
- Chrysler has partnered with Electrovaya for the 12.9 kWh battery, which will be charged through an on-board 6.6 kW charger
- Results of study will be used by Chrysler to understand consumer needs and refine PHEV requirements to enable volume production
- Built off of the existing Dodge Ram Hybrid platform, deployment of the PHEV is scheduled to begin before May 2011

Impact

The results from this project will allow for the development of improved PHEV technology. As a result, reduced gas consumption will lessen foreign oil dependence, create domestic jobs, and boost the sales of Chrysler and other US parts manufacturers that contribute to these vehicles.

D. Navistar, Inc.

Objective

Navistar will develop and deploy a line of light- and medium-duty battery-electric trucks, manufactured in Elkhart, IN. The initial deployment of 400 trucks will be Class 3 (12,100 lb GVWR) vehicles with a 100-mile range, 8-hour charge time, and a top speed of 50mph. These vehicles will be deployed in Portland, OR, Chicago, IL, and Sacramento, CA.

Description

- Develop, validate, deploy 950 advanced Battery Electric delivery trucks (12,100 lbs GVWR) with a 100-mile range
- Manufacturing in Elkhard Co., IN; Deployment in Portland, Chicago, and Sacramento
- Vehicles are currently being deployed, with full deployment scheduled for June 2011

Impact

Increasing efficiency of light-and medium-duty trucks, especially those used as fleet vehicles, has the capability to have a large impact on US oil consumption. Gasoline costs for fleet vehicles make up a large percentage of overhead costs for delivery vehicles, so reductions in fuel use will eventually lead to savings for the consumer. These gasoline savings will also lead to cleaner air and less dependence on foreign oil.

E. South Coast Air Quality Management District (SCAQMD)

Objective

SCAQMD will develop a fully integrated production plug-in hybrid electric propulsion system for Class 2-5 vehicles (8,501 – 19,500 lbs GVWR). A demonstration of fleet of 378 vehicles will be deployed through 50 fleet/utility partners nationwide. The demonstration fleet will consist of trucks based on the Ford F-550 chassis, utilizing an Eaton PHEV system with an A123 energy storage system, as well as shuttle buses based on the Ford E-450 chassis incorporating an electric-drive system from Azure Dynamics. The trucks will be manufactured in Galesburg, MI, while the shuttle buses will be made in Elizabethtown, KY. Charging infrastructure will be deployed in conjunction with the demonstration fleet.

Description

Development of a fully integrated, production PHEV system for Class 2-5 vehicles (8,501-19,500 lbs GVWR).

Demonstration of 378 trucks and shuttle buses through a nationwide network of 50 partner fleets

Vehicles will include:

- Electric utility "trouble trucks" based on Ford F-550, utilizing an Eaton-based PHEV system and 6.7L diesel engine
- Shuttle busses based on Ford F-450, utilizing an Azure Dynamics PHEV system and 5.4L gasoline engine

Impact

The US stands to reap economic benefits from this project in job creation in green manufacturing in economically depressed areas. The result of transitioning to electric vehicles will also yield environmental benefits in mitigating green house gas emissions in areas that traditionally have had air quality issues. Additionally, energy benefits resulting from this project include reduction of oil usage without disrupting established routes and routines.

F. Cascade Sierra Solutions

Objective

Cascade Sierra Solutions will deploy truck-stop electrification infrastructure at 50 sites along major U.S. interstate corridors. Furthermore, the program will provide 5,450 rebates for 50% of the cost to implement idle-reduction technologies in Class 8 trucks. Such technologies include electric auxiliary power units, electric evaporative coolers, battery-powered cab comfort systems, and engine heat recovery systems.

Description

Deployment of truck stop electrification infrastructure at 50 sites along major US interstate corridors

Provision for 5,450 rebates of 25% of the cost for truck modification to incorporate idle reduction technologies

Impact

Tractor trailer idling contributes to air pollution, noise pollution, and is a significant source of fuel usage. Since about 70% of the total freight in the US is transported via tractor-trailer, and trends show that this number will continue to rise, idle-reducing technologies have the potential to significantly reduce harmful emissions. The reduced cost for implementing such idle-reduction systems will encourage trucking companies to invest in these technologies, which will also yield an economic benefit for such manufacturing companies.

G. Smith Electric Vehicles

Objective

Smith Electric Vehicles will develop and deploy up to 100 electric "Newton" medium-duty delivery trucks across a range of commercial and public-sector markets in diverse geographic and climatic environments. These vehicles will be manufactured in Kansas City, MO. Furthermore, the project will involve the collection and analysis of real-world performance data using an automatic GPS-based telemetry system provided by partner AT&T. Data analysis and reporting efforts will be handled by Missouri Institute of Science and Technology.

Description

- Develop and deploy up to 500 medium-duty electric trucks.
- Manufacturing in Kansas City, MO; Deployment in conjunction with 20 launch partners representing a range of commercial and public sector markets, geographies, and climates
- Vehicles are currently being deployed, with full deployment scheduled for October 2011

Impact

The benefit of establishing these all-electric fleets will advance domestic capabilities for electric vehicle production, which are environmentally friendly, and employ the US workforce. These more efficient fleets will reduce the carbon footprint, create jobs, and enable the electric vehicle industry to analyze and determine ease of market entrance for these electric vehicles.

H. General Motors Corporation

Objective

General Motors will develop, demonstrate, and analyze a fleet of 115 Chevrolet Volt Extended-Range Electric Vehicles (EREVs) deployed through ten electric utility partners' fleets. The project also includes the installation of hundreds of electric charging stations covering home, workplace, and public locations. Vehicle data will be collected and transmitted through the existing OnStar network for analysis by Idaho National Laboratory.

Description

- Development, demonstration, and analysis of 115 Chevy Volt EREVs through electric utility partner fleets
- Project includes the installation of approximately 650 EVSEs in home, workplace, and public locations; Smart Charging and DC Fast Charging will also be demonstrated
- Data will collected through GM's OnStar network and transferred to Idaho National Lab for analysis
- As of October 21, 2010, 43 DOE program vehicles have been entered into GM's captured test fleet, as well as 105 charging stations
- Data collection will begin in November 2010, with vehicles delivered to customers in December

Impact

GM's Chevrolet Volt is one leading the introduction of electric vehicles to the US market. Its support of the energy efficient vehicle accelerates the acceptance of electric vehicles. Widespread use of the electric vehicle will create green jobs in manufacturing for the vehicle, charging stations, and infrastructure development.

III. LABORATORY AND FIELD TESTING (LIGHT DUTY)

A. Plug-in Hybrid Electric Vehicle Testing by DOE's Advanced Vehicle Testing Activity (AVTA)

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Objective

- Benchmark the plug-in hybrid electric vehicle (PHEV) technology concept to determine the contribution PHEV technologies can have to significantly reduce petroleum consumption in the United States.
- Benchmark individual PHEV models from original equipment manufacturers (OEMs).
- Reduce the uncertainties about PHEV performance and PHEV battery performance and life.
- Reduce the uncertainties about drivers' recharging practices and PHEV acceptance.
- Provide PHEV testing results to vehicle modelers and designers, technology target setters, industry stakeholders, and DOE, as well as fleet managers and the general public to support their PHEV acquisition and deployment decisions.

Approach

- Document via various testing methods the fuel (petroleum and electricity) use over various trip types and distances.
- Report petroleum and electricity use separately.
- Document PHEV charger performance (profile and demand), charging times, and infrastructure needs, as well as operator behavior impact on charging times and frequencies.
- Document environmental factors, such as temperature and terrain, that impact PHEV fuel consumption.
- Use PHEV testing specifications and procedures developed by the AVTA that are reviewed by industry, national laboratories, and other interested stakeholders.
- Obtain PHEVs for testing to the reviewed PHEV testing specifications and procedures.
- Perform baseline performance track and laboratory tests, accelerated on-road tests, and fleet demonstrations on PHEVs.
- Place PHEVs in environmentally and geographically diverse test fleets.
- Continue to use and develop cost-shared partnerships with public, private, and regional groups to test, deploy, and demonstrate PHEVs and infrastructure technologies in order to highly leverage DOE funding resources with the Advanced Vehicle Testing Activity's (AVTA) 90+ PHEV testing partners.
- Expand the use of automated data collection, analysis, and reporting processes.
- Reach additional cooperative research and development agreements (CRADA) and non-disclosure agreements (NDA) in preparation for the testing of PHEVs from additional OEMs.

Accomplishments

- Completed a cooperative research and development agreement (CRADA) with Ford Motor Company to cover the data collection from 22 Ford Escape PHEVs

- Initiated the placement of a NDA with General Motors/OnStar for the development of data collection from approximately 150 Volts extended range electric vehicles (EREVs).
- Initiated the placement of a NDA with Chrysler for the development of data collection from 145 Ram Pickup PHEVs.
- Initiated the placement of a NDA with ECOtality North America for the development of data collection from 15,350 Level 2 electric vehicle supply equipment and fast chargers, 5,700 Nissan Leaf electric vehicles (EVs), and 2,600 General Motors Volt EREVs.
- Initiated the placement of a NDA with Coulomb for the development of data collection from 4,000 Level 2 electric vehicle supply equipment.
- Continued testing PHEVs in fleet operations and demonstrations with 2.6 million total PHEV test miles reached in fiscal year (FY) 2010.
- Initiated the study of codes and standards requirements necessary to support the potential introduction of vehicle to grid charging in 12 U.S. cities. This is being conducted in cooperation with Ford Motor Company.
- Initiated the development of a workshop to access the current needs for codes and standards to support grid-connected vehicle charging, for light-, medium-, and heavy-duty vehicles. This is being conducted in partnership with the American National Standards Institute (ANSI).
- Initiated the development of an emerging vehicle technology cost impacts model to comply with the Government Performance and Results Act (GPRA).
- Completed real-time (not modeled) instrumentation and data collection of PHEV demand and energy costs at Tacoma Power, in Tacoma Washington.
- Obtained and tested a cumulative total of 267 PHEVs representing 12 PHEV models (by battery chemistry and manufacturer and vehicle model) at the end of FY 2010.
- Tested PHEVs with lithium batteries from ten manufactures and non-lithium batteries (lead and NiCad) from two manufacturers.
- Conducted cooperative PHEV testing with more than 90 organizations that provided testing access to PHEVs operating in diverse demonstration fleets that ranged from Finland and Canada to Hawaii and 24 other states. The testing partners include, but are not limited to: A123Systems, EnergyCS, University of California at Davis, Ohio State University, University of Hawaii, Google, Austin Energy, Central Vermont Public Service Company, Duke Energy, Advanced Energy, Salem Electric, Progress Energy, Portland Gas and Electric, Pacific Gas and Electric, San Diego Gas and Electric, Basin Electric, Buckeye Power, Wisconsin Public Power, Madison General Electric, Reliant Energy, SCANA Energy, Hawaii Center for Advanced Transportation Technologies, State of Hawaii, Hawaii Electric, Maui Electric, BC Hydro, Government of British Columbia, City of Seattle, Tacoma Power, Port of Chelan, Port of Seattle, Puget Sound Clean Air Agency, City of Wenatchee, King County, Fairfax County, Benton County, Chelan County, Douglas County, several Canadian Universities and government agencies, National Rural Cooperative Association, and the New York State Energy Research Development Agency.
- Conducted geographically and mission-diverse PHEV testing and demonstration activities in 25 states, three Canadian provinces, and Finland. The 25 U.S. states include: Arizona, California, Connecticut, District of Columbia, Florida, Georgia, Hawaii, Illinois, Iowa, Kentucky, Maryland, Michigan, Minnesota, New York, North Carolina, North Dakota, Ohio, Oregon, South Carolina, Tennessee, Texas, Vermont, Virginia, Washington, and Wisconsin.
- Developed a three-page PHEV reporting format fact sheet generated from a PHEV database.
- Sent more than 3,000 unique PHEV testing results fact sheets to the AVTA's fleet testing partners.
- Continued to operate in a highly leveraged manner, with DOE only purchasing two of the 267 PHEVs in the AVTA data collection and demonstration fleet.
- Completed and presented 26 formal reports and industry presentations on PHEV operations and petroleum reductions to outside groups.
- Gave another 10 presentations on PHEV performance to Idaho National Laboratory (INL) site visitors and dignitaries
- Performed due diligence on other PHEV models to determine their suitability as test candidates.

Future Activities

- Complete the development of the data collection process from 22 Ford Escape PHEVs and report the petroleum reduction capabilities and operations of the same vehicles.
- Complete the NDA process with Chrysler and the development of the data collection process for the 145 Chrysler Ram Pickup Trucks and report the petroleum reduction capabilities and operations of the same vehicles.
- Complete the NDA process with General Motors/OnStar and the development of the data collection process for approximately 150 Chevrolet Volts EREVs and report the petroleum reduction capabilities and operations of thosevehicles.
- Complete the NDA process with Ecotality N.A. and the development of the data collection process for approximately 15,350 EVSE and fast chargers, as well as 8,300 Nissan Leafs and Chevrolet Volts and report the petroleum reduction capabilities and operations of the same vehicles, as well as charging infrastructure utilization patterns.
- Hold the codes and standards grid-connected vehicle workshop in the spring of 2011 and report out the results.
- Continue performing due diligence on potential PHEV suppliers and obtain PHEVs for testing as appropriate.
- Identify additional PHEV models (approximately 10 to 12 models) that will be added to the fleet demonstrations in FY 2011.
- Complete a PHEV codes and standards review and report on the regulations, standards and codes related to the charging and discharging of electric drive vehicles from and to the electric grid based on current practices in 12 U.S. cities.
- Complete the development of an emerging vehicle technology cost impacts model to comply with the Government Performance and Results Act (GPRA).
-
- Develop additional low-cost PHEV demonstration relationships and support the deployment of PHEVs in these testing fleets.
- Continue to coordinate PHEV and charging infrastructure testing with industry and other DOE directed entities.

Background

The U.S. Department of Energy's (DOE's) Advanced Vehicle Testing (AVTA) is part of DOE's Vehicle Technologies Program (VTP), which is within DOE's Office of Energy Efficiency and Renewable Energy (EERE). The AVTA is the only DOE activity tasked to conduct field evaluations of vehicle technologies that use advanced technology systems and subsystems in light-duty vehicles to reduce petroleum consumption. Most of these advanced technologies include the use of advanced electric drive propulsion systems and advanced energy storage systems. However, other vehicle technologies that employ advanced designs, control systems, or other advanced technologies with production potential and significant petroleum reduction potential are also considered viable candidates for testing by the ATVA.

The AVTA is conducted by the Idaho National Laboratory (INL) for DOE. INL has responsibility for the AVTA's execution, direction, management, and reporting, as well as data collection, analysis and test reporting. The INL is supported in this role by the private sector company ECOtality North America. ECOtality's competitively awarded contract is managed by DOE's National Energy Technology Laboratory (NETL). Unless otherwise specifically called out, this and the following Operational and Fleet Testing sections of the FY 2010 Annual Program Report jointly cover the testing work performed by INL and ECOtality for the AVTA. In addition, when appropriate, the AVTA also partners with other governmental, public, and private sector organizations to provide maximum testing and economic value to DOE and the United States taxpayers, via various cost sharing agreements.

Introduction

DOE's AVTA is evaluating PHEV technology in order to understand the capability of the technology to significantly reduce petroleum consumption when PHEVs are used for personal transportation. In addition, many companies and groups are proposing, planning, and have started to introduce PHEVs into their fleets. During FY10, most of the test PHEVs were obtained from local PHEV conversion shops and sometimes at local colleges with automotive education programs. The primary focus during FY10 was to study the PHEV technology's potential contribution to petroleum reduction, and to understand and document charging patterns. The drive to focus on the overall petroleum reduction potential of PHEV technology versus testing individual PHEV conversion models was driven by the mostly conversion nature of the available PHEVs during FY10, and the non-likelihood that the conversion vehicles would be the majority of PHEV deployments in future years.

The PHEVs available for public purchase during FY10 used an HEV as the base vehicle, and either added a second PHEV battery or replaced the base HEV battery with a larger PHEV battery pack, with a 5-kWh PHEV battery size the most typical size to date. However, some PHEVs used a single PHEV battery pack that ranged from 10 to 15 kWh. PHEV control systems and power electronics are also added to the base vehicle to complete the upgrade. These larger additional or replacement battery packs are sometimes recharged by the onboard regenerative braking and generator subsystems, but all of them must also use onboard chargers connected to the off-board electric grid to fully recharge the PHEV battery packs.

In addition to the battery and control system upgrades, PHEVs in the AVTA test and demonstration fleet also have onboard data loggers installed when the vehicles are converted, or when they enter the AVTA demonstration fleet. Experience has shown that wireless and automated data collection in fleet environments is the only way to ensure accurate data is collected.

The concept of additional onboard energy storage and grid-connected charging raises issues that include the life and performance of these larger batteries; the charging infrastructure required; how often the vehicles will actually be charged; and the actual amount of petroleum displaced over various missions, drive cycles, and drive distances.

Approach

The AVTA supports the introduction of PHEVs by testing the emerging group of PHEV models and documenting vehicle and battery performances, as well as electricity and petroleum use in cost-shared agreements with the AVTA's fleet testing partners.

As a first step, the AVTA developed a 400-page test plan for inspection, dynamometer, test track, accelerated, and fleet testing of PHEVs. A total of twelve PHEV models have been obtained and tested in various demonstrations and missions, with additional candidate test PHEVs being considered for testing.

The AVTA signed testing, demonstration, and data collection agreements with several additional non-DOE fleets that operate PHEVs. AVTA will collect performance and charging data to characterize the performance of the PHEVs and the charging infrastructure.

The AVTA initiated a review of the codes and standards required to support the conduct of a study to examine governmental regulations and building code requirements impacting the introduction and use of vehicles with vehicle-to-grid (V2G) capability in order to develop a common set of regulations, standards and building codes that would apply in broad geographic areas that would allow widespread use of V2G vehicles. In addition, the regulations, standards and building codes requiring modification to allow for a single national regulatory framework will also be identified. This work is being coordinated with Ford Motor Company.

The AVTA initiated the development of a comprehensive workshop to assess the codes and standards status and needs to facilitate the successful introduction, and wide-spread acceptance and deployment of light-, medium-, and heavy-duty onroad electric drive vehicles (EDVs) that must be connected to the electric grid for recharging of their propulsion energy storage systems (which in most cases will be batteries). This work is being performed in coordination with the American National Standards Institute (ANSI).

The AVTA initiated the collection of data generated by onboard data loggers from 22 Ford Escape PHEVs, 145 Chrysler Ram Pickup PHEVs, and approximately 150 Chevrolet Volt extended range electric vehicles (EREVs). These are being conducted in partnerships with the respective OEMs. The AVTA initiated the collection of data from 15,300 EVSE and fast chargers, and 8,300 Nissan Leafs and Chevrolet Volts in a partnership project with ECOtality. Finally, the AVTA initiated the collection of data from 4,000 Level EVSE in a partnership with Coulomb.

PHEV Testing Methods

Three types of testing methods are used to test PHEVs and they discussed below.

Baseline performance testing

Baseline performance testing during which a PHEV model is track and dynamometer tested. The track testing includes acceleration, braking, and fuel use (both electricity and gasoline) at different states-of-charge. The PHEV model is also coast-down tested to determine dynamometer coefficients, which are used during the urban and highway dynamometer test cycles. Normally, the AVTA would have tested several PHEVs during FY 2010. However, all of the PHEV conversions were baseline performance tested during previous years, and the new PHEVs from original equipment manufacturers (OEMs) will not be available until FY 2011. Note that the AVTA PHEV dynamometer testing was conducted by Argonne National Laboratory.

Accelerated Testing

Accelerated Testing uses dedicated drivers to complete a series of drives and charges on city and highway streets in the Phoenix, AZ area (Table 1). Note that between each individual 10 to 200 mile drive, the PHEVs are charged from 4 to 12 hours. All of the PHEV conversions were accelerated tested prior to FY 2010 and the OEM PHEVs will not be tested until FY 2011.

Table 1. PHEV accelerated testing distances.

Cycle (mi)	Urban (10 mi)	Highway (10 mi)	Charge (hours)	Repe-titions (N)	Total (mi)	Repe-titions (%)	Miles (%)	Cumula-tive (mi)
10	1	0	4	60	600	37%	11%	600
20	1	1	8	30	600	19%	11%	1,200
40	4	0	12	15	600	9%	11%	1,800
40	2	2	12	15	600	9%	11%	2,400
40	0	4	12	15	600	9%	11%	3,000
60	2	4	12	10	600	6%	11%	3,600
80	2	6	12	8	640	5%	12%	4,240
100	2	8	12	6	600	4%	11%	4,840
200	2	18	12	3	600	2%	11%	5,440
Total	2,340	3,100	1,344	162	5,440			5,440
Avg.	43%	57%	8.3	18.0				

Fleet Testing

Fleet testing is normally conducted by PHEVs operating in fleets with no predefined structure to repeatable testing. The AVTA partners with government, private, and public fleets for PHEV fleet testing, as these fleets are overwhelmingly the earliest adaptors of PHEVs. Note that the AVTA fleet testing does include some operations by the general public, primarily through a partnership with the University of California, Davis. A total of 267 PHEVs were tested by AVTA by the end of FY 2010; the fleet testing results are discussed below.

The twelve PHEVs that were tested by the AVTA to date are listed below. Only one PHEV, the Renault Kango, completed testing prior to FY 2010. The PHEV models include:

Ford Escape E85 PHEV (from Ford), with a Johnson Controls / Saft (JCS) lithium battery pack.

Toyota Prius converted by EnergyCS, with a Valance lithium battery pack.

Toyota Prius converted by EnergyCS, with an Altair Nano lithium battery pack.

Toyota Prius converted by Hymotion, with an A123Systems lithium pack.

Ford Escape converted by Hymotion, with an A123Systems lithium battery pack.

Ford Escape converted by Electrovaya, with an Electrovaya lithium battery pack.

Ford Escape converted by Hybrids Plus, with a Hybrids Plus lithium battery pack.

Ford Escape converted by Hybrids Plus, with a K2 Energy Solutions lithium battery pack.

Toyota Prius converted by Hybrids Plus, with a lithium battery pack.

Renault Kangoo with a Nickel Cadmium battery pack.

Toyota Prius converted by Manzanita with a Thunder Sky lithium battery pack.

Toyota Prius converted by Manzanita with a lead acid battery pack.

Fleet Testing Results

As of the end of FY 2010, there were approximately 1,500 PHEVs operating in North America and most of these were in the United States. In order to collect data on PHEVs in fleet operations, at the beginning of FY 2008, AVTA partnered with the two PHEV conversion companies that had performed the most PHEV conversions to date. By the end of FY 2010, AVTA has partnered with more than 90 organizations in the United States, Canada, and Finland (Figure 1). The mix of organizations includes:

38 electric utilities (includes the National Rural Electric Cooperative Association)

9 city governments

10 county governments

4 state governments

10 universities and colleges

2 clean air agencies

5 private companies and advocacy organizations

10 governments of Canadian provinces

3 sea ports and U.S. military organizations

1 Finnish research centers

2 PHEV conversion companies.

The 90 PHEV fleet testing partners have operated 267 PHEVs in 25 states, three Canadian provinces, and Finland as of the end of FY 2010. Note that the AVTA has only purchased two of the 267 PHEVs, making this a highly leveraged testing activity that benefits both DOE and the United States taxpayer. Initially, AVTA provided some cost-sharing for the data loggers, but going forward, all data logger, base vehicle, and conversion costs are incurred by the fleets.

The benefit to the vehicle operators in participating in the AVTA PHEV Demonstration is the three-page PHEV fact sheet the AVTA provides to each participant on a monthly basis. The format and content are discussed below. This type of value-for-value arrangement allows AVTA to operate in a highly funding-leveraged manner, again providing maximum benefit both to DOE and the taxpayer.

The initial 53 vehicles in the test fleet used Kvaser data loggers, which by design include a data logger and a memory card that must be physically removed from the data logger and then either physically mailed to INL or uploaded to INL via the Internet. An additional 184 fleet PHEVs have been added to the PHEV data collection fleet that use GridPoint (formally V2Green) onboard data loggers, GPS units, and cellular communications. The advantage of the GridPoint wireless data collection communication system is significantly increased data collection accuracy and timeliness. There are also a few dozen other non-Kvaser and non-GridPoint data collection devices being used.

About 228 of the 267 PHEVs are Hymotion PHEV conversions of Toyota Prius HEVs; an additional twelve are EnergyCS conversions of Toyota Prius HEVs; and approximately 10 more are Hybrids Plus conversions of Prius and Ford Escape HEVs. The remaining PHEVs are a mixture of a couple of lead acid PHEV conversions or a couple of Hymotion Escape conversions. The heavy concentration of Hymotion Prius PHEVs reflects the fact that 75% or more of all PHEVs in North America are Hymotion

Prius conversions, thus the AVTA's testing partners are mostly operating the Hymotion Prius PHEV conversions. While it is not necessarily desirable to be collecting PHEV data from a single PHEV conversion company model, using the large number of Hymotion Prius PHEVs does allow for data collection in very diverse fleets in very diverse operating and environmental areas.

The first AVTA PHEV test fleet was in the Seattle and Tacoma area of Washington State, with 15 PHEVs in the fleets of:

- City of Seattle / Seattle City Light
- King County
- Port of Seattle
- Puget Sound Clean Air Agency
- Tacoma Power.

Another AVTA PHEV Washington State demonstration of 14 PHEVs is lead by the Port of Chelan. The University of California at Davis has more than a dozen PHEVs in a test fleet with nearly 100 public drivers that are providing data to the AVTA. The State of California's General Services Administration (CA-GSA) acquired approximately 50 Hymotion Prius conversions during FY 2010. The AVTA was contacted by CA-GSA who requested that their 50 PHEVs be allowed to participate in the AVTA's PHEV demonstration.

The CA-GSA fleet has been the largest single fleet of PHEVs that the AVTA has collected data from to date. The government of British Columbia, and electric utility BCHydro have the combined second largest fleet of PHEVs participating in the AVTA's PHEV demonstration. With eight PHEVs operating in Hawaii, the Canada and United States PHEV fleets provide excellent environmental diversity of temperature, terrain, mission, and other operating conditions. The AVTA also has a testing support agreement with NYSERDA to support fleet testing of PHEVs in New York State fleets.

Hymotion Prius PHEVs with Kvaser Data Loggers Fleet Testing Results

A sample of the types of data being accumulated from the PHEV fleet testing and demonstrations can be seen in the three-page summary report for the North American PHEV Demonstration (Figures 2 through 4). The summary is for the 44 Hymotion Prius PHEVs with Kvaser data loggers that provided data from January 2008 to June 2010.

As can be seen in Figure 2, these PHEVs were driven a total of 385,000 miles during this period. The vehicle operations are broken down into three operations modes:

<u>Charge Depleting (CD) Mode</u>: During each entire trip, there is electric energy in the battery pack to provide either all-electric propulsion or electric assist propulsion.

<u>Charge Sustaining (CS) Mode</u>: During a trip, there is no electrical energy available in the PHEV battery pack to provide any electric propulsion support.

<u>Combined (or Mixed) Charge Depleting and Charge Sustaining (CD/CS) Mode</u>: There is electric energy in the PHEV battery pack available at the beginning of a trip. However, during the trip, the battery is fully depleted.

It should be noted that the only way to recharge the Hymotion A123Systems battery packs is to plug in the vehicle. The vast majority of these vehicles are recharged at Level 1 (110 volts and 12 amps). This PHEV design does not accept energy for recharging during regenerative braking or from the onboard electric generator. The Hymotion design keeps the original stock Toyota Prius HEV battery and only this battery can accept onboard energy from recharging or regenerative braking.

As can also be seen in the first page of the summary sheet (Figure 2), the overall fuel economy for the 46,789 trips was 46 mpg. However, for the 25,383 trips in CD mode, it was 59 mpg—a 33% improvement over the 39 mpg for the 16,143 trips taken in CS mode.

As can be seen on page two of the summary sheet (Figure 3), the fuel economy is broken down by city and highway trips. Classifying if a trip is city or highway is determined by a combination of average speed, number of stops per mile, amount of time accelerating, number of acceleration events per mile, and the number of seconds cruising per mile.

This data breakdown by city or highway trip, and by CD, CS, or mixed operations mode, documents average mpg results that range from 34 to 62 mpg. This figure also shows the impacts on PHEV mpg when drivers drive more aggressively. This is measured by the accelerator pedal position and the amount of time spent during a trip at a higher accelerator pedal position. The higher position is based on how far down the pedal is pushed by the driver; if the pedal is pushed to the floor, it is considered to be in the 100% position—the most aggressive position. In the graph on Figure 3, entitled "Effect Of Driving Aggressiveness on Fuel Economy," the bottom 0-2 bar represents all trips driven when the pedal position was at 40% or more for only 20% or less time of each individual trip, and the average fuel economy was about 60 mpg. Note that some individual trips had fuel economies between 300 to almost 400 mpg per trip.

The third page (Figure 4) provides recharging information and patterns. The average number of charging events per day when a vehicle is driven was 1.4 charges, the vehicles were driven an average of 30.3 miles between charging events, with 3.6 trips per charging event, the average charge was for 2.0 hours, and the average energy charged was 1.6 DC kWh.

Figure 4 also shows that the peak drive time was between 2 and 5 p.m., the peak time of day when charging, as measured by DC kWh use, was between 5 and 10 p.m., and the peak time that charging started was between 4 and 6 p.m. However, there were additional peak charge time starts between 8 and 9 p.m. as well as 11 p.m. and midnight. Both of these two additional peaks represent the fleets controlling the start of charging events to off-peak grid times. It should be noted that most of these vehicles are operating in fleets, so most of the driving would occur during work hours, and most of the charging would occur either during breaks or at the end of the workday.

Hymotion Prius PHEVs with GridPoint (V2Green) Data Loggers Fleet Testing Results

Another and larger set of fleet testing results that is being accumulated from the PHEV fleet demonstrations can be seen in the three-page summary report for the North American PHEV Demonstration vehicles equipped with GridPoint (previously known as V2Green) data loggers (Figures 5 through 7). This summary is for the 184 Hymotion Prius PHEVs equipped with GridPoint data loggers with GPS and cellular communications that have provided data from April 2008 through September 2010.

As can be seen in Figure 5, these PHEVs were driven a total of almost 2 million (1,989,000 miles) fleet test miles during this period. As with the PHEVs with the Kvaser data loggers, the vehicle operations are broken down into the three operations modes of CD, CS, and mixed CD/CS. As can be seen in the first page of the summary sheet (Figure 5), the overall fuel economy for the 208,118 trips was 48 mpg; but for the 89,236 trips in CD mode, it was 63 mpg—a 47% improvement over the 43 mpg for the 102,376 trips taken in CS mode.

As can be seen on page two of the summary sheet (Figure 6), the fuel economy is broken down by city and highway trips (described in the previous section of this report). This breakdown by city, highway, and CD, CS, and mixed modes documents average mpg results that range from 37 to 66 mpg, which is a 78% increase. Figure 6 also shows the impacts on PHEV mpg when drivers drive more aggressively. In the graph entitled "Effect Of Driving Aggressiveness on Fuel Economy," the bottom 0-2 bar represents all trips driven when the pedal position was at 40% or more for only 20% or less time of each individual trip. The average fuel economy was about 70 to 75 mpg. Note that some individual trips had fuel economies between 300 to almost 400 mpg per trip.

The third page (Figure 7) provides recharging information and patterns. The average number of charging events per day when a vehicle is driven was 1.0 charges, the vehicles were driven an average of 49.3 miles between charging events, with 5.2 trips per charging event. The average charge was for 2.8 hours, and the average energy charged was 2.7 AC kWh. Note that while on average, each PHEV in this group was plugged in 22.7 hours per charging event, while actual charging only occurred for the before mentioned 2.8 hours. The average plugged in time of 22.7 hours is heavily influenced by the fleet vehicles in this group being plugged in all weekend, every week.

Page three also shows that the peak drive time was between 8 a.m. and 3 p.m., the peak time of day when charging was measured by AC kWh use as between 2 and 8 p.m., and the peak start of charging between 1 and 4 p.m. It should be noted that most of these vehicles are operating in fleets, most of the driving occurs during daytime work hours, and most of the charging occurs either during daytime driving breaks or at the end of the workday.

Previous Annual Progress Reports have highlighted other operating includes on PHEV technology's ability to reduce petroleum use, especially the report for FY 2009, and they will not be repeated her

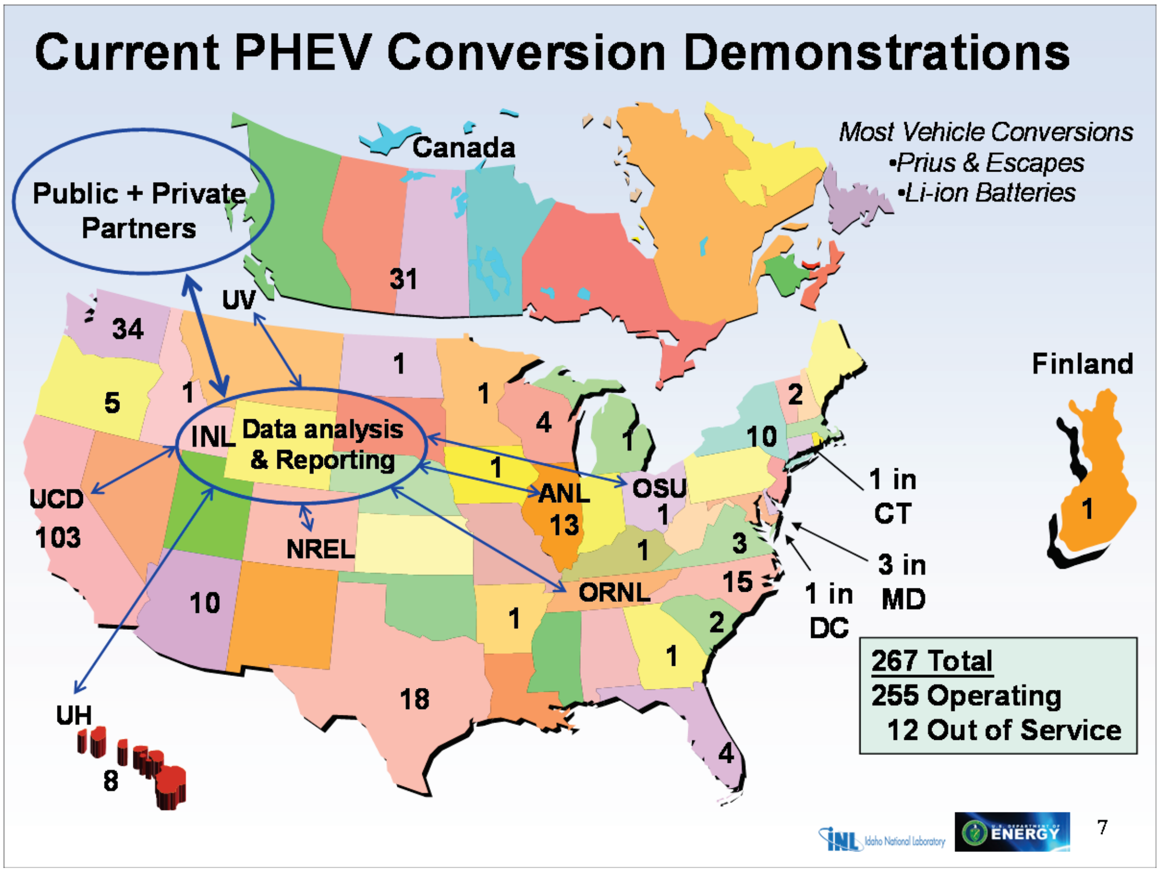


Figure 1. Location of PHEVs in the AVTA fleet testing demonstration.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

North American PHEV Demonstration

Vehicle Technologies Program

Fleet Summary Report - Hymotion Prius (Kvaser data logger)

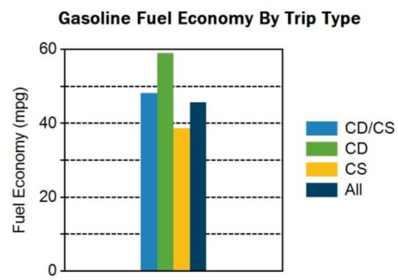
Number of vehicles: 44

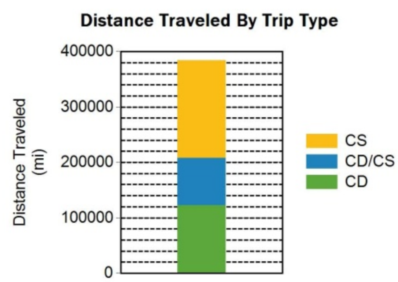
Reporting Period: Jan 08 - June 10

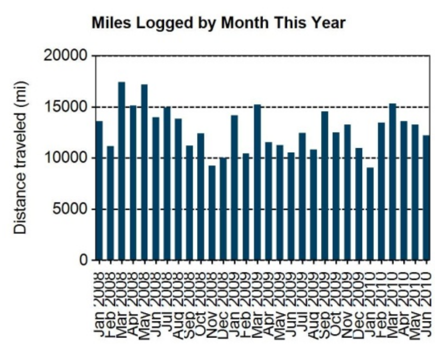
Date range of data received: 1/1/2008 to 6/30/2010

Number of days the vehicles were driven: 366

All Trips Combined	
Overall gasoline fuel economy (mpg)	46
Overall DC electrical energy consumption (DC Wh/mi) [2]	54
Total number of trips	45789
Total distance traveled (mi)	384547
Trips in Charge Depleting (CD) mode [3]	
Gasoline fuel economy (mpg)	59
DC electrical energy consumption (DC Wh/mi) [4]	134
Number of trips	25383
Percent of trips city / highway	84% / 16%
Distance traveled (mi)	122724
Percent of total distance traveled	32%
Trips in both Charge Depleting and Charge Sustaining (CD/CS) modes [5]	
Gasoline fuel economy (mpg)	48
DC electrical energy consumption (DC Wh/mi) [6]	52
Number of trips	4263
Percent of trips city / highway	49% / 51%
Distance traveled (mi)	85338
Percent of total distance traveled	22%
Trips in Charge Sustaining (CS) mode [7]	
Gasoline fuel economy (mpg)	39
Number of trips	16143
Percent of trips city / highway	71% / 29%
Distance traveled (mi)	176484
Percent of total distance traveled	46%
Number of trips when the plug-in battery pack was turned off by the vehicle operator [8]	2283
Distance traveled with plug-in battery pack turned off by vehicle operator(mi) [9]	38769





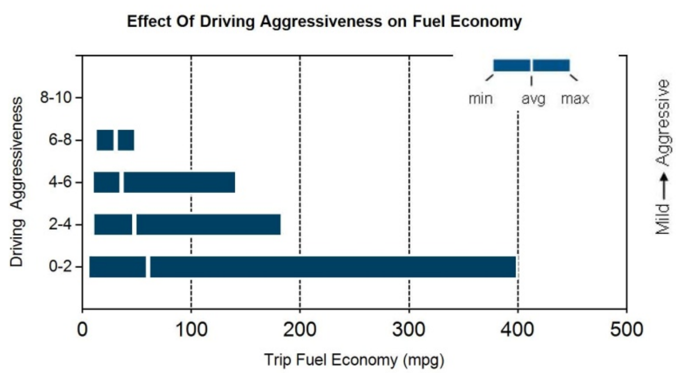


Notes: 1 - 9. Please see http://avt.inel.gov/phev/reportnotes for an explanation of all PHEV Fleet Testing Report notes.

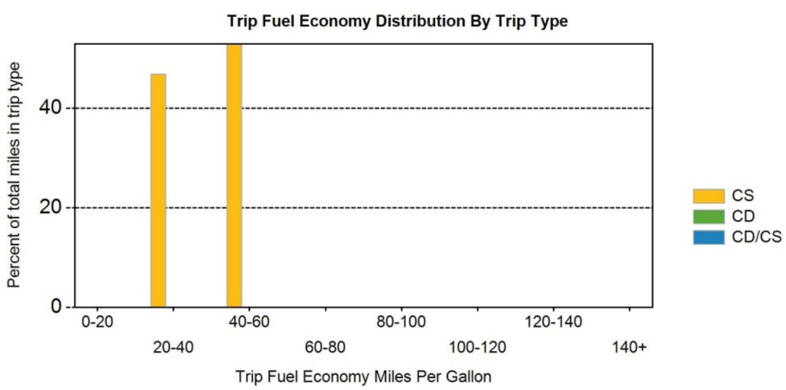
MonthlyReportAllFleet Summary Report - Hymotion Prius (Kvaser data logger) 1 7/23/2010 8:43:10 AM

Figure 2. Page 1 of 3 for the PHEV summary report for 44 PHEVs operating January 2008 – June 2010 with onboard Kvaser data loggers.

Trips in Charge Depleting (CD) mode	City	Highway
Gasoline fuel economy (mpg)	56	62
DC electrical energ consumption (DC Wh/mi)	157	108
Percent of miles with internal combustion engine off	33%	11%
Average trip aggressiveness (on scale 0 - 10)	2.0	1.9
Average trip distance (mi)	3.0	14.1
Trips in combined Charge Depleting and Charge Sustaining (CD/CS) modes		
Gasoline fuel economy (mpg)	47	48
DC electrical energy consumption (DC Kw/mi)	78	48
Percent of miles with internal combustion engine off	27%	6%
Average trip aggressiveness (on scale 0 - 10)	2.1	1.6
Average trip distance (mi)	6.2	33.6
Trips in Charge Sustaining (CS) mode		
Gasoline fuel economy (mpg)	34	40
Percent of miles with internal combustion engine off	23%	5%
Average trip aggressiveness (on scale 0 - 10)	1.8	1.5
Average trip distance (mi)	3.5	29.3



Aggressiveness factor is based on accelerator pedal position. The more time spent during a trip at higher accelerator pedal position, the higher the trip aggressiveness.



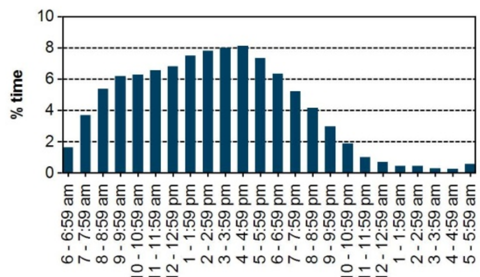
MonthlyReportAllFleet Summary Report - Hymotion Prius (Kvaser data logger) 2 7/23/2010 8:43:10 AM

Figure 3. Page 2 of 3 for the PHEV summary report for 44 PHEVs operating January 2008 – June 2010 with onboard Kvaser data loggers.

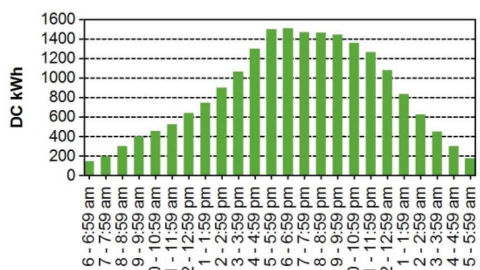
Plug-in charging

Average number of charging events per vehicle per month when driven	21
Average number of charging events per vehicle per day when vehicle driven	1.4
Average distance driven between charging events (mi)	30.3
Average number of trips between charging events	3.6
Average time charging per charging event (hr)*	2.0
Average energy per charging event (DC kWh)	1.6
Average charging energy per vehicle per month (DC kWh)	33.1
Total number of charging events	12704
Total charging energy (DC kWh)	20182

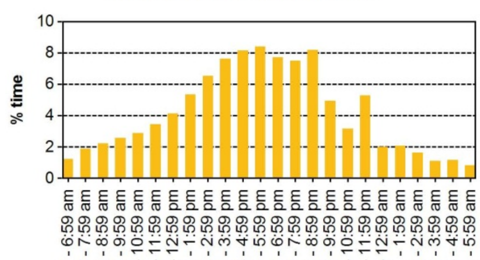
Time of Day When Driving



Time of Day When Charging



Time at the Start of Charging Events



* Time charging per charging event is the average length of time per charging event when the vehicle was drawing power from the electrical grid. It does not necessarily represent the total duration when the vehicle was plugged in per charging event.

MonthlyReportAllFleet Summary Report - Hymotion Prius (Kvaser data logger) 3 7/23/2010 8:43:10 AM

Figure 4. Page 3 of 3 for the PHEV summary report for 44 PHEVs operating January 2008 – June 2010 with onboard Kvaser data loggers.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

North American PHEV Demonstration

Vehicle Technologies Program

Fleet Summary Report: Hymotion Prius (V2Green data logger)

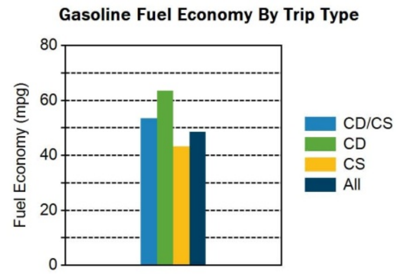
Number of vehicles: 184

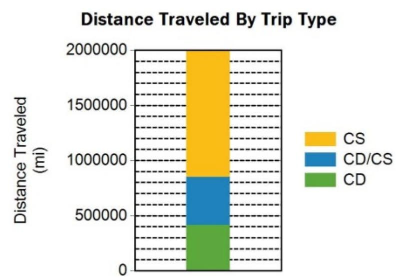
Reporting Period: Apr 08 - Sept 10

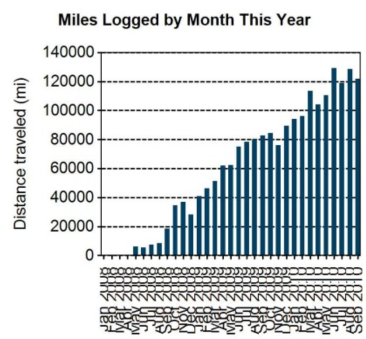
Date range of data received: 4/18/2008 to 9/30/2010

Number of days the vehicles were driven: 889

All Trips Combined	
Overall gasoline fuel economy (mpg)	48
Overall AC electrical energy consumption (AC Wh/mi) [1]	55
Overall DC electrical energy consumption (DC Wh/mi) [2]	40
Total number of trips	208,118
Total distance traveled (mi)	1,988,916
Trips in Charge Depleting (CD) mode [3]	
Gasoline fuel economy (mpg)	63
DC electrical energy consumption (DC Wh/mi) [4]	141
Number of trips	89,246
Percent of trips city / highway	87% / 13%
Distance traveled (mi)	415,267
Percent of total distance traveled	21%
Trips in both Charge Depleting and Charge Sustaining (CD/CS) modes [5]	
Gasoline fuel economy (mpg)	53
DC electrical energy consumption (DC Wh/mi) [6]	49
Number of trips	16,487
Percent of trips city / highway	47% / 53%
Distance traveled (mi)	436,508
Percent of total distance traveled	22%
Trips in Charge Sustaining (CS) mode [7]	
Gasoline fuel economy (mpg)	43
Number of trips	102,376
Percent of trips city / highway	76% / 24%
Distance traveled (mi)	1,140,570
Percent of total distance traveled	57%
Number of trips when the plug-in battery pack was turned off by the vehicle operator [8]	7155
Distance traveled with plug-in battery pack turned off by the vehicle operator (mi) [9]	187,800







Notes: 1 - 9. Please see http://avt.inel.gov/phev/reportnotes for an explanation of all PHEV Fleet Testing Report notes.

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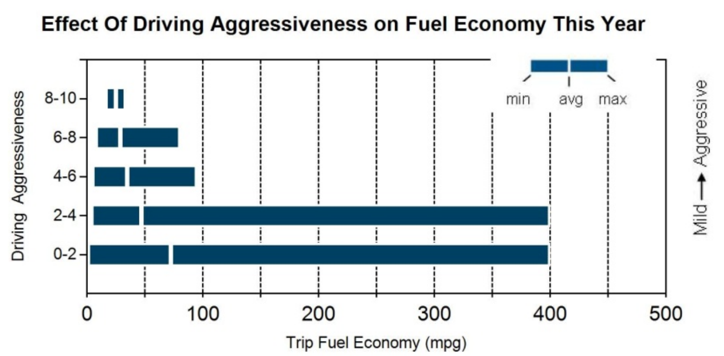
Figure 5. Page 1 of 3 for the PHEV summary report for 184 PHEVs operating April 2008 – September 2010 with onboard GridPoint data loggers.

Trips in Charge Depleting (CD) mode	**City**	**Highway**
Gasoline fuel economy (mpg)	61	66
DC electrical energy consumption (DC Wh/mi)	165	109
Percent of miles with internal combustion engine off	32%	14%
Average trip aggressiveness (on scale 0 - 10)	1.8	1.8
Average trip distance (mi)	3.0	15.2
Trips in both Charge Depleting and Charge Sustaining (CD/CS) modes		
Gasoline fuel economy (mpg)	54	53
DC electrical energy consumption (DC Wh/mi)	79	44
Percent of miles with internal combustion engine off	26%	8%
Average trip aggressiveness (on scale 0 - 10)	1.9	1.6
Average trip distance (mi)	8.8	41.9
Trips in Charge Sustaining (CS) mode		
Gasoline fuel economy (mpg)	37	46
Percent of miles with internal combustion engine off	23%	7%
Average trip aggressiveness (on scale 0 - 10)	1.9	1.7
Average trip distance (mi)	3.5	35.1



Aggressiveness factor is based on accelerator pedal position. The more time spent during a trip at higher accelerator pedal position, the higher the trip aggressiveness.

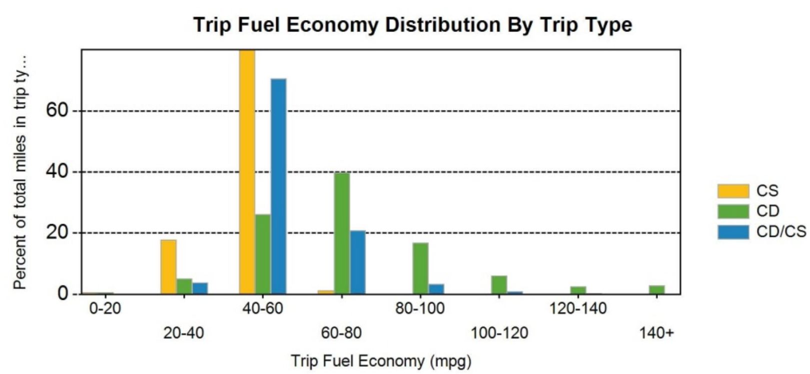


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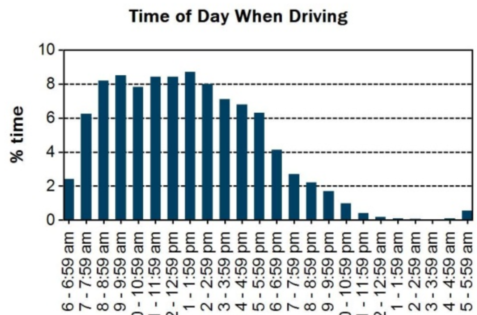
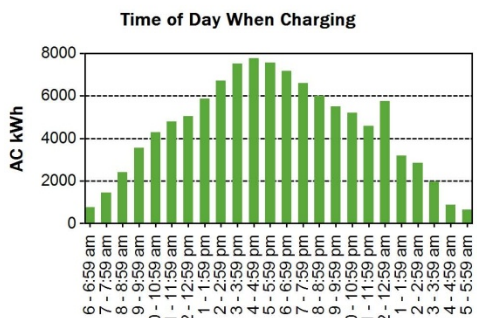
Figure 6. Page 2 of 3 for the PHEV summary report for 184 PHEVs operating April 2008 – September 2010 with onboard GridPoint data loggers.

Plug-in charging

Average number of charging events per vehicle per month when driven	13
Average number of charging events per vehicle per day when vehicle driven	1.0
Average distance driven between charging events (mi)	49.3
Average number of trips between charging events	5.2
Average time plugged in per charging event (hr)	22.7
Average time charging per charging event (hr)	2.8
Average energy per charging event (AC kWh)	2.7
Average charging energy per vehicle per month (AC kWh)	36.5
Total number of charging events	40,363
Total charging energy (AC kWh)	109,302





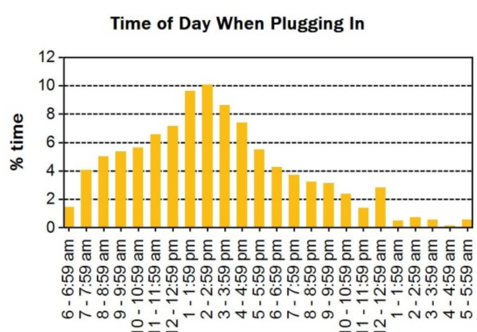


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Figure 7. Page 3 of 3 for the PHEV summary report for 184 PHEVs operating April 2008 – September 2010 with onboard GridPoint data loggers.

PHEV Battery Capacity Impacts by Ambient Temperature

Figure 8 shows the impact of cold weather vehicle operations on a Hymotion Prius PHEV conversion lithium battery pack's usable state of charge (SOC) and usable energy at colder temperatures. Figure 9 also highlights colder temperature impacts on lithium battery internal resistance for a Hymotion Prius PHEV battery.

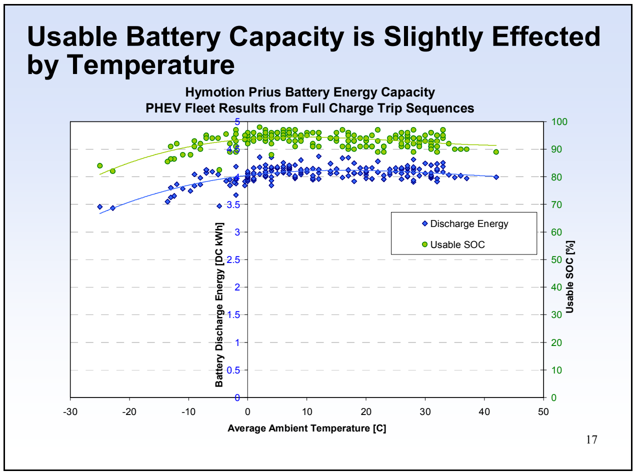

Figure 8. Usable battery capacity by temperature.

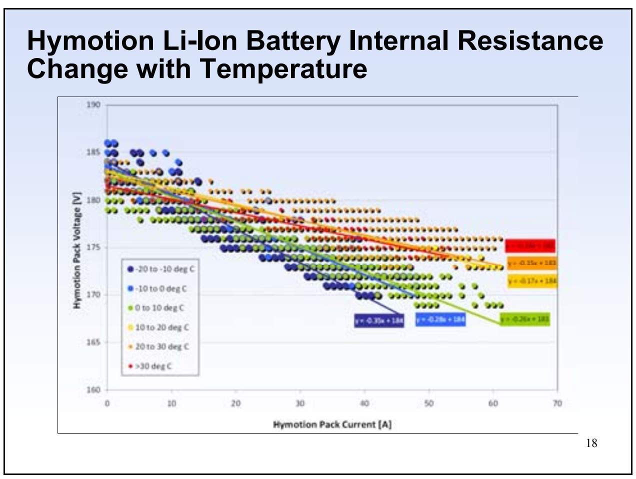

Figure 9. Hymotion Prius PHEV battery internal resistance change with temperature.

Both Figures 8 and 9 demonstrate ambient temperature impacts on lithium batteries. However, there are methods for mitigating these impacts that include the option of adding active thermal conditioning onboard PHEVs.

PHEV Charging Times Analysis

In addition to the time of the day that PHEVs are plugged in and charged as shown in Figures 4 and 7, charge times are also analyzed by commercial fleets (Figure 11) and private fleets (Figure 10). Both of these figures show the charging demand by kW, by hour, and by day of the week.

As Figure 11 shows, the privately operated PHEV Hymotion conversions had peak charge times from 5 to 10 p.m., Tuesday through Thursday evenings.

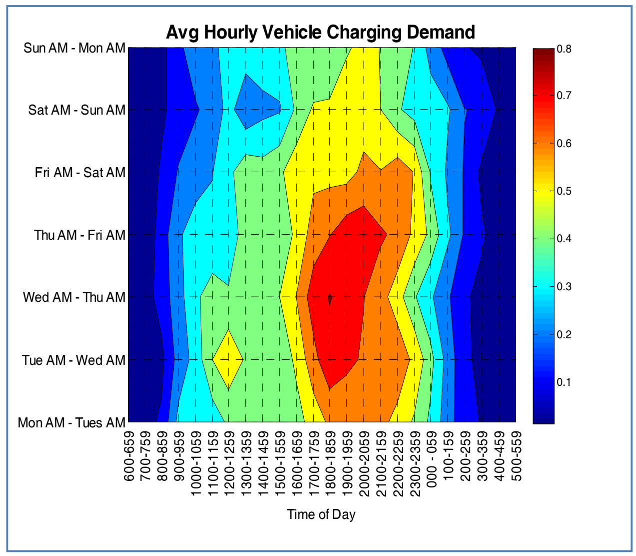

Figure 10. Average hourly charging demand for charging Hymotion Prius PHEV conversions for vehicles operated by households in California. Scale is from 0.1 to 0.8 (dark red) kW.

Figure 11 shows that the commercially operated PHEV Hymotion conversions were charged most intensively from 2 to 5 p.m., Monday through Thursday afternoons, and slightly less intensively from 1 to about 8 a.m., again Monday through Thursday afternoons into early evening.

Uncontrolled PHEV charging for both the private and commercial fleets occurs during what appears to be peak electricity demand times.

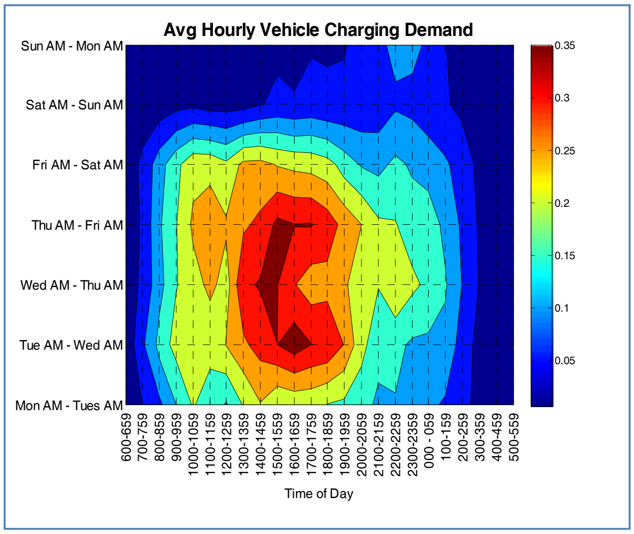

Figure 11. Average hourly charging demand for charging Hymotion Prius PHEV conversions for vehicles operated by commercial fleets in the United States. Note that the scale is different for the graphs for the commercial and private vehicles. The scale for this figure is from 0.05 to 0.35 (dark red) kW.

PHEV MPG Reporting

As reported in the FY 2009 Annual Program Report, PHEV mpg reporting can be difficult due to the many different ways PHEVs operate and the many significant impacts on mpg results such as drivers, charge frequency, auxiliary use, and environmental impacts. The AVTA report *Plug-in Hybrid Electric Fuel Use Reporting Methods and Results Report* discusses these impacts and provides sample results in detail. The report can be found at:

http://avt.inl.gov/pdf/phev/phev_mpg_report_july09.pdf

Vehicle-to-Grid (V2G) Codes and Standards Review

Parts of the United States electric utility transmission and distribution grid operations are at times near, at, or beyond capacity, which results in, at a minimum, voltage reductions or rolling blackouts. It is believed by some groups that as more light-duty vehicles are propelled by electric drive systems, and larger and larger onboard energy storage systems, bi-directional energy transfer will allow vehicle batteries to reduce the grid stress by either putting battery energy back onto the grid, or to be used to support voltage

Based on data presented in Figure 12, overall, the Hymotion Prius PHEVs are only driven about 3% of the time each month, and they are plugged in approximately 52% of the time each month. Therefore, the remaining 45% of the time, they are parked but not plugged in.

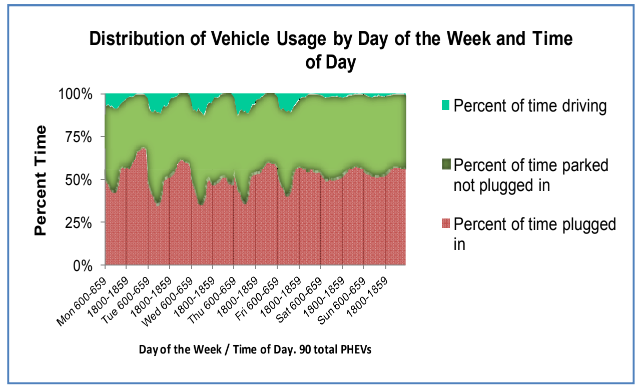

Figure 12. Percent of time 90 Hymotion Prius PHEVs are plugged in, driven, and parked but not plugged in during a one month period.

levels. This concept is known as vehicle-to-grid or V2G.

There are many unknowns at this point in the development of the V2G technology, including the regulations, standards, and building costs that will be required to support V2G, as well as battery life and warranty issues. The real economic viability of V2G is also an unknown. However, the AVTA is examining the V2G codes, regulations and standards required if V2G is implemented in the United States.

Specifically, governmental regulations and building code requirements impacting the introduction and use of vehicles with V2G capability is being studied in order to: (1) Develop a common set of regulations, standards and building codes that would apply in broad geographic areas that would allow widespread use of V2G vehicles; and, (2) Identify regulations, standards and building codes requiring modification to allow for a single national regulatory framework. Note that this does not answer battery life and warranty issues, which are likely to have significant technical and economic negative impacts on V2G implementation.

Published and planned V2G operating modes as well as other anticipated or projected modes to categorize the important design aspects of a V2G system are being documented. Perspectives of utilities, EVSE providers, potential V2G equipment suppliers, and other suppliers of distributed power equipment (solar, wind, UPS, etc.) are being obtained.

As case studies, the AVTA is documenting the existing codes and regulations for vehicle charging and V2G for the following metropolitan areas: Phoenix, AZ; Orlando, FL; Boston, MA; Detroit, MI; Raleigh, NC; Maui, HI; San Diego, CA; Dallas, TX; Seattle, WA; Washington, DC; Portland, OR; and New York, NY.

This task will document commonalities and conflicts, develop a set of possible common regulations, recommend an action plan to implement the common regulations, and evaluate the onboard and off-board equipment required to operate under the recommended common regulations. This work was initiated during FY 2010 and it is anticipated to be completed during late FY 2011.

Grid Connected Vehicle Workshop

As part of its duties, the AVTA supports strategic program planning, and project and technology assessments for the DOE. These responsibilities include supporting the development and adaption of industry best-practices, and codes and standards adaption, including for the recharging of grid-connected electric drive vehicles (GCEDVs) such as PHEVs.

Many diverse government, industry and other stakeholder organizations are working to define and implement GCEDV charging codes and standards, with little, if any, overall comprehensive coordination. The AVTA, in support of DOE requirements for additional light-, medium-, and heavy-duty on-road GCEDV charging codes and standards coordination, is organizing a comprehensive workshop to assess the codes and standards status and needs. The workshop goal will be to facilitate the successful introduction, and wide-spread acceptance and deployment of light-, medium, and heavy-duty onroad EDVs.

This task also commenced during late FY2010 and it is anticipated that a workshop will be held during the spring of calendar year 2011 that will bring together the many various parties, organizations, industry groups, and special interests that are working to support the advancement of the charging infrastructure needed for the successful deployment of GCEDVs. The final product will be recommendations to DOE regarding possible coordination or other leadership needs.

AVTA/Tacoma Power PHEV Demand and Energy cost Demonstration

Tacoma Power, an electric utility located in Tacoma, WA, is the first site where AVTA installed instrumentation to better understand onsite PHEV recharging infrastructure requirements and any impacts on electricity use and demand at a representative facility. The final report from this task provides the data collection and analysis results from charging several PHEVs at the Tacoma Power facility as a preliminary assessment of how PHEVs will impact the electricity grid.

Specifically, the study examined the load impact on the electricity grid of charging three of Tacoma Power's PHEVs. Data collection required measuring attributes such as current, voltage, power, and energy in a real-time environment. Based on the project scope, three PHEVs from the facility car pool were identified for study use. Monitoring full power consumption was deemed impractical due to the large size of the Tacoma Power facility. Instead, a circuit providing power to a section of the facility was identified as a suitable "mimic" for the entire facility, and monitoring of this circuit was conducted.

Data were collected over a 3-month period for analysis. AVTA examined the data for patterns in demand energy, time-of-day use, and relational behavior between the facility mimic and PHEV activity. The results presented show PHEV charge event history, output power, standby power, facility power, maximum daily power, and a comparison of the maximum daily power to the facility power.

The task also included an analysis of cost as it is currently defined for normal residential and commercial service. Monthly and quarterly cost tables were created to support a cost analysis. The tables contain totals for charging and vehicle standby time. Two different utility service plans from Tacoma Power and Salt River Project, respectively, were used in creating cost tables referred to as Base Plan and Time-of-Use Plan. The reason for inclusion of the latter is that the Salt River Project is one of the few U.S. utilities with rates that vary with time of use.

The study showed significant charging and standby power differences between PHEV conversion integrators Hymotion and Manzanita. Additionally, the study illustrated the potential cost impact of standby/hotel loads. After an examination of all data in the 3-month study period, the key finding is that when all three vehicles were being charged, the maximum percent difference between the facility power and PHEV charging power sum added to the facility power was approximately 5%. Therefore, a potential for demand load problems exist if additional PHEVs are added to the facility mimic.

Ford Escape PHEV Onboard Data Loggers

During FY 2010, the AVTA signed a CRADA with Ford Motor Company that includes the data collection, analysis and reporting by the AVTA of vehicle performance, fuel use, and charging patterns for 22 Ford Escape PHEVs demonstration vehicles. During FY 2010, computer, data dictionary, reporting, and security systems between the AVTA and Ford were developed in order to automate the process for data transfer and reporting. As FY 2010 ended, the AVTA was receiving the first data sets from the 22 PHEVs; the results will be reported periodically during FY 2011.

Chrysler Ram Pickup PHEV Data Collection

During FY 2010, the AVTA initiated the development of a NDA with Chrysler Corporation to cover the data collection, analysis and reporting by the AVTA of vehicle performance, charging patterns, and reporting for the 145 Ram Pickup PHEVs that Chrysler will be deploying during FY 2011. During FY 2010, the design process of computer, data dictionary, reporting, and security systems between the AVTA and Chrysler were initiated. The testing results will be reported periodically during FY 2011.

Chevrolet Volt EREVs Data Collection

As FY 2010 ended, the AVTA completed an NDA with General Motors and OnStar to cover the data collection, analysis and reporting by the AVTA of vehicle performance, charging patterns, and reporting for the approximately 150 Chevrolet Volt extended range electric vehicles (EVREs) that Chevrolet will be deploying during FY 2011. During FY 2010, the design process of computer, data dictionary, reporting, and security systems between the AVTA and GM/OnStar were initiated, with sample data sets being transferred. The testing results will be reported periodically during FY 2011.

EV Project Charging Infrastructure Data Collection, Analysis, and Reporting

During FY 2010, INL and ECOtality initiated an NDA that will cover the EV Project's collection of charging data from 15,000 Level 2 EVSE and 350 fast chargers. ECOtality is using its MICROClimate process to identify travel, shopping, and parking clustering patterns in order to identify public EVSE and fast charger placement for the subset of the 15,350 ECOtality branded Blink units will be deployed in non-home locations. The EV Project will install charging infrastructure in select cities in the states of Arizona, California, Oregon, Tennessee, Texas, and Washington, as well as in Washington D.C. All 15,300 units will all be equipped with data loggers and, via ECOtality, INL will receive data from every charging event. As part of the EV Project, data will also be received by INL from 8,300 Nissan Leafs and Chevrolet Volts every time they have a key-on and key-off event.

These multiple data streams will be used by INL to report on charger placement and utilization patterns over time, as well as dynamic driver recharging behaviors. This charger-rich environment will act as a large learning laboratory to guide the design of future charging infrastructures that will be required for the eventual deployment of millions of additional GCEDVs, including PHEVs.

The first infrastructure and vehicles will be deployed, and data collection initiated, during FY 2011 (Winter 2010 – 2011). The EV Project is lead by ECOtality. For more information, see the EVProject website at:

http://www.theevproject.com/index.php

Development of Emerging Vehicle Technology Cost Impacts

The Government Performance and Results Act (GPRA) of 1993 (Public Law 103-62) requires that "the head of each agency shall submit to the Director of the Office of Management and Budget and to the Congress a strategic plan for program activities." GPRA also states that "the strategic plan shall cover a period of not less than five years forward from the fiscal year in which it is submitted, and shall be updated and revised at least every three years." In support of GPRA activities associated with the Department of Energy's (DOE) Office of Vehicle Technologies, updated cost impacts are required to be associated with all reported vehicle technology performance benefits.

The AVTA has been tasked by DOE with developing accurate system level cost models for up to 2,000 technology combinations of passenger vehicles that incorporate proper accounting of enabling technologies, synergies between technologies, time, and volumes for light-duty, on-highway vehicles. To support the performance of this task, the AVTA partnered with Ricardo, an engineering and design support firm, to rapidly identify market costs for the significant number of potential technology combinations. This task was initiated during FY 2010 and it will be completed during FY 2011.

This work includes the review and analysis of new, emerging, and existing light vehicle fuel economy-improving technologies and information for consideration within DOE technology models and for reporting purposes in conjunction with GPRA, as well as the development, summarization, cataloging, and categorizing of the costs of energy efficient technology vehicle systems.

Conclusions

The PHEV industry is still in its infancy, with approximately 1,500 light-duty PHEVs deployed in North America as of the end of FY 2010. However, many of the OEMs have announced upcoming PHEV product offerings starting in FY2011 and beyond. Total independent test miles on any single PHEV battery pack are still rather limited in terms of independent research. If the Volt EREV is included in the ranks of PHEVs, consumers will have the ability to start purchasing PHEVs in significantly larger numbers from OEMs.

In spite of the limited number of test vehicles (PHEVs represent about 0.0004% of all light-duty vehicles in the United States), initial testing of PHEVs suggests that the technology has great potential for reducing petroleum consumption.

The current cost to convert an HEV to a PHEV ranges from \$10,000 to \$40,000 per vehicle, plus the base cost of the HEV and long-term battery life is unknown. Therefore, on an economic basis, the current cost to the vehicle operator to reduce petroleum consumption with PHEV conversions is considerable. However, the cost of ground-built PHEVs from OEMs, are better known. The Volt has an announced cost of \$41,000 and there is a Federal Tax Credit (\$7,500) will lower this cost. In addition, the Volt should have significantly lower operating costs than a conventional internal combustion engine vehicle.

There is discussion about PHEVs being able to provide electricity back to the electric grid during periods of peak demand. However, this concept may remain theoretical at least for the near future due to limits in the amount of electric energy that can be transferred quickly, and the not insignificant questions about battery life and warranty impacts.

Some in the PHEV industry support all-electric ranges, while others support greater use of additional electric assist that will theoretically help maximize battery life. Regardless of any uncertainties regarding the operational designs of future PHEVs, the PHEVs currently in operation have demonstrated the significant potential of PHEVs to reduce the use of petroleum for personnel transportation.

Future Activities

AVTA will continue to test new PHEV models from OEMs as they become available. PHEV use patterns, and PHEV charging patterns and demands, will continue to be documented in the effort to increase the testing sample size. This will aid in better understanding of charging demands, infrastructure requirements, and cost impacts for distribution (e.g., building and neighborhood), transmission, and generation changes.

Developing additional PHEV testing partnerships will be pursued that support the objectives of testing PHEVs in diverse geographic and electric generation regions. This will support a greater understanding of vehicle and battery maintenance needs, functionality, operational life, and life-cycle costs.

Above all else, the AVTA will strive to continue to test PHEVs in a highly leveraged manner in order to accumulate test miles at the lowest cost possible both to DOE and the taxpayer in a technology- and fuel-neutral manner.

Publications

Previous annual reports have identified AVTA's baseline performance testing procedures, vehicle specifications, and pre-FY 2010 reports. All of these documents can be found at: http://avt.inl.gov/hev.shtml and http://www.eere.energy.gov/vehiclesandfuels/avta/light_duty/hev/hev_reports.shtml. The PHEV reports published and formal presentations that occurred during FY 2010 are listed below.

1. J.E. Francfort. October 2009. *PHEV Operations, Performance and Charging Profiles*. INL/CON-09-17005. Hawaii Electric Company. Honolulu, HI.
2. J.E. Francfort. November 2009. *E.V. Road Map – Preparing Oregon for the Introduction of Electric Vehicles*. Portland State University. Portland, OR. INL/CON-09-17242.
3. J.E. Francfort. March 2010. Clean Cities Webinar - Electric Drive Vehicles and Their Infrastructure Issues (March 2010). Clean Cities Webinar. INL/CON-10-18052.
4. J.E. Francfort. March 2010. *AVTA Electric Drive Vehicle Testing Activities & Infrastructure Requirements - NAFA (March 2010)*. National Association of Fleet Managers. Seattle, WA. INL/CON-10-18073
5. J.E. Francfort. September 2010. Plug-in Hybrid Electric Vehicle Testing Results Achieved by the U.S. DOE's Advanced Vehicle Testing Activity. Vancouver, Canada. INL/CON-10-18322.
6. J.E. Francfort. June 2010. AVTA – PHEV Demonstrations and Testing (DOE FY10 Merit Review). Washington, D.C. INL/CON-10-18396.
7. S. White. June 2010. Geographic Information System for Visualization of PHEV Fleet Data. Washington, D.C. INL/ON-10-18606.
8. J.E. Francfort. September 2010. Transportation Electrification ARRA Demonstration and Education Projects, and INL Data Collection - 2010 Clean Cities Coordinator Leadership Retreat. Rapid City, SD. INL/CON-10-19919.
9. J.E. Francfort. March 2010. Tacoma Power / AVTA PHEV Demand & Energy Cost Demonstration Analysis Report. Idaho Falls, ID. INL/EXT-10-18207.
10. M. Shirk. July 2010. Gen II Hymotion Prius Plug-In Hybrid Battery Test Results. Idaho Falls, ID. INL/EXT-10-19028.
11. M. Shirk. July 2010. *Gen I Hymotion Prius Plug-In Hybrid Battery Test Results*. Idaho Falls, ID. INL/EXT-10-19029.
12. Shirk. July 2010. *Energy CS Prius Plug-In Hybrid Battery Test Results*. Idaho Falls, ID. INL/EXT-10-19030.
13. J. Smart. November 2009. *Advanced Electric Vehicle Testing and Evaluation Results.* Idaho Falls, ID. INL/MIS-09-17280.
14. J. Francfort. January 2010. Advanced Vehicle Testing Activity (AVTA) FY 2009 Accomplishments. Phoenix, AZ. INL/MIS-10-17655.
15. J. Francfort. May 2010. *AVTA Vehicle Testing and Demonstrations – Chubu & JEPIC.* Idaho Falls, ID. INL/MIS-10-18838.
16. Carlson. June 2010. U.S. Department of Energy, Vehicle Technologies Program; AVTA Vehicle Testing and Demonstrations. Idaho Falls, ID. INL/MIS-10-18931.

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26. J. Smart. July 2010. North American PHEV Demonstration Charging and Driving Behavior Report. Idaho Falls, ID. INL/MIS-10-19480.

B. Hybrid Electric Vehicle Testing by DOE's Advanced Vehicle Testing Activity (AVTA)

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Objective

- Benchmark hybrid electric vehicle (HEV) fuel use, component performance, maintenance requirements, battery performance, and life-cycle costs.
- Provide HEV testing results to vehicle modelers, DOE, the general public, and technology target setters.
- Eliminate any uncertainties about HEV battery life.

Approach

- Performed baseline performance testing on 22 HEV models and 56 HEVs to-date.
- Operate at least two of each HEV model over 36 months to accumulate 160,000 miles per vehicle in fleets to obtain fuel economy, maintenance, operations, and other life cycle related vehicle data under actual road conditions.
- Test HEV batteries when new and at 160,000 miles.

Accomplishments

- Accelerated testing for the HEV fleet, consisting of 56 individual HEVs and 22 HEV models, exhibited varying fuel economies that ranged from 17.9 mpg for the Chevrolet Silverado to 45.6 for the second generation Honda Insight.
- One additional HEV (Mercedes S400, the first HEV with a lithium battery offered for sale in the United States) was baseline performance tested during fiscal year FY 2010, and testing started on four new HEV models (Honda CRZ, Smart Fortwo, Mazda 3, and Volkswagen Gold TDI) during FY 2010.
- Demonstrated an average decrease in HEV mpg from the use of auxiliary loads (air conditioning) of 21.8%. The range of decreases were from 8 to 28.7% by HEV model.
- As of September 2010, 5.2 million HEV test miles have been accumulated.
- Provided HEV testing results to the automotive industry, DOE, and other national laboratories via the DOE Vehicle Technologies Program's Vehicle Simulation and Analysis Technical Team.
- Shared used HEV power electronics parts with Oak Ridge National Laboratory (ORNL) for its power electronics testing, and made an HEV available to another DOE laboratory for cabin temperature testing.
- Provided used HEVs to the Environmental Protection Agency (EPA) for its HEV life cycle testing.

Future Activities

- Benchmark new HEVs available during FY 2011, including new HEVs with advanced batteries and start-stop control technologies.
- Ascertain HEV battery life by accelerated testing at the end of 160,000 miles.
- Continue testing coordination with industry and other DOE entities.

Introduction

Today's light-duty HEVs use a gasoline internal combustion engine (ICE), electric traction motors or electric stop-start technology, along with approximately 600 watt-hour (Wh) to 1.6 kilowatt-hour (kWh) of onboard energy storage (the battery), to increase petroleum efficiency as measured by higher mpg results compared to comparable non-HEV models. HEVs are never connected to the grid for charging the battery. The HEV batteries are charged by an onboard the vehicle ICE-powered generator, as well as by regenerative braking systems.

Seventeen of the nineteen HEV models baseline performance tested to-date by the AVTA use nickel metal hybrid (NiMH) battery chemistries as the onboard HEV battery. Only one HEV model, the 2004 Chevrolet Silverado, uses a lead acid battery, and the new Mercedes Benz S400 uses a lithium-ion battery. It has been anticipated that future HEVs will use lithium battery technologies. However, lead acid batteries are being considered by some manufacturers as possible HEV batteries in the future.

In addition to providing benchmark data to modelers and technology target setters, AVTA benchmarks and tests HEVs to document petroleum reduction and life-cycle costs, and also to provide testing results to the public and fleet managers.

Approach

As of the end of FY 2010, AVTA has performed, or is performing, accelerated and fleet testing on 56 HEVs, comprised of 22 HEV models. The HEV models and number of each model tested are listed below:

- Generation (Gen) I Toyota Prius - 6
- Gen II Toyota Prius - 2
- Gen I Honda Insight - 6
- Honda Accord - 2
- Chevrolet Silverado - 2
- Gen I Honda Civic - 4
- Gen II Honda Civic - 2
- Ford Escape - 2
- Lexus RX400h - 3
- Toyota Highlander - 2
- Toyota Camry - 2
- Saturn Vue - 2
- Nissan Altima - 2
- Chevrolet Tahoe - 2
- Gen II Honda Insight - 2
- Gen III Toyota Prius - 2
- Ford Fusion - 2
- Mercedes S400 – 2
- Honda CRZ – 2
- Smart Fortwo Pure Coupe – 3
- MAZDA 3 Hatchback - 2
- Volkswagen Golf TDI – 2.

Baseline performance testing has been completed on 19 of HEV models, with the Smart Fortwo, Mazda 3 and Volkswagen Golf testing just starting as FY 2010 ended. Note that the difference between fleet and accelerated testing is that some vehicles are placed in fleet operations without a deliberate effort to place maximum miles on a vehicle (fleet testing). While in HEV accelerated testing, two of each HEV model will each accumulate 160,000 on-road miles in approximately 36 months by being placed in a bank courier fleet in Arizona.

All testing has been completed on the following 14 HEV models:

- Generation (Gen) I Toyota Prius
- Gen II Toyota Prius
- Gen I Honda Insight
- Honda Accord
- Gen I Honda Civic
- Ford Escape
- Lexus RX400h
- Chevrolet Silverado
- Toyota Highlander
- Toyota Camry
- Gen II Honda Civic
- Nissan Altima
- Saturn Vue
- Chevrolet Tahoe

Results

As of the end of FY 2010, the 56 HEVs had accumulated 5.2 million total accelerated and fleet test miles (Figure 1). During FY 2010, the HEVs accumulated a total of 492,000 test miles, averaging 41,000 test miles per month. The average fuel use per HEV model ranged from 17.9 mpg for the Silverado to 45.6 mpg for the Gen II Honda Civic (Figure 2).

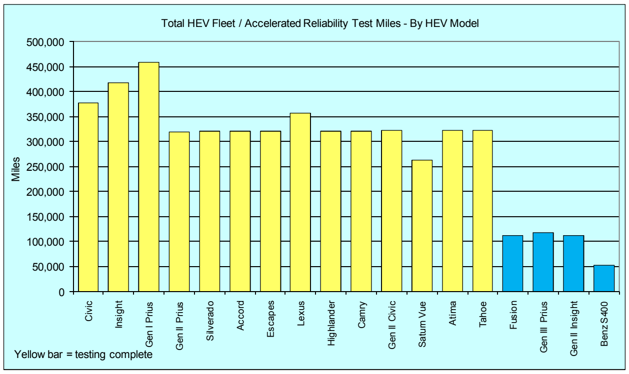


Figure 1. Total HEV test miles by vehicle model. Note that the Mazda 3, Smart Fortwo, Honda CRZ, and Volkswagen Golf were just starting accelerated testing as FY 2010 ended.

All of the HEVs in use to date have exhibited reductions in fuel economy results due to auxiliary loads such as air conditioning. The impact from using the air conditioning is most evident from the baseline performance testing results (Figure 3), when the average HEV mpg results decreases 9.0 mpg when the air conditioning is on during dynamometer testing. In terms of mpg, the negative air conditioning impact varies from 2.8 mpg for the Silverado to 15.0 mpg for the Gen III Prius and 15.8 for the Gen II Civic. In terms of percentage impacts, the air conditioning impact varies from 8.0% for the Saturn Vue to 28.7% for the Ford Fusion, with an average negative impact of 21.8% (Figure 4).

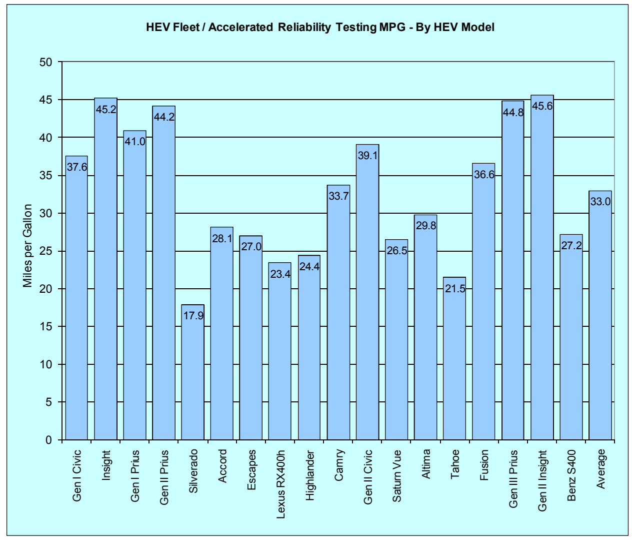


Figure 2. HEV fuel economy (mpg) test results for each HEV model in fleet and accelerated testing.

In addition to the HEV fuel economy and total test miles data being collected, all maintenance and repair event data (including the event costs, whether the event was covered under warranty, dates, and vehicle miles when an event occurred) is collected to compile lifecycle vehicle costs. This data is presented on AVTA's Web pages as both a maintenance fact sheet (Figure 5) and an HEV fact sheet, which includes miles driven, fuel economy, fuel economy at different speeds, mission, and lifecycle costs on a per-mile basis (Figures 6 and 7).

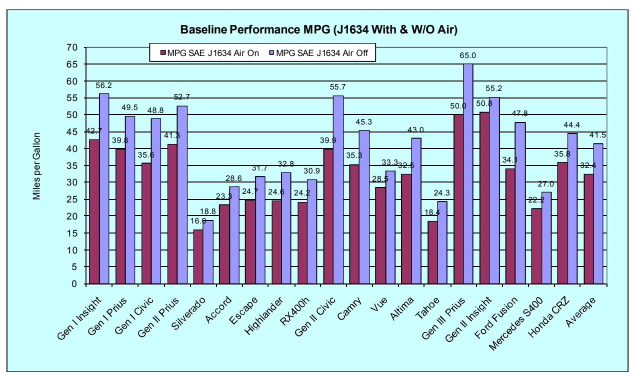


Figure 3. Baseline performance fuel economy test results for SAE J1634 drive cycle testing with the air conditioning on and off.

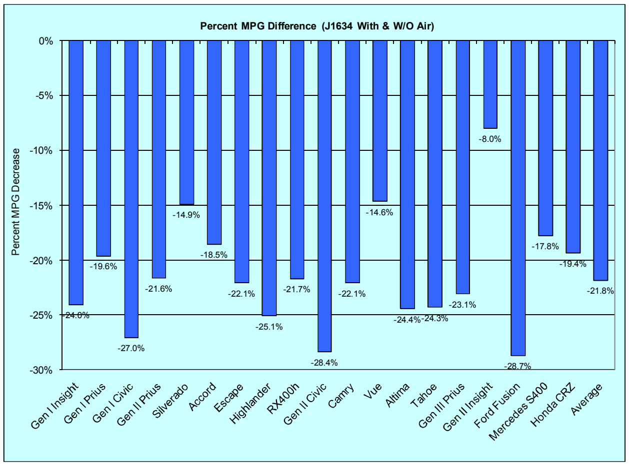
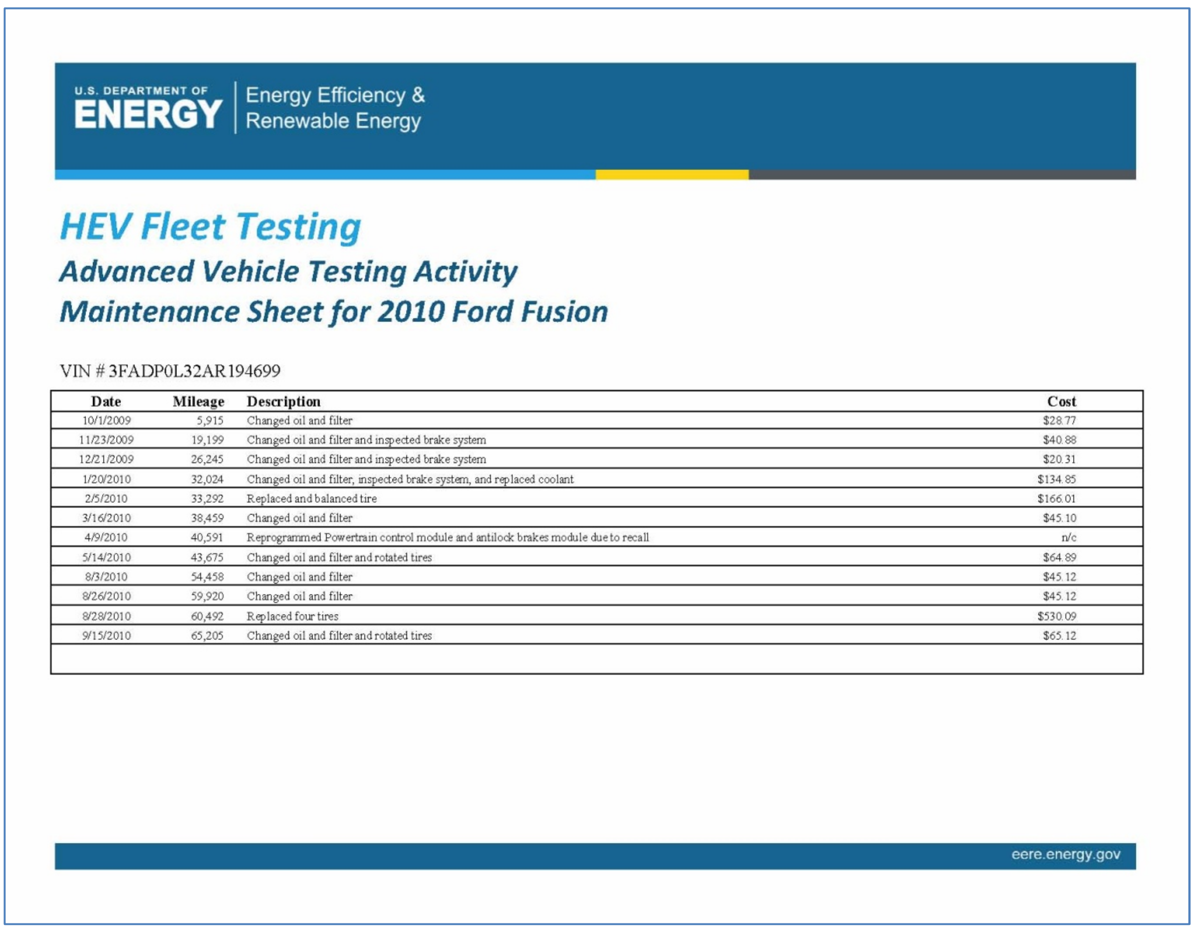


Figure 4. Percentage decrease in baseline performance fuel economy test results for SAE J1634 drive cycle testing when the air conditioning is turned on during the testing.

At the end of FT 2010, the AVTA had conducted 30 HEV battery tests for when vehicles were new or at 160,000 miles. To date, 22 battery tests reports have been posted, with six new HEV battery test reports posted during FY 2010 and these can be found at http://avt.inl.gov/hev.shtml In addition to information on the HPPC and Static Capacity testing, the most recent battery test reports include the following graphed information:

- Voltage versus Energy Discharged
- Charge Pulse Resistance versus Energy Discharged
- Charge Pulse Power versus Energy Discharged
- Discharge Pulse Resistance versus Energy Discharged
- Discharge Pulse Power versus Energy Discharged
- Peak Power Values with DOE Performance Goals
- Useable Energy



U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

HEV Fleet Testing

Advanced Vehicle Testing Activity

Maintenance Sheet for 2010 Ford Fusion

VIN # 3FADP0L32AR194699

Date	Mileage	Description	Cost
10/1/2009	5,915	Changed oil and filter	$28.77
11/23/2009	19,199	Changed oil and filter and inspected brake system	$40.88
12/21/2009	26,245	Changed oil and filter and inspected brake system	$20.31
1/20/2010	32,024	Changed oil and filter, inspected brake system, and replaced coolant	$134.85
2/5/2010	33,292	Replaced and balanced tire	$166.01
3/16/2010	38,459	Changed oil and filter	$45.10
4/9/2010	40,591	Reprogrammed Powertrain control module and antilock brakes module due to recall	n/c
5/14/2010	43,675	Changed oil and filter and rotated tires	$64.89
8/3/2010	54,458	Changed oil and filter	$45.12
8/26/2010	59,920	Changed oil and filter	$45.12
8/28/2010	60,492	Replaced four tires	$530.09
9/15/2010	65,205	Changed oil and filter and rotated tires	$65.12

eere.energy.gov

Figure 5. Actual 2010 Ford Fusion maintenance sheet is provided as an example of a HEV maintenance sheet.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

VEHICLE TECHNOLOGIES PROGRAM

HEV Fleet Testing

2007 Toyota Camry Hybrid

Final Fleet Testing Results

Operating Statistics

Number of Vehicles Tested: 2

Distance Driven[1]: 320,189 mi

Average Trip Distance[2]: 25.3 mi

Stop Time with Engine Idling[2]: 19%

Trip Type City/Highway[2]: 52%/48%

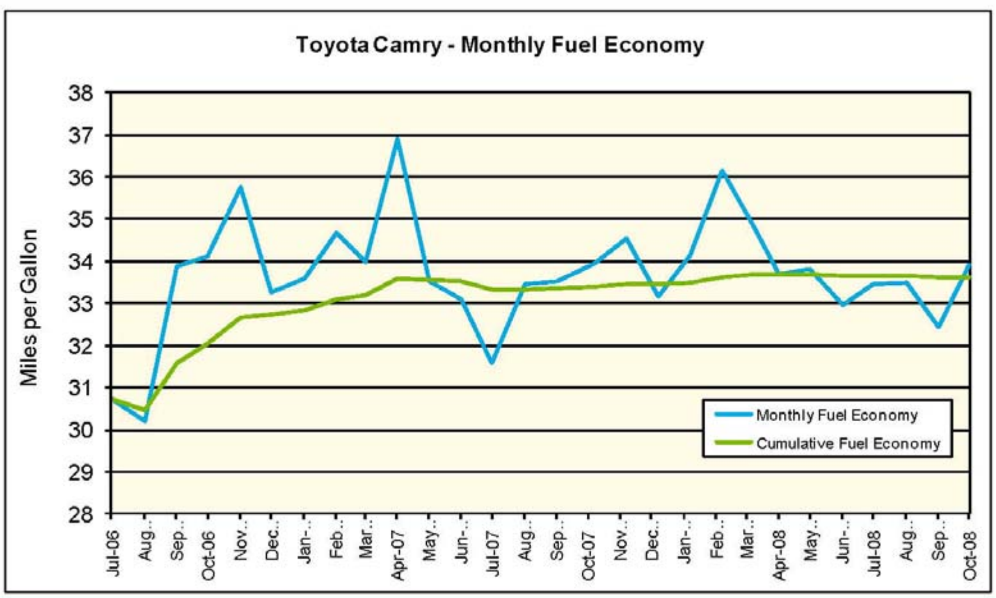
Operating Performance

Cumulative MPG[1]: 33.6

See HEV America Baseline Performance and Fleet Testing Fuel Economy fact sheets for more information on vehicle specifications and fuel usage reporting, available at http://avt.inl.gov/

Test Notes

1. Calculated over the life of the vehicle based on odometer reading and fuel logs. More information available in Fleet Testing Fuel Economy sheet.
2. Calculated from electronic data logged over a subset of total miles traveled equal to 162,418 miles.
3. Fuel economy calculated for this figure using mass air flow over dynamic vehicle operation.



continued >

Figure 6.Actual Toyota Camry fact sheet is provided as an example of a HEV fact sheet.

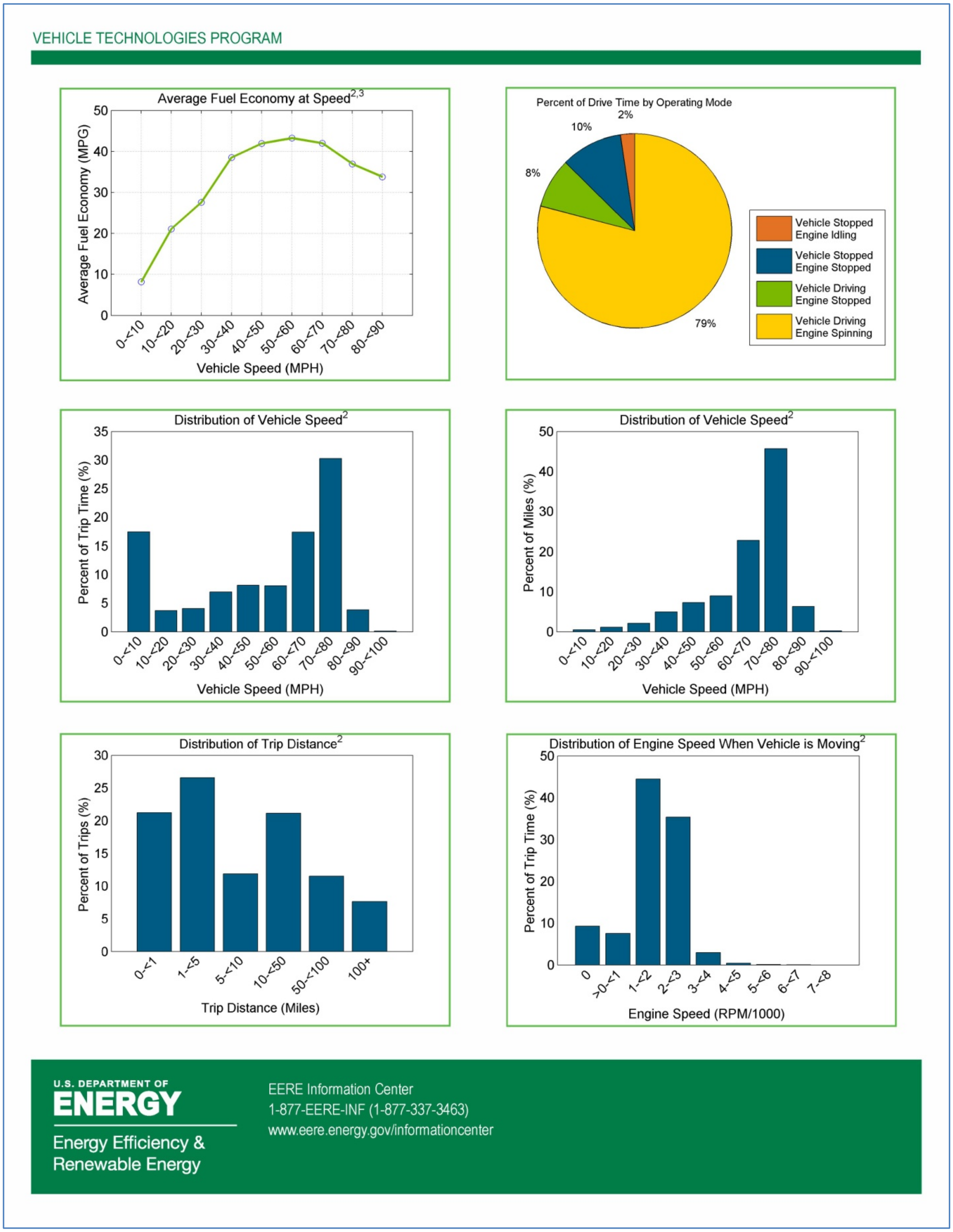


Figure 7. Actual Toyota Camry fact sheet is provided as an example of a HEV fact sheet.

Ultra (Lead Acid) Battery - Development and Testing for HEV Applications

Recent industry developments in advanced lead acid battery technology have resulted in the development of an advanced lead acid battery incorporating the properties of an asymmetric supercapacitor. A version developed at the Commonwealth Scientific Industrial & Research Organization (CSIRO) is currently manufactured by the Furukawa Battery Co., Ltd., Japan (Furukawa) and branded as the "Ultra Battery." A license to manufacture this battery in the United States has been secured by East Penn Manufacturing Co., Inc. (East Penn). East Penn is currently transferring the technology requisite to production of the Ultra Battery in Pennsylvania.

The Advanced Lead Acid Battery Consortium (ALABC), in conjunction with Furukawa, has demonstrated the capabilities of the Ultra battery by replacing the standard nickel-metal hydride (NiMH) battery pack in a Honda Civic HEV with the Ultra Battery and operating the vehicle for 100,000 miles. The ALABC and East Penn asked DOE to demonstrate the capabilities of the Ultra Battery as a HEV battery in a mild-HEV design light-duty vehicle in an independent environment.

DOE directed the AVTA to independently test the Ultra Battery as part of the AVTA's HEV baseline performance and HEV fleet testing regimes. This work includes the modification of a Honda Civic HEV using the Ultra Battery for electric energy storage as the HEV traction battery.

Comparing data collected during AVTA testing of a 2006 Honda Civic with the results of testing in the ALABC Project, it appears that an Ultra Battery conversion of a 2008 Honda Civic will be capable of meeting the objectives presented below.

- To convert a Honda Civic HEV to operate using an Ultra Battery manufactured by East Penn
- To maintain a minimum vehicle payload of 800 pounds (four passengers plus 200 pounds)
- To provide packaging favorable to battery life, but not integral with existing vehicle dimensions
- To provide a fuel economy equivalent to the unconverted, base HEV Civic with a NiMH stock battery
- To maintain vehicle emissions performance equal to or better than the base vehicle
- To obtain an "Experimental Vehicle" permit from the California Air Resources Board for the converted vehicle
- To install conversion components without violating vehicle Federal Motor Vehicle Safety Standard (FMVSS) certification
- To baseline vehicle performance within the AVTA's HEVAmerica test program
- To conduct fleet testing within the AVTA.

During FY 2010, the conversion of the Honda Civic commenced and laboratory testing of Ultra Battery modules had started. On-road and in dynamometer testing of the Ultra Battery equipped Civic will commence during FY2011.

Conclusions

The single largest negative impact on fuel economy (mpg) is from the use of the air conditioning. However, operator and passenger comfort is essential to most operators.

HEV battery packs generally appear to be robust from a life viewpoint. However, as of the end of FY 2010 and 5.2 million test miles, there were five NiMH HEV battery failures. But, understanding the failure circumstances reinforces the statement that the HEV NiMH batteries are robust.

One OEM's NiMH HEV battery pack failure was due to a battery controller failure at 75,000 miles. This should not be attributed as a pack failure, as the battery controller completely and fatally discharged the HEV battery pack. The same OEM's second NiMH pack failed at 147,000 miles and was again replaced under warranty.

The second OEM had two NiMH pack failures on a single vehicle at 22,000 and 56,000 miles, before this HEV test vehicle was totaled in a crash at 103,000 miles. In addition, this same OEM's other HEV model's NiMH battery pack also failed in the second test vehicle at 90,000 miles. There appears to be a problem with this HEV battery selection or operating scheme, as there were three failures within 263,000 miles. Excluding the three pack failures from this one HEV model, and the battery controller failure, there was only a single high-mileage HEV NiMH battery pack failure out of almost 5 million test miles which suggests that most of the NiMH HEV batteries are very robust.

AVTA has partnered with private fleets to conduct the high mileage HEV testing. All 5.2 million HEV test miles have been accumulated with no driver costs to DOE. In addition, several of the HEV models get secondary test value after completing the 160,000 miles of HEV testing. Oak Ridge and Argonne National Laboratories have purchased several used HEVs and they use the HEV power electronics subsystems and other subsystems for end-of-life testing. The EPA has also purchased several HEVs at AVTA testing completion so they can conduct their own end-of-life testing to support their HEV life-cycle models.

Future Activities

New HEVs available from U.S., Japanese, and European manufacturers will be benchmarked during FY 2011. These will introduce advanced technologies such as lithium or advanced lead acid designs. Most new HEVs will be tested to reduce uncertainties about HEV technologies, especially the life and performance of their batteries, and any other onboard energy storage systems, and unique start/stop strategies. Just one example of this is Mazda 3's unique top-of-piston-cylinder-compression restart scheme. While the Mercedes S400 is the first HEV in the United States with a lithium battery, it is anticipated battery chemistries other than NiMH will arrive with new HEV models.

Publications

More than 200 HEV baseline performance, fleet, and accelerated testing fact and maintenance sheets, reports, and presentations have been generated by AVTA and all are available on the AVTA's Web pages. The HEV baseline performance testing procedures and vehicle specifications were also updated and republished on the AVTA's Web pages. The new 36 HEV reports, papers, fact sheets and presentations published during FY 2010 are listed below.

In addition to the below testing fact sheets, reports, and papers, the maintenance requirements and fuel use fact sheets are generated every three months for all of the HEVs. All of these documents can be found at: http://avt.inl.gov/hev.shtml and http://www.eere.energy.gov/vehiclesandfuels/avta/light_duty/hev/hev_reports.shtml.

The AVTA often reports on more than one vehicle technology in a single report or presentation. Therefore, HEV testing activities are often reported in the same document as PHEV testing. If such a presentation or report was listed in the PHEV Publications section, it will not be repeated below.

1. 2010 Mercedes Benz S400 VIN 5883 Baseline Performance Testing Fact Sheet. http://avt.inel.gov/pdf/hev/fact2010mercedesbenz.pdf
2. 2010 Mercedes Benz S400 HEV Accelerated Testing Fuel Use. http://avt.inel.gov/pdf/hev/mercedesbenz_ar.pdf
3. 2010 Mercedes Benz S400 VIN 6231 Fleet Testing Fact Sheet http://avt.inel.gov/pdf/hev/6231MercedesBenz10factsheet.pdf
4. 2010 Mercedes Benz S400 VIN 6231 Maintenance History http://avt.inel.gov/pdf/hev/ms_6231_2010_mercedes_benz.pdf
5. 2010 Mercedes Benz S400 VIN 5883 Fleet Testing Fact Sheet http://avt.inel.gov/pdf/hev/5883MercedesBenz10factsheet.pdf
6. 2010 Mercedes Benz S400 VIN 5883 Maintenance History http://avt.inel.gov/pdf/hev/ms_5883_2010_mercedes_benz.pdf
7. 2010 Toyota Prius VIN 0462 Baseline Performance Testing Fact Sheet. http://avt.inel.gov/pdf/hev/fact2010toyotaprius.pdf
8. 2010 Toyota Prius HEV Accelerated Testing Fuel Use. http://avt.inel.gov/pdf/hev/toyotapriusIII_ar.pdf
9. 2010 Toyota Prius VIN 0462 Fleet Testing Fact Sheet

http://avt.inel.gov/pdf/hev/0462ToyotaPrius10factsheet.pdf
10. 2010 Toyota Prius VIN 0462 Maintenance History http://avt.inel.gov/pdf/hev/ms_0462_2010_toyota_prius.pdf
11. 2010 Toyota Prius VIN 6063 Fleet Testing Fact Sheet http://avt.inel.gov/pdf/hev/6063ToyotaPrius10factsheet.pdf
12. 2010 Toyota Prius VIN 6063 Maintenance History http://avt.inel.gov/pdf/hev/ms_6063_2010_toyota_prius.pdf
13. 2010 Ford Fusion VIN 4757 Baseline Performance Testing Fact Sheet. http://avt.inel.gov/pdf/hev/fact2010fordfusion.pdf
14. 2010 Ford Fusion HEV Accelerated Testing Fuel Use. http://avt.inel.gov/pdf/hev/fordfusion_ar.pdf
15. 2010 Ford Fusion VIN 4699 Fleet Testing Fact Sheet http://avt.inel.gov/pdf/hev/4699FordFusion10factsheet.pdf
16. 2010 Ford Fusion VIN 0462 Maintenance History http://avt.inel.gov/pdf/hev/ms_4699_2010_ford_fusion.pdf
17. 2010 Ford Fusion VIN 4757 Fleet Testing Fact Sheet http://avt.inel.gov/pdf/hev/4757FordFusion10factsheet.pdf
18. 2010 Ford Fusion VIN 6063 Maintenance History http://avt.inel.gov/pdf/hev/ms_4757_2010_ford_fusion.pdf
19. 2010 Honda Insight VIN 0141 Baseline Performance Testing Fact Sheet. http://avt.inel.gov/pdf/hev/fact2010hondainsight.pdf
20. 2010 Honda Insight HEV Accelerated Testing Fuel Use. http://avt.inel.gov/pdf/hev/hondainsightII_ar.pdf
21. 2010 Honda Insight VIN 0141 Fleet Testing Fact Sheet http://avt.inel.gov/pdf/hev/0141HondaInsight10factsheet.pdf
22. 2010 Honda Insight VIN 0141 Maintenance History http://avt.inel.gov/pdf/hev/ms_0141_2010_honda_insight.pdf
23. 2010 Honda Insight VIN 1748 Fleet Testing Fact Sheet http://avt.inel.gov/pdf/hev/1748HondaInsight10factsheet.pdf
24. 2010 Honda Insight VIN 1748 Maintenance History http://avt.inel.gov/pdf/hev/ms_1748_2010_honda_insight.pdf
25. T. Gray. January 2010. 2007 Nissan Altima 2351 Hybrid Electric Vehicle Battery Test Results. Idaho Falls, ID. INL/EXT-10-17581.
26. T. Gray. January 2010. 2007 Nissan Altima 7982 Hybrid electric Vehicle Battery Test Results. Idaho Falls, ID. INL/EXT-10-17578.
27. T. Gray. January 2010. 2007 Toyota Camry 6330 Hybrid Electric Vehicle Battery Test Results. Idaho Falls, ID. INL/EXT-09-15276
28. T. Gray. January 2010. 2007 Toyota Camry 7129 Hybrid Electric Vehicle Battery Test Results. Idaho Falls, ID. INL/EXT-09-16113.
29. T. Gray. January 2010. 2006 Lexus RX400h 2575 Hybrid Electric Vehicle Battery Test Results. Idaho Falls, ID. INL/EXT-09-16116.
30. T. Gray. January 2010. 2006 Lexus RX400h 6395 Hybrid Electric Vehicle Battery Test Results. Idaho Falls, ID. INL/EXT-09-16115.
31. T. Gray. January 2010. 2006 Toyota Highlander 5681 Hybrid Electric Vehicle Battery Test Results. Idaho Falls, ID. INL/EXT-09-16114.
32. T. Gray. January 2010. 2006 Toyota Highlander 6395 Hybrid Electric Vehicle Battery Test Results. Idaho Falls, ID. INL/EXT-09-16115.
33. J. Francfort. September 2010. Hybrid Electric Vehicle Testing Results Achieved by the U.S. DOE's Advanced Vehicle Testing Activity. Idaho Falls, ID. INL/CON-10-18315

34. J. Francfort. June 2010. AVTA HEV, NEV, BEV and HICEV Demonstrations and Testing (DOE FY10 Merit Review). Washington, DC. INL/CON-10-18510
35. Carlson. September 2010. *AVTA: Hybrid Electric Vehicle Testing.* Vancouver, Canada. INL/CON-10-19769
36. J. Smart. September 2010. Hybrid and Battery Electric Vehicle Speed Curves: Results from the Advanced Vehicle Testing Activity. Idaho Falls, ID. INL/MIS-10-19895

C. Hydrogen Internal Combustion Engine (ICE) Vehicle Testing by DOE's Advanced Vehicle Testing Activity (AVTA)

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Objectives

- Assess the safety, and operating characteristics of 100% hydrogen fueled internal combustion engine (HICE) vehicles.
- Identify any engine and vehicle system degradations when operating HICE vehicles on 100% hydrogen.
- Perform independent testing on candidate 100% HICE vehicles.
- Quantify vehicle use patterns and fuel use per mile for the HICE vehicles currently providing data to the Advanced Vehicle Testing Activity (AVTA).

Approach

- Use the Integrated Waste Hydrogen Utilization Project (IWHUP) in Vancouver, British Columbia as a source of inexpensive high volume hydrogen to fuel eight 100% HICE pickups converted from natural gas fuel to 100% hydrogen fuel operations.
- Four additional same model HICE pickups are operating in four U.S. states
- AVTA collects, analyzes and reports the results from the data collected from the onboard data loggers on the twelve HICE pickups that are owned and operated by non-AVTA fleets.

Accomplishments

- Fleet testing of the HICE vehicles has demonstrated no safety problems during vehicle fueling and operations as the vehicles demonstrated consistent, reliable behavior.
- The 12 HICE vehicles averaged 13.5 miles per gasoline gallon equivalent (mpgge) after 80,899 test miles and 14,074 fleet trips.
- This is a very low-cost data collection effort for the Department of Energy (DOE) as no AVTA funds are being used to purchase, fuel, maintain, and operate the vehicles.

Future Directions

- There are currently no plans for additional work in this area beyond FT 2010.

Introduction

In past fiscal years (FY), AVTA was very actively involved in monitoring the Arizona Public Service Alternative Fuel Pilot Plant and testing 100% HICE vehicles, as well as ICE vehicles operating on blends of hydrogen and compressed natural gas (CNG). Four different HICE vehicle models that operated only on 100% hydrogen fuel, plus three additional vehicle models that operated on 15 to 50% hydrogen blended with CNG, were subjected to baseline performance and emissions testing. In addition, a small fleet of approximately 15 ICE vehicles that accumulated 240,000 test miles while fueled on hydrogen/CNG blends were also tracked for fuel use and operations.

During FY 2010, the AVTA hydrogen work was limited to tracking a group of 12 eTec/Roush Chevrolet Silverado pickups that were converted from natural gas to operate on 100% hydrogen. It should be noted that no OEMs were involved in converting these vehicles to operate on hydrogen.

Approach and Results

Given the recent decreased interest in hydrogen, this vehicle technology has not been an area of major research for AVTA. However, AVTA has continued to collect data on the eight eTec/Roush pickups operating at IWHUP in Vancouver, BC, as well as the four same model pickups operating in four U.S. states. All vehicle costs, from purchase to fueling, operations, and maintenance are paid for by the fleets operating the vehicles. Therefore, this is a very low-cost testing activity for the AVTA.

The twelve vehicles are all compressed natural gas Chevy Silverado base vehicles converted to operate on 100% hydrogen fuel. The vehicles are of a "crew cab" configuration, with six seat belt positions. All use three Dynetek carbon-fiber-wrap aluminum-lined tanks installed in the bed of the pickup (Figure 1) for onboard hydrogen storage. The nominal pressure is 5,000 psi (at 25°C) with a maximum pressure of 6,350 psi. The total fuel capacity for all three tanks is 10.5 gasoline gallon equivalents (gge). In addition to the fuel tanks, other modifications included a supercharger, hydrogen fuel rails, hydrogen injectors, and significant engine mapping control testing and modifications.

The AVTA completed the data collection for these vehicles during FY 2010. The twelve vehicles were operated for 80,899 miles. Based on the onboard data loggers, they are averaging 13.5 mpgge of hydrogen (Figures 2 and 3). The vehicles have been driven on 14,074 trips, during which they had an average trip distance of 5.7 miles.

The average idle time per trip is 16%, as measured as a percentage of the total engine run hours. The air conditioning was used an average of 11% of the time while the engine was running. Note that as would be expected, the fuel used per mile appears to be heavily influenced by the idle time per trip. As seen in Figure 2, bottom left graph, trips with engine-on idling times approaching 0% can have fuel use rates exceeding 20 mpgge. At the other extreme, trips with idle times exceeding 80% will have fuel use results of 5 mpgge or less. Note that the mpgge conversion used is: 1 GGE = 1.012 kg H_2.

Figure 1. Dynetek hydrogen fuel tanks in the bed of the pickup.

The vehicles safely used a total of 6,072 kg of hydrogen. The total engine run time was 3,198 hours and total idle time was 514 hours.

Future Activities

Unless DOE directs AVTA to test a technically interesting or innovative HICE vehicle, AVTA has discontinued HICE data collection and testing activities.

Publications and Presentations

Various publications document the pre-FY 2010 HICE testing. These 50-plus documents, as well as the two-page HICE fleet fact sheet, can be found at http://avt.inel.gov/hydrogen.shtml. The two-page eTec/Roush HICE vehicle fleet testing fact sheet can be found at:

http://avt.inel.gov/pdf/hydrogen/FactSheetChevy1500HDHydrogenICE.pdf

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

VEHICLE TECHNOLOGIES PROGRAM

HICE Fleet Testing - Summary Fact Sheet

Advanced Vehicle Testing Activity

2005 Chevrolet Silverado 1500HD Hydrogen ICE[1] Conversion

Fleet Performance

Operating Statistics[2]:

Vehicles in Fleet: 12

Total Miles: 80,899

Total Number of Trips: 14,074

Average Trip Distance (miles): 5.7

Percent Idle Time: 16%[3]

Percent Air Conditioner On Time: 11%[3]

Operating Performance:

Cumulative MPGGE: 13.5[4]

Total Fuel Consumed (kg H_2): 6,072

Total Engine Run Time (hours): 3,198

Total Engine Idle Time (hours): 514

Vehicle Specifications

Engine: 6.0 L V8

Fuel Capacity: 10.5 GGE

Nominal Tank Pressure: 5,000 psi

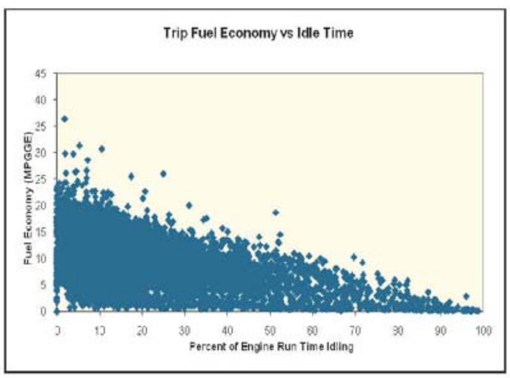
Seatbelt Positions: Five

Payload: 2,775 lbs

Features:

Four Speed Automatic Transmission

See HICEVAmerica Baseline Performance Fact Sheet for more information



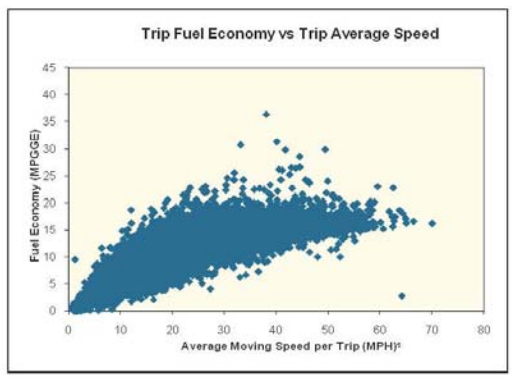


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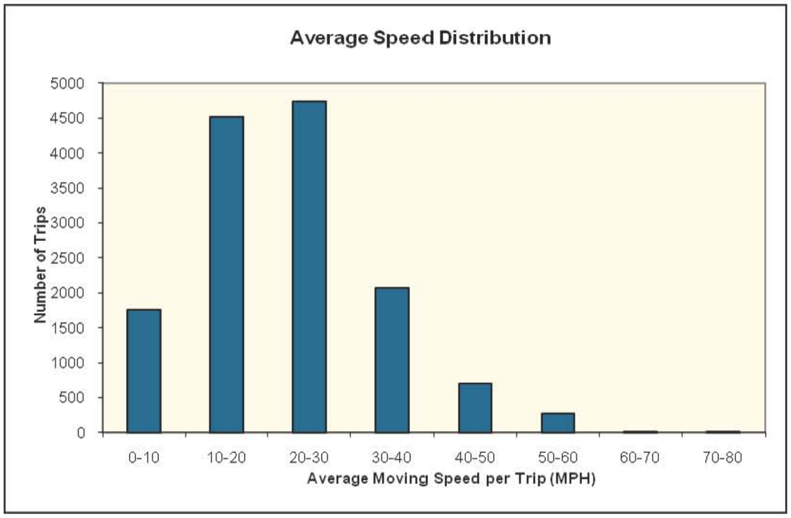
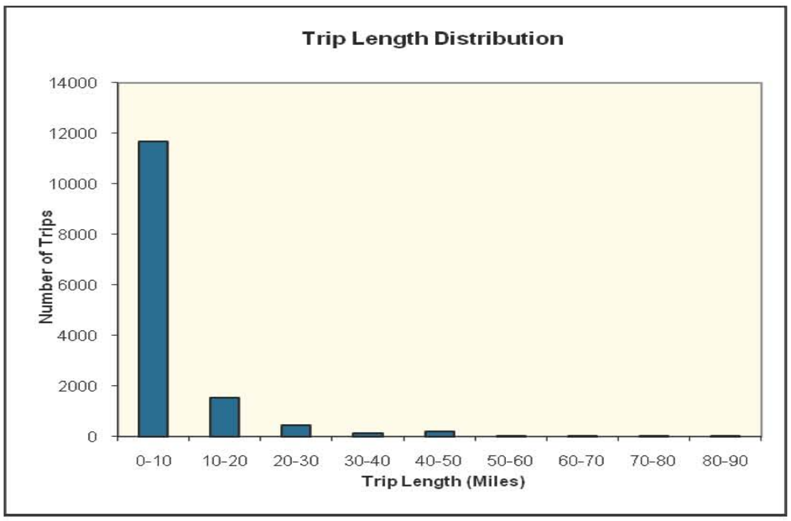
Figure 2. Page 1 of the eTec/Roush Chevrolet Silverado fleet testing activity fact sheet.





Notes:

1. Internal Combustion Engine
2. Data presented represents all electonically logged data, which is a subset of the overall fleet mileage
3. Percentage of total engine run hours
4. Miles per gallon gasoline equivalent (1 GGE = 1.012 kg H2)
5. Average speed of vehicle when moving, idle time not included in calculation

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Figure 3. Page 2 of the eTec/Roush Chevrolet Silverado fleet testing activity fact sheet.

D. Battery Electric Vehicle Testing by DOE's Advanced Vehicle Testing Activity (AVTA)

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Objective

- Support Federal and other fleet requirements for quality test data on pure battery electric vehicle (EV) models.
- Maintain documented test procedures and capabilities to support the continued introduction and operations of EVs in fleet environments, and expand the EV test base.

Approach

- Conduct EV testing on new models as requested by DOE, industry and other stakeholders.

Results

- Conducted EVAmerica baseline performance testing on the 2009 BMW Mini E EV during FY 2010. A total of 23 full size EV models have now been baseline performance tested by the AVTA.
- Initiated the testing of five EV conversions of United State Postal Service (USPS) light-duty Long Life Vehicles (LLVs).
- Initiated the development of Electric Drive and Advanced Battery (EDAB) Testbed Vehicle capable of testing a wide range of energy storage systems (ESS) during on-road driving and in dynamometer testing environments.

Future Activities

- Given the potential of this market and the expanding use of EVs, when manufacturers introduce additional EVs (such as the Nissan Leaf), the AVTA will test suitable new entrants.
- Complete the testing of USPS's electric LLVs (eLLVs) during FY 2011.

Introduction

FY 2010 saw the first non-specialty all electric vehicle (EV) from an original equipment manufacturer (OEM) since 1999. The BMW Mini E, while only released in limited numbers and limited states as a demonstration / test program, was the first full-size OEM EV tested by the AVTA since the 1999 Chrysler Epic. Recent announcements by numerous domestic and foreign OEMs and others, suggest upwards of 25 EVs may be offered in the United States in the next few years, including during FY 2011.

Approach and Results

BMW Mini E

The Mini E was subjected to the AVTA's EV America baseline performance testing, which included test track and dynamometer testing. The testing results highlights included:

A range of 129.5 miles at a constant speed of 55 mph and 104.2 miles at a constant speed of 65 mph

An UDDS dynamometer driving cycle test range of 142.5 miles

- A Highway dynamometer driving cycle test range of 137.3 miles
- Recharge times of 26.5 hours at Level 1 (110V / 12A), 4.5 hours at Level 2 (240V / 32A) and, 3 hours at Level 2 (240V / 48A)
- Acceleration time of 8.3 seconds (0 to 50 mph at 100% SOC)
- Maximum speed of 81.1 mpg at 100% SOC, with a 332 pound payload.

USPS eLLV Testing

The AVTA supported the United States Postal Service's (USPS) introduction and testing of approximately 500 electric delivery vehicles in the late 1990's, by reporting on the deployment and performance of these vehicles, including average driving profiles and energy (electricity) use. See the following website (middle of the page) for the nine reports that documented this activity. http://avt.inel.gov/fsev.shtml

The USPS is currently investigating the possibility of converting some or all of their current fleet of 142,000 light-duty long life vehicles (LLVs) into all-electric LLVs (eLLVs). The LLVs are the small box-like vehicles that make the final mail deliveries to homes and business in the United States. The USPS has contracted with five companies to convert one each LLV into eLLVs. The five companies are: AutoPort Inc., Bright Automotive, EDAG, Quantum, and Zap World. The USPS, not DOE, is paying the five conversion companies directly to convert the existing LLVs into eLLVs.

Given the USPS's past positive relationship with the AVTA and the AVTA's expertise in previously testing more than 100 different electric drive vehicle models, the USPS requested testing support from the AVTA. The testing parameters will include energy (electricity) use and range per charge under various test cycles and speeds, payload impacts, acceleration rates, maximum speed, maximum gradeability, charging efficiency, and time(s) to recharge. The operational fuel costs as well as the drivability of the five LLVs will also be gauged. The AVTA will assist in documenting all test procedures, conducting all phases of testing, installing onboard data loggers, analyzing the testing data, and reporting of the test results.

During FY 2010, the AVTA, in conjunction with the USPS, developed a series of industry standard and USPS specific testing regimes that will be used for testing all five ELLVs, including:

- Acceptance testing
- Inspection and measurement evaluation (onsite)
- Dynamic evaluation and testing (on closed test track)
- *EVAmerica* baseline performance testing (test track and dynamometer testing)
- Accelerated durability (on-road driving)
- USPS specific drive cycle testing on-road and on a dynamometer

As FY 2010 ended, the first eLLVs were being acceptance tested and being prepared for the EVAmerica and accelerated testing during FY 2011.

Electric Drive and Advanced Battery Testbed Vehicle Project

The AVTA initiated during FY 2010 the Electric Drive and Advanced Battery (EDAB) Testbed Vehicle Project, which includes the development of a testbed vehicle capable of testing a wide range of energy storage systems (ESS) during on-road driving and vehicle-based dynamometer testing. The testbed will be used to operate and utilize many different energy storage systems of various shapes and sizes typical battery electric vehicles. The testbed vehicle will also be capable of testing ESS intended for PHEVs and EREVs. The data acquisition system includes an on-board logger with on-board data storage. The logger will record CAN message parameters as well as analog signals as necessary to fully characterize the operation of the ESS during on-road driving and charging. The data acquisition system will be reconfigured prior to each ESS tested since the communication protocols and CAN messages will likely be different for each ESS tested.

This primary purpose of the EDAB is to be able to test the new ESSs that will be delivered to DOE for testing during FY2011.

Future Plans

The AVTA anticipates testing approximately six new models of OEM EVs during FY 2011; completing the testing of the five USPS eLLVs; and the initial testing of ESS deliverables via the EDAB.

Publications

The AVTA has published more than 100 testing reports, fact sheets, test plans, and other EV related documents prior to FY2010. All can be found at: http://avt.inel.gov/fsev.shtml

The only EV publication during FY 2010 was the Mini E EV America testing fact sheet, which can be found at: http://avt.inel.gov/pdf/uev/fact2009bmwmini.pdf

E. Advanced Technology Vehicle Level 1 Benchmark Summary

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Objectives

- Provide independent evaluation of advanced automotive technology by benchmarking high-efficiency vehicles as part of DOE's mission to obtain laboratory and field evaluations of HEVs, PHEVs, and EVs.
- Establish the state-of-the-art automotive technology baseline for powertrain systems and components through data from testing and analysis.
- Disseminate vehicle and component testing data to partners of DOE, such as national laboratories, USCAR, OEMs, and suppliers. Dispense data to support codes and standards developments. Provide support for model development and validation with test data.

Approach

- Utilize advanced and unique facilities with extensive instrumentation expertise. The Advanced Powertrain Research Facility (APRF) includes both a 4WD and 2WD chassis dynamometers with a wide range of instrumentation equipment and a focus on measuring energy consumption (fuel and electric).
- Refine test procedures and test plans based on a decade of experience in vehicle testing.
- Test the powertrain systems as well as the components in the system.
- Conduct baseline dynamometer testing of DOE's Advanced Vehicle Testing Activity (AVTA) vehicles before the accelerated fleet testing portion of the testing performed at Idaho National Lab.

Accomplishments

- ANL has benchmarked vehicles that range from mild hybrids to full hybrids, including a pure battery electric vehicle, by comprehensive testing on the chassis dynamometer with complete instrumentation.
- Distributed the test results and analysis through several mechanisms, such as reports, presentations, a web-based database and raw data sharing.
- Utilized the testing activity to directly assist in the development of codes and standards for PHEV and BEV test procedures; and to support model development and validation.

Future Directions

- Provide testing and vehicle systems expertise to further contribute to DOE's mission.

Introduction

The Advanced Powertrain Research Facility (APRF) has been testing advanced technology vehicles to benchmark the latest automotive technologies and components for the U.S. Department of Energy (DOE). The staff has tested a large number of vehicles of different types, such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and conventional vehicles (including alternative fuel vehicles).

Over the last decade, the staff have developed and earned a fundamental expertise in the testing of the next wave of energy-efficient vehicles. During this time, the instrumentation of the powertrains has evolved, and the test procedures have been refined. Two main levels of testing exist today. The first level is a basic but complete non-invasive instrumentation of a vehicle, which leaves the vehicle unmarked after the testing. The second level is an in-depth and comprehensive invasive instrumentation of a vehicle and the powertrain components, which leaves the vehicle with irreversible alterations.

This report summarizes Argonne's level 1 benchmark activities for FY10. The test approach is described in the first section, followed by a review of the DOE Advanced Vehicle Test Activity (AVTA) vehicle tests. The final sections focus on some special testing.

Approach

General Test Instrumentation and Approach

The testing presented in this report focuses on the basic and complete non-invasive level 1 type. Typically, Argonne receives the test vehicles on a loan from partners. Therefore, the vehicles must leave the test facility in the "as-received" condition. This limits the instrumentation to sensors that can be easily removed without leaving any damage.

Despite this requirement, Argonne strives to achieve a minimum level of instrumentation. If an internal combustion engine is in the vehicle, the speed, fuel flow (at least from modal emissions or the fuel flow meter, if possible), and engine oil temperature (achieved through dip stick instrumentation) are instrumented. For electrified vehicles, a power analyzer is used to record, at a minimum, the voltage and main current of the energy storage. If the vehicle requires charging, the electric power from the source is recorded. Furthermore, any sensors that can be implemented without permanent damage are typically included, such as temperature sensors in locations of interest (e.g., a battery pack vent). These additional sensors vary from vehicle to vehicle. A final part of the level 1 benchmark is the recording of messages from the vehicle information buses. This information will also vary widely from vehicle to vehicle.

In addition to the minimum instrumentation described above, further sensors may be added, depending on the vehicle powertrain and special interests. Such additions also must be non-invasive.

Purpose of the Benchmark

A major goal of the benchmarking is to enable petroleum displacement through data dissemination and technology assessment. The data generated from the vehicle testing and analyses are shared through several mechanisms, such as raw data, processed data, presentations, and reports.

A fundamental gateway to the data is the Downloadable Dynamometer Database (D^3), which is a public website (https://webapps.anl.gov/vehicle_data/). The D^3 provides access to data and reports from vehicles tested on the standard test cycles. Further information on D^3 is available in a separate section of the FY2010 annual reports entitled, "Upgrade On-Line Database for Vehicle Testing Results."

The data directly serve the development of codes and standards; as well as the development and validation of simulation models. These activities impact the modification of test plans and instrumentation. Additional partners in the testing are the U.S. manufacturers and suppliers that are available through the U.S. Council for Automotive Research (USCAR).

Many DOE research activities rely on the benchmark laboratory and fleet testing results to make progress toward their own goals. Figure 1 details some of these DOE research activities and partners.

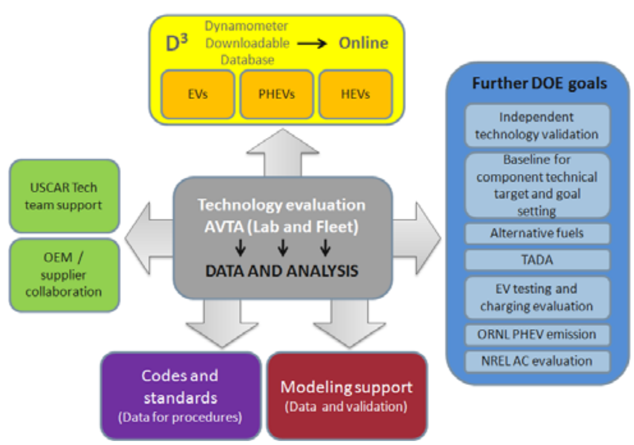

Figure 1. Data Dissemination and Partners

The benchmark program leverages DOE's AVTA activities. Idaho National Laboratory (INL) procures new advanced technology vehicles to be tested in accelerated fleet testing. As part of the evaluation, these vehicles are benchmarked in the ARPF. Figure 2 illustrates the process. Further information on AVTA is available at http://avt.inel.gov/.

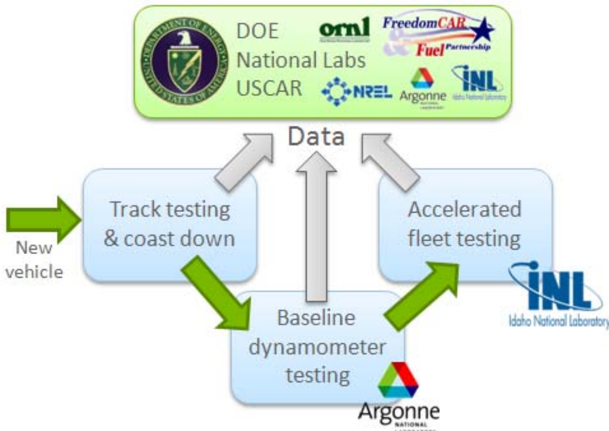

Figure 2. Advanced Vehicle Testing Activity Process

Overview of ATVA Vehicles Tested

Each year, the ATVA partners select a set of vehicles that best represents the new technologies available on the market. For FY2010, the selected vehicles were the 2010 Honda Insight, 2010 Toyota Prius (third generation), 2010 Ford Fusion Hybrid, 2010 Mercedes S400 Hybrid, and the 2010 Mini E.

Figure 3 presents pictures of all the AVTA test vehicles on the dynamometer, as well as the reasons to test the vehicles and some further points of interest. Each of these points of interest will be addressed in the respective vehicle sections of this report.

Figure 3 also includes the label fuel economy comparisons between the tested vehicles and their closest conventional counterparts in each manufacturer's lineup. The hybrid systems of these vehicles appear to provide a significant improvement in efficiency. The conventional vehicles show an increase in fuel economy, from 30% to 50% for the mild hybrids to the full hybrids, respectively.

The following sections of this report provide a vehicle description, review the powertrain operation, and address some of the interesting aspects of each vehicle.

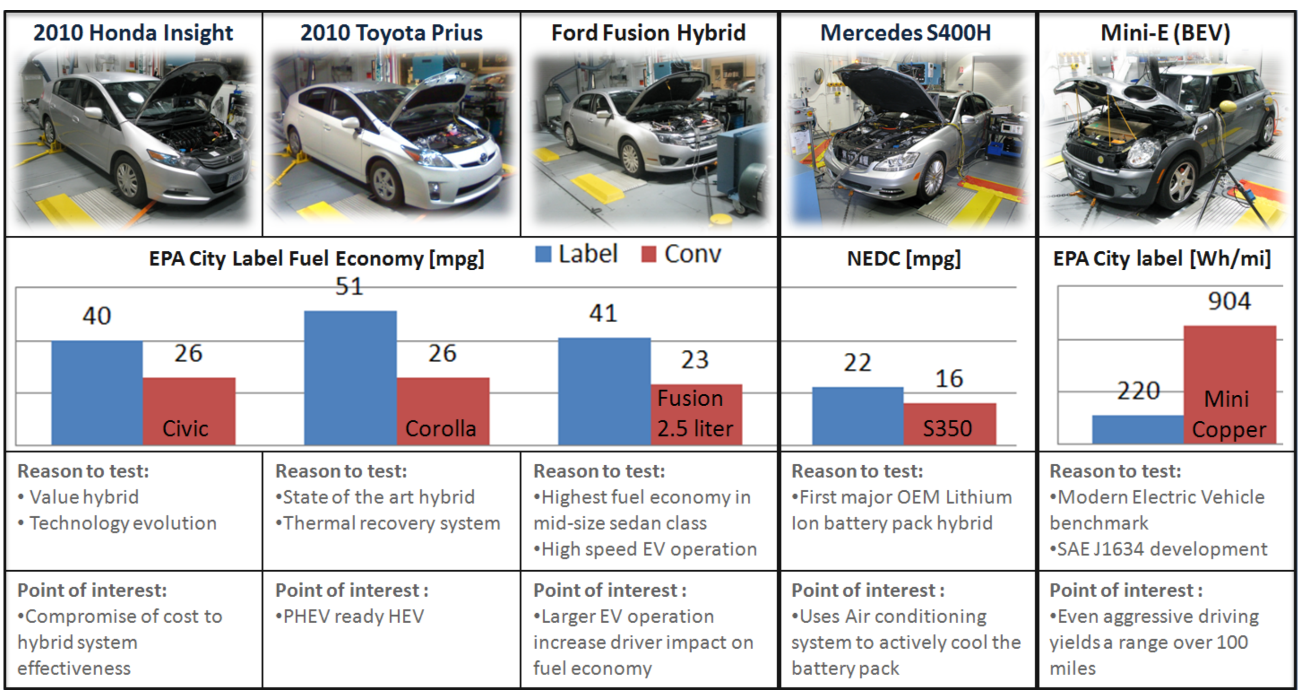

Figure 3. Summary and Overview of Vehicles for Level 1 Benchmarking in FY2010

2010 Honda Insight: The Value Hybrid

Vehicle Description

The Insight uses the newest generation of Honda's Integrated Motor Assist (IMA) system paired to a mechanical continuously variable transmission (CVT) to provide fuel economy improvements.

Table 1 presents the technical specifications.

Table 1: 2010 Honda Insight Powertrain Specifications

Architecture	Pre-transmission mild hybrid
Engine	1.3-L in-line 4-cylinder i-VTEC 98 bhp @ 5,800 rpm 123 ft.lb @ 1,000–1,700 rpm
Transmission	Continuously variable transmission (CVT)
Motor	PM AC synchronous motor 13 hp (10 kW) @ 1,500 rpm 58 ft.lb
Battery	Nickel metal hydride (NiMH) 35 hp (26 kW) 5.75-Ahr rated capacity 100.8 V nominal

Vehicle Operation

Figure 4 shows the powertrain operation of the Insight. The system uses a single, small electric machine directly coupled to the engine, which enables engine idle stop, electric assist, regenerative braking, and fuel cut-off operation. This configuration does not enable electric-only operation. Through the CVT, the engine speed is decoupled from the wheel speed. The engine operates between 1,000 and 1,500 rpm over 50% of usage through the UDDS, Highway, and US06 cycles.

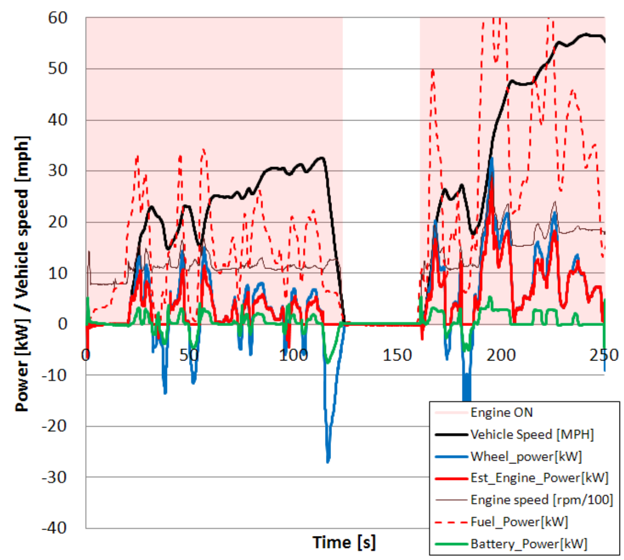

Figure 4. Insight Operation on a Hot-start UDDS

The driver can select an "Econ" mode, which primarily "softens" the accelerator pedal mapping to reduce the driver inputs. There was no fuel economy difference between the "Normal" mode and the "Econ" mode on the UDDS cycle, but one could expect an impact in real-world driving.

Further data, more cycles, and additional analysis for the Insight operation are available in the vehicle-specific report.

Points of Interest

This generation of Honda hybrid is intended to reduce the cost and purchase price. A comparison between a 2006 Honda Civic hybrid and the Insight system shows the following:

Reduced maximum regenerative power capabilities, from over 10 kW for the Civic to 8 kW for the Insight, as measured at the battery pack; and

Reduced hybrid system usage during driving, as shown in Figure 5.

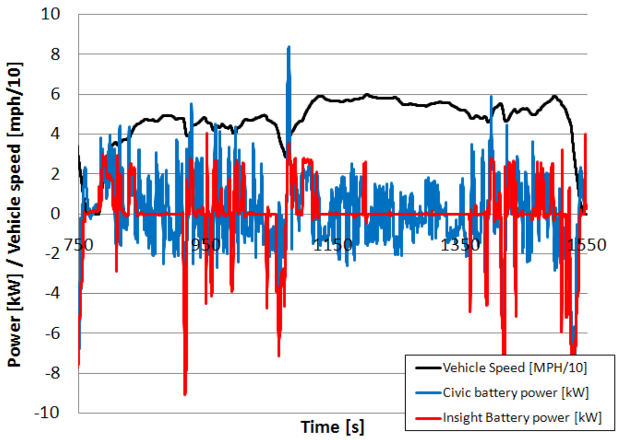

Figure 5. Usage of Hybrid System of an Insight Compared with a Civic Hybrid

The system cost reduction appears to be achieved through the new motor and battery limits and reduced usage. The reduced usage could also be the consequence of prolonging component life.

2010 Toyota Prius: The Reference Hybrid

Vehicle Description

The third generation Prius uses the newest generation of the Toyota hybrid system, which includes an Atkinson-cycle engine, two electric machines, and a power split device used to control the proportion of power transfer between the mechanical and the electrical path. Table 2 presents the technical specifications.

Table 2: 2010 Toyota Prius Powertrain Specifications

Architecture	Power split hybrid
Engine	1.8-L in-line 4-cylinder DI VVT-i Atkinson-cycle 98 bhp (73 kW) @ 5,200 rpm 105 ft.lb (142 N.m) @ 4,000 rpm
Transmission	Power split (EVT)
Motor	PM AC synchronous motor 80 hp (60 kW) 153 ft-lb (142 N.m)
Battery	Nickel metal hydride (NiMH) 36 hp (27 kW) Ahr rated capacity 201.6 V nominal

Further technical powertrain attributes that contribute to increased fuel economy include exhaust gas recirculation (EGR), an electrical coolant pump, an exhaust heat recirculation system, and a specialized generator motor.

Vehicle Operation

The Prius operation features that enable fuel savings are engine idle stop, electric operation at low road lows up to 38 mph, regenerative braking, electric assist, and engine operation at higher efficiency by decoupling it from the road load.

Figure 6 shows the operation of the Prius in urban driving. After a key cycle event, the engine seems to operate at nominal load during a warm-up where the road load transients are provided by the hybrid system. Figure 7 presents the hybrid operation, which appears to be a brief electric launch with an acceleration phase with the engine ON, followed by an electric cruise and regenerative braking. On a warm UDDS, the powertrain operates with the engine OFF for 66% of the time.

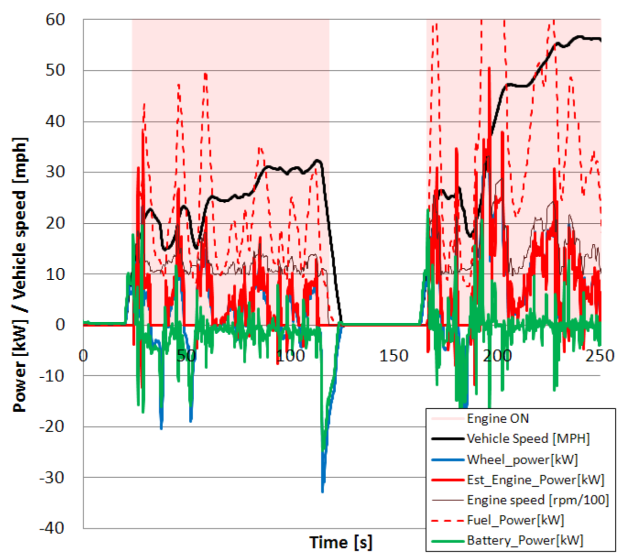

Figure 6. Prius Operation on a Hot-start UDDS

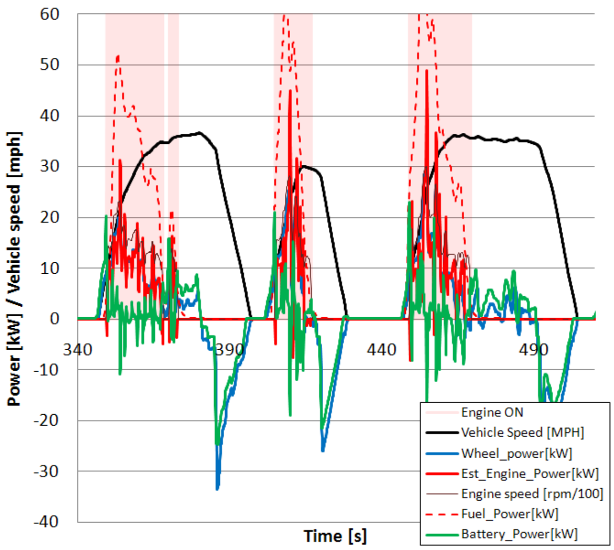

Figure 7. Prius Operation on a Hot-start UDDS

Compared with earlier Prius generations, the larger engine appears to operate at lower engine speeds more frequently to increase average system efficiency. This contributes to improved fuel economy, especially at higher vehicle speeds.

Similar to the Insight, the Prius features an "ECO" mode that is available to the driver, which changes the pedal mapping of the vehicle. However, it does not change fuel economy results on the drive cycles.

Further data, more cycles, and additional analysis for the Prius operation are available in the vehicle-specific report.

Points of Interest

A significant focus in the new generation has centered on thermal management, including the engine and catalyst warm-up strategy. Testing of past PHEVs has shown prolonged periods of engine OFF time, which can be a challenge for emissions and reaching a powertrain operating temperature.

For the first 200 seconds of a cold-start UDDS, the engine operation is much less dynamic from the warm operation. Additionally, a constant fueling rate is observed during the first 50 seconds of engine operation, which is most likely used for the catalyst warm-up.

The exhaust heat recirculation system enables the powertrain to reach steady operating temperatures sooner compared with earlier Prius generations. This is reflected by a lower cold-start penalty on the UDDS of 10%, compared with that of 15% for the second-generation Prius.

These improvements help the fuel economy and emissions for the standard hybrid, but they would enable much greater gains for PHEVs.

2010 Ford Fusion Hybrid:

Vehicle Description

The Fusion is Ford's first car to add a hybrid powertrain. It can be considered the second generation of Ford's hybrid system, after the hybrid Escape. Similar to the Prius, the Fusion uses an Atkinson-cycle engine, two electric machines, and a power split device used to control the proportion of power transfer between the mechanical and the electrical path. Table 3 presents the technical specifications.

Table 3. 2010 Ford Fusion Hybrid Powertrain Specifications

Architecture	Power split hybrid
Engine	2.5-L in-line 4-cylinder DI Atkinson-cycle 156 bhp (116 kW) @ 6,000 rpm 135 ft.lb (183 N.m) @ 2,250 rpm
Transmission	Power split (eCVT)
Motor	PM AC synchronous motor 105 hp (78 kW) 153 ft.lb (207 N.m)
Battery	Nickel metal hydride (NiMH) 35 hp (26 kW) Ahr rated capacity 275 V nominal

Vehicle Operation

The Fusion operation features that enable fuel savings are engine idle stop, electric operation at low road loads up to 47 mph, regenerative braking, electric assist, and engine operation at higher efficiency by decoupling it from the road load. The vehicle acceleration performance is at a high level due to the larger engine.

Figure 8 presents the hybrid operation, which appears to include a brief electric launch with an acceleration phase with the engine ON, followed by an electric cruise and regenerative braking. Compared with the Prius, the engine is cycled ON/OFF more frequently. However, the overall ON time of the engine over a hot-start UDDS cycle is the same as the 66% for the Prius.

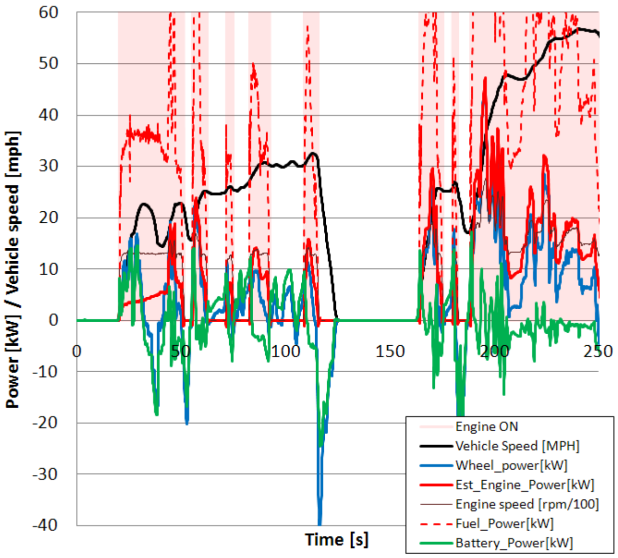

Figure 8. Fusion Operation on a Hot-start UDDS

Further data, more cycles, and additional analysis for the Fusion operation are available in the vehicle-specific report.

Points of Interest

The cycle-to-cycle powertrain variability induced by the driver is quite significant on the Fusion. This can be explained by the electric vehicle (EV) operation envelope of the Fusion, as shown in green in Figure 9. Each point represents the effort at the wheel at a vehicle speed for the UDDS cycle. A large number of operating points are closely located around the limit of the electric-only operation envelope. Therefore, minimal changes in pedal input from the driver may or may not cause the engine to turn ON.

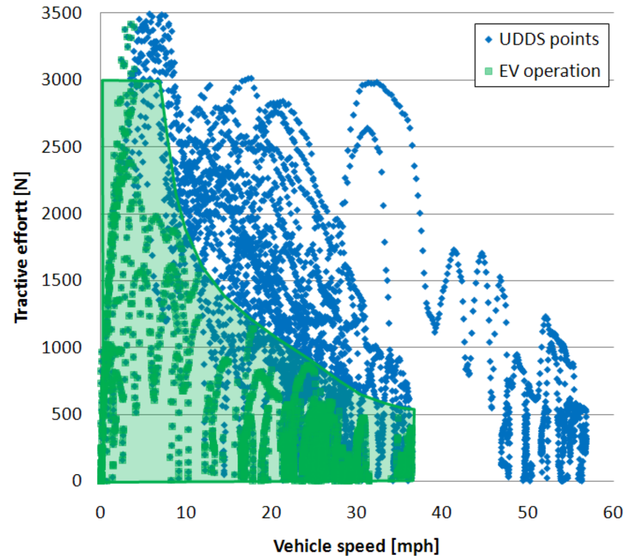

Figure 9. Electric-only Operation Area Overlaid with Urban Cycle Operating Points

2010 Mercedes Hybrid: Production Li-ion Hybrid

Vehicle Description

The S400h is Mercedes' first hybrid sold in the United States. Similar to the Insight, the S400h has a single, small electric motor directly coupled to the engine, but a 7-speed automatic transmission brings power to the wheels.

Table 4 presents the technical specifications.

Table 4: 2010 Mercedes S400 Hybrid Powertrain Specifications

Architecture	Power split hybrid
Engine	2.5-L In-line 4-cylinder DI Atkinson-cycle 275 bhp (205 kW) @ 6,000 rpm 284 ft.lb (385 N.m) @ 2,400–5,000 rpm
Transmission	7-speed automatic transmission
Motor	PM AC synchronous motor 20 hp (15 kW) 118 ft.lb (160 N.m)
Battery	Lithium-i (Li-ion) 35 hp (26 kW) Ahr rated capacity 275 V nominal

Furthermore, the air-conditioning compressor, the power steering, and the 12-V charging system are all powered by the high-voltage system.

Vehicle Operation

Figure 10 presents the operation of the S400h. The system uses the single, small electric machine directly coupled to the engine, which enables engine idle stop, electric assist, regenerative braking, and fuel cut-off operation. This configuration does not enable electric-only operation.

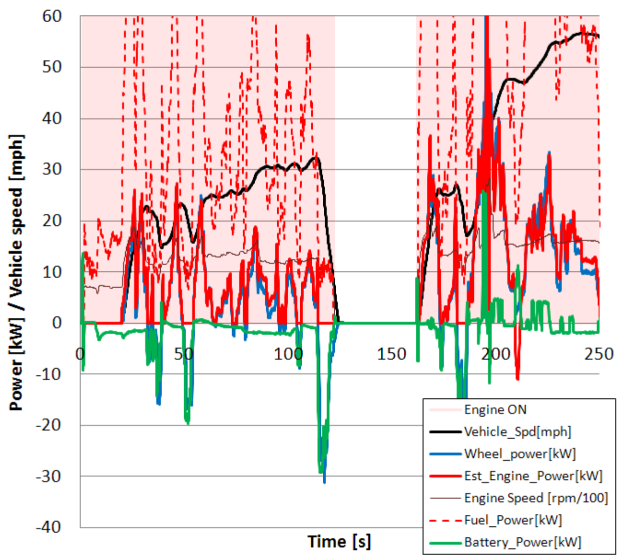

Figure 10: S400h Operation on a Hot-start UDDS

The 7-speed automatic transmission enables significant fuel savings by maintaining the lower engine speed and increasing the average engine load, thus improving the average engine efficiency.

The hybrid system assist seems to be limited on the rather "mild" UDDS. The hybrid system appears to assist during the shift events and aids the recovery of braking energy.

Points of Interest

This production Li-ion battery is well-protected by an aggressive cooling system, which actively uses the air-conditioning system. At a 25°C test cell temperature, the air-conditioning system automatically starts to cool the battery pack down after a period of more aggressive driving, such as a 20% scaled UDDS cycle (20% faster speeds and 20% shorter time period; therefore, equidistant), as shown in Figure 11. The cabin temperature is unaffected, but the driver cannot force the air-conditioning to turn off. The engine idle stop feature is maintained during this forced cooling, since the air-conditioning compressor is powered by the high-voltage bus.

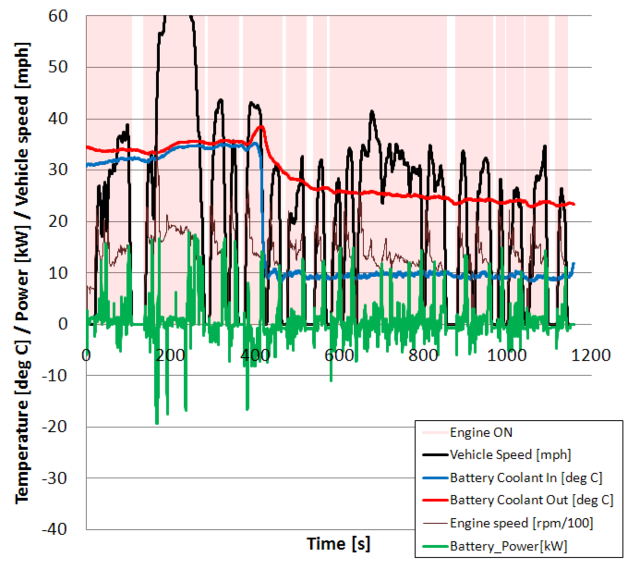

Figure 11: Forced Battery Pack Cooling Using the Air-conditioning System

The Li-ion chemistry does present significant advantages, such as a better energy capacity-to-weight ratio than the more standard NiMH batteries. Another feature that contributes to overall system efficiency is the lower battery resistance losses compared with NiMH, as shown in Figure 12. The system resistance of the S400h is 0.08 ohms, while the other systems have resistances that are about 3 times higher.

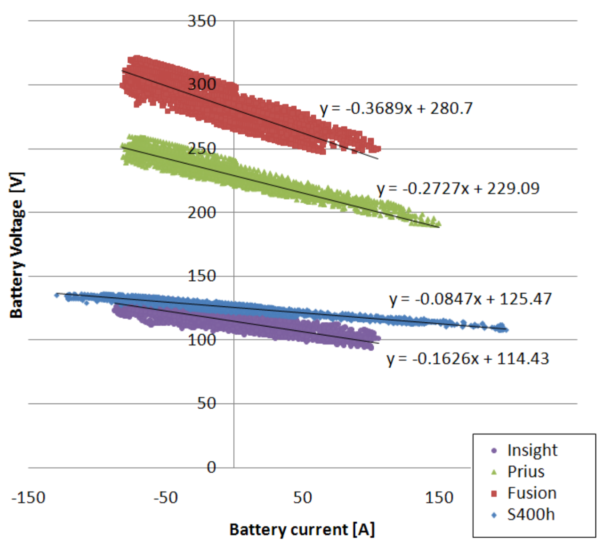

Figure 12: Different Battery Polarization Curve Comparisons

Further data, more cycles, and additional analysis for the S400h operation are available in the vehicle-specific report.

<u>2010 BMW Mini E: Production Electric Vehicle</u>

The Mini-E is an OEM-level conversion of a Mini Cooper to a pure BEV. BMW has operated an experimental fleet of 500 vehicles in the United States. An electric motor drives the front wheels through a differential. A Li-ion battery pack is the energy storage system on-board, which provides the electric power. Table 5 presents the technical specifications. All accessories, such as the air-conditioning compressor, the 12-V charging system, and the power steering run off the high-voltage bus.

Table 5: 2010 Mini-E Powertrain Specifications

Architecture	Battery electric vehicle
Transmission	Single gear
Motor	AC motor 200 hp (150 kW)
Battery	Lithium-ion (Li-ion) 35-kWh capability

Vehicle Operation

The operation of BEVs is straightforward. The motor provides the tractive power to the wheel during accelerations and cruise periods, and it also provides regenerative braking torque during decelerations. At very low speeds the hydraulic brakes are engaged, and the regenerative brake torque is faded out. The final mode of the vehicle is charging. Further information is available at the AVTA website at http://avt.inel.gov/.

Points of Interest

This BEV is useful for investigating the proposed EV short-cut test methods. The current test protocol for BEVs requires one to fully charge the vehicle and repeat the test cycles until the vehicle cannot meet the trace. The total distance driven determines the EV range. The recharge event determines the amount of electric energy used by the vehicle, which combined with the range, defines the electric energy consumption. Since the range of modern EV Li-ion battery technology can reach 150 to 250 miles, the full-charge method can take from 12 to 18 hours of continuous testing. Therefore, a short-cut method is needed and is under investigation.

The proposed short-cut methods involve two parts. The first part consists of completing four test cycles with a fully charged vehicle. The charge after the four test cycles is recorded and combined with the distance driven to provide the electric energy consumption. In the second part, the capacity of the battery pack is tested by discharging the pack by driving at high steady speeds, such as 55 mph. The battery capacity is combined with the energy consumption to extrapolate the vehicle's range. Figure 13 shows examples of the full-charge test and some short-cut test data points.

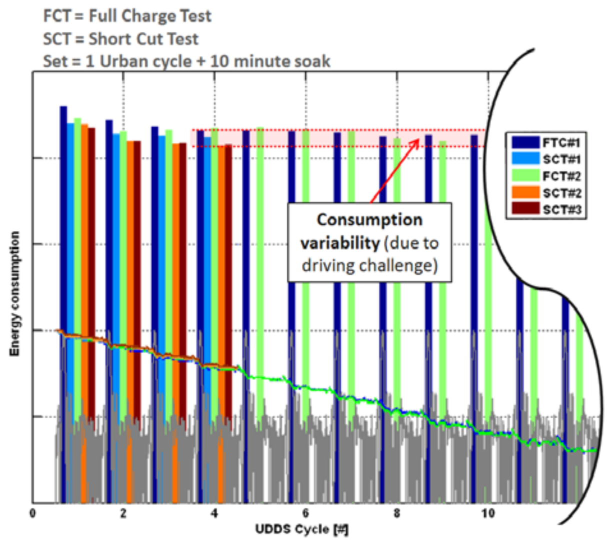

Figure 13: Full-charge Tests on the UDDS Cycle, Including the Short-cut Tests

The short-cut method predicted the range within 8% of the actual range for the UDDS and within 1% for the highway cycle. The variability is driven by the inconsistencies induced by the driver, battery cooling energy, and cold-start energy consumption differences.

Driving Intensity Impact on Energy Consumption

Most drivers on the road drive more aggressively than the certification cycles. Therefore, a standard part of the test plan is to investigate the impact of driving intensity on energy consumption with scaled UDDS cycles. Scaled UDDS cycles are obtained by scaling the vehicle speed profile and the time scale proportionally, so that the total distance driven on the scaled cycle is the same as on the standard cycle.

Figure 14 shows the energy consumption results over scaled UDDS cycles, as well as the US06 cycles for the different powertrain types tested in FY2010. The EV is the most sensitive to driving intensity, and the mild hybrid is the least sensitive. The S400h is proportionally less affected by more aggressive driving because of overall lower average powertrain system efficiency. The higher average loads actually cause the engine to operate at a higher average efficiency, which, in turn, is negated by the higher average power. However, the Mini-E powertrain system efficiency is higher compared with the S400h. Therefore, the higher average power required by more-aggressive driving is not offset by higher system efficiency, thus resulting in a higher impact on energy consumption.

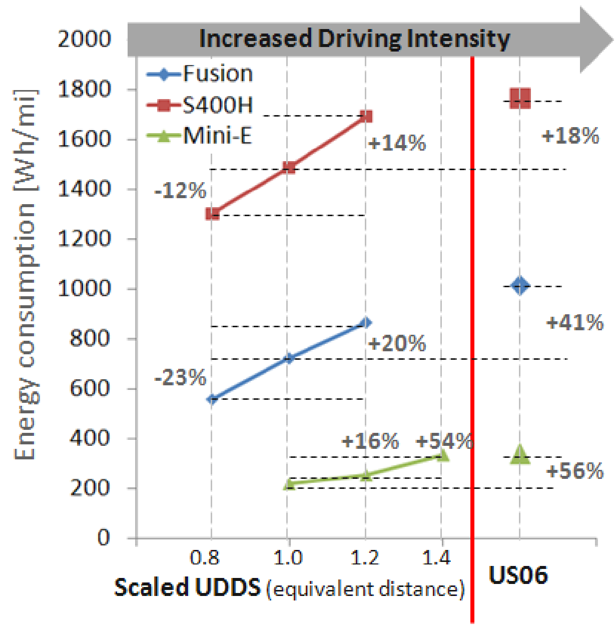

Figure 14: Drive Intensity Impact on Energy Consumption for Different Powertrains

Air-Conditioning Impact

The air-conditioning system in vehicles is another element that has a large impact on energy consumption. Figure 15 illustrates the impact of the air-conditioning system on the UDDS and highway cycle for the different powertrain types tested in FY2010. The average power required by the air-conditioner in the EV increases the energy consumption by over 80%. The least impacted is the mild hybrid with the larger engine. In this case, because the average powertrain efficiency is lower, the impact of the average air-conditioner is lower.

The ratio of average air-conditioning power to average tractive power is lower during higher-speed driving. As such, the overall impact of the air-conditioning system is lower for highway driving than for urban driving.

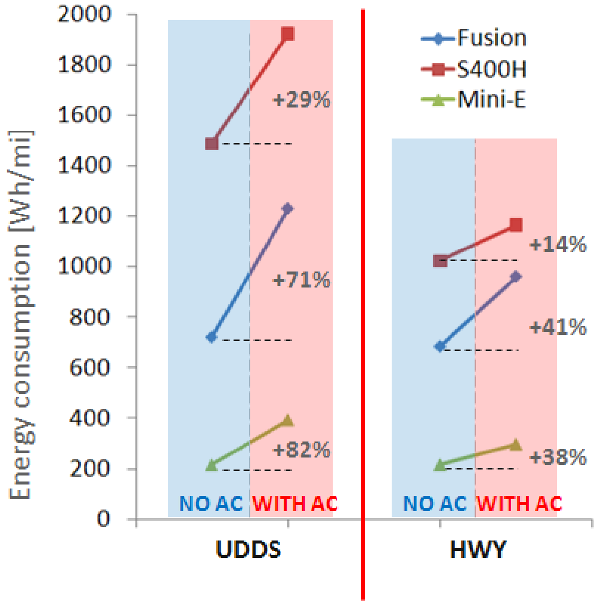

Figure 15: Air-conditioning Impact on Energy Consumption for Different Powertrains

<u>Conclusions</u>

Argonne benchmarked vehicles that range from mild hybrids to full hybrids, including a pure BEV. The benchmarking involved comprehensive testing on the chassis dynamometer with complete vehicle instrumentation. The test results and analyses were distributed through several mechanisms, such as reports, presentations, and raw data sharing. The testing activity directly benefited the development of some codes and standards and supported model development and validation.

This report summarizes Argonne's basic vehicle benchmark activity for FY2010. To obtain more detailed information and further analysis for each vehicle, the reader is encouraged to review the vehicle reports.

<u>Selected List Publications/Presentations</u>

1. Rask, Duoba, Lohse-Busch, Bocci, 2010, "Model Year 2010 (Gen 3) Toyota Prius Level 1 Testing Report," ANL/ES/RP-67317.
2. Rask, Bocci, Duoba, Lohse-Busch, 2010, "Model Year 2010 Honda Insight Level 1 Testing Report," ANL/ES/RP-67317.
3. Rask, Bocci, Lohse-Busch, Duoba, 2010, "Model Year 2010 Ford Fusion Level 1 Testing Report," ANL/ES/RP-67317.
4. Lohse-Busch, 2010, "Advanced Technology Vehicle Benchmark and Assessment," VSS016, 2010 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review.

F. In-depth Research of Light Duty Vehicles – Model Year 2010 Toyota Prius

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Objectives

- Perform thorough vehicle instrumentation, testing, and analysis of the model year (MY) 2010 Toyota Prius.
- The data collected will be used for a wide range of tasks, including:
- Technology benchmarking and evaluation,
- Simulation validation,
- Advanced vehicle component evaluation, and
- Vehicle testing procedure/methodology development.

Approach

- Purchase the vehicle to be tested and its corresponding service manuals and diagnostic tools.
- Leverage previous high-level data collection practices and experience.
- Install engine and driveshaft torque sensors. This part of the preparations is unique to in-depth vehicle research data collection.
- Develop, create, and install significant instrumentation.
- Record controller area network (CAN) signals through testing as a means of measuring parameters that would otherwise be too difficult, too expensive, or impossible to obtain.
- Run a broad range of tests for cycle fuel economy, energy consumption, performance testing, and steady-state operation for vehicle assessment, component evaluation, and technology benchmarking.

Accomplishments

- Improved engine torque sensor design, with minimal vehicle reconfiguration required for integration.
- Developed methods for CAN and scan-tool-based data acquisition for recording signals within the vehicle bus.
- Successfully conducted significant vehicle and component testing and analysis for the MY 2010 Toyota Prius.

Future Directions

- Continued data collection leveraging on this test vehicle, making further use of the installed vehicle instrumentation.
- Areas of particular interest include:
- Improved engine efficiency testing and mapping
- Vehicle temperature sensitivity to more extreme ambient conditions

Introduction

For this work, a MY 2010 Toyota Prius (Gen 3) Hybrid Level 2 benchmark was conducted. The intensive evaluation of this industry-leading vehicle will serve many purposes relating to vehicle technology benchmarking and evaluation.

The MY 2010 Toyota Prius represents the most recent iteration of Toyota's hybrid system, which began wide-scale production in 1997. As with the majority of Toyota hybrid systems, this version includes an Atkinson-cycle engine, two electric machines, and a power-split device used to control the allocation of energy between the electric and mechanical (fuel) power paths. To the same degree as most hybrid systems, fuel economy and emission gains are enabled through regenerative braking, engine-off at idle, electric operation at low road loads, electric assist, and the general ability to operate the engine more optimally. In addition to Toyota's broad goal of generally improving fuel economy, its goals for the MY 2010 Prius are to improve the vehicle's real-world fuel economy — namely, hot and cold weather operation — and to improve high-speed operation with minimal compromise in terms of urban driving.

To accomplish these goals, the majority of the Prius' hybrid components have been redesigned or updated. Engine displacement has increased to 1.8L versus the previous 1.4L, to increase efficiency at higher vehicle speeds. To maintain low-speed vehicle efficiency, an exhaust gas recirculation (EGR) system was included. Additional engine related improvements include an electric water pump and an exhaust-heat recirculation system. This recirculation system allows for exhaust heat (loss) leaving the engine, to be absorbed into the engine coolant when desired. The hybrid transmission and electric machines were also redesigned to facilitate an overall transmission length and mass reduction. More specifically, gearing was included between the motor/planetary gear set and compound gearing was also included. The motor/planetary gearing is to allow for reduced motor torque while still providing high power through increased motor speed (~13,000 rpm maximum versus the previous ~9000 rpm maximum speed). The compound gearing integrates several functions, such as a parking gear and counter drive, into a more compact package. In addition to these mechanical components, the power electronics and battery packaging have also been redesigned to facilitate mass and volume reductions. Overall, the changes support the focus of reducing the mass and volume of the newly developed system while continuing to improve its fuel economy.

Vehicle Data Acquisition

The Toyota Prius was outfitted with a significant amount of sensors to provide a range of information, from temperatures to mechanical and electrical power flows. While the following sections do not discuss all of the instrumentation included in this vehicle, they provide a more thorough discussion of the important sensor categories developed for analyzing the MY 2010 Toyota Prius.

Temperature Sensor Overview

Given the MY 2010 Prius' significant improvements related to real-world fuel economy (and more specifically to hot-and-cold ambient operation), the vehicle was extensively outfitted with thermocouples to evaluate a large range of component and general operating temperatures. Figure 1 shows an overview of the main cooling system for the MY 2010 Prius, as well as the sensor placement within the cooling system. The significant amount of temperature information available from this instrumentation allows for a thorough analysis of energy flow within the cooling system from the various components, which is important in understanding the impact of operating temperature on vehicle efficiency. In addition to thermocouples, a flow sensor is also included in the exhaust heat recovery system to better understand its operation and efficiency.

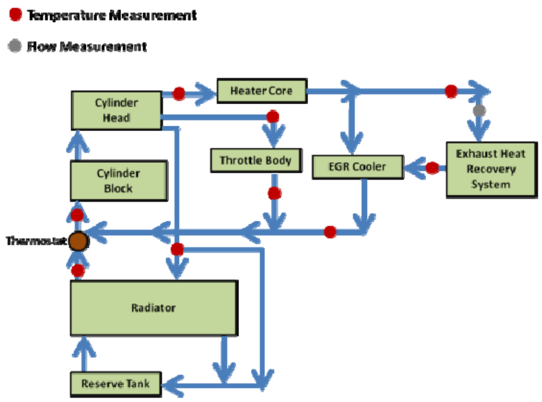

Figure 1. Main Cooling System Overview and Thermocouple Placement.

In addition to the main cooling system, significant temperature instrumentation has been included in the separate power electronics cooling loop for the Prius. The Prius uses a separate, stand-alone loop for cooling the vehicle power electronics and one of the electric machines. Given the significant component coolant research that is ongoing throughout many DOE laboratories and in industry, this information is particularly valuable. Figure 2 shows the power electronics cooling loop and the location of the temperature sensors.

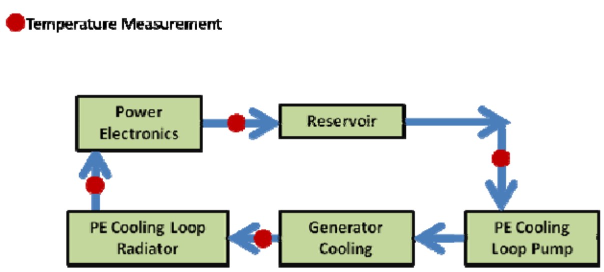

Figure 2. Power Electronics Cooling System and Thermocouple Placement

In addition to the coolant temperatures illustrated in Figures 1 and 2, instrumentation was also included to determine the exhaust and catalyst temperature for the emissions/exhaust system. Given the importance of understanding emissions for advanced vehicles, these temperature sensors will assist in evaluating emissions strategies in a vehicle with frequent engine stops and starts. Additionally, exhaust pressure sensors were included before and after the exhaust heat recovery system to assess the restriction in exhaust flow and, thus, reduction in power related to the exchanger system. Figure 3 shows the exhaust system instrumentation.

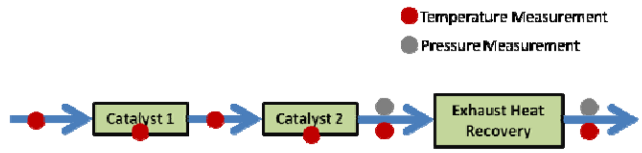

Figure 3. Exhaust System Instrumentation

Engine and transmission oil temperatures are also signals of significant interest. Both engine and transmission temperatures have a significant impact on vehicle fuel economy. Moreover, these working fluids are often particularly sensitive to temperature and, thus, very relevant to the real-world fuel economy of the MY 2010 Prius. Figures 4 and 5 show the thermocouple placement for the engine oil and transmission oil respectively.

Figure 4. Engine Oil Temperature Sensor

Figure 5. Transmission Oil Temperature Sensor

Vehicle Data Network Acquisition

The tested version of the MY 2010 Prius utilizes two controller area networks (CANs): one to monitor the more traditional vehicle operation and the second (CAN 2) to monitor the advanced hybrid powertrain operation. Relevant CAN signals were read into a computer with a compatible software interface, which allowed recognized signals to be measured and recorded. While many additional CAN signals were decoded and collected during the testing of the Prius, the most relevant signals collected are shown in Table 1.

Table 1. Selected CAN Signals Collected

Primary Analysis Signals	
CAN Signal	**Units**
Accel Pedal Position	%
Brake Pedal	%
PRNDL Position	
ECO Bar Indicator	
EcoMode	
PwrMode	
EVMode	
Brake Regen	Nm
Brake Mechanical Torque	Nm
Brake SW	
Drive Torque	Nm
Engine Torque	Nm
Engine MAP	kPa
Engine Speed	RPM
Engine Coolant Temperature	C
Engine Temp. Intake	C
MG2 Speed	RPM
AC Compressor Spd	RPM
AC On/Off	
Rough Battery SOC	%
Battery Current	A

HV Electrical System Measurement

For high-voltage (HV) electrical energy consumption, a current clamp and a voltage tap were installed. Details on the locations are shown in Figure 6.

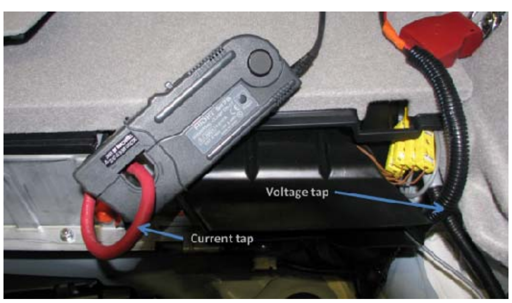

Figure 6. Position of Current Clamp and Voltage Tap

Fuel Flow Measurement

To measure fuel flow, the production fuel line was spliced, allowing a high-resolution, in-line fuel flow meter to be integrated downstream from the fuel tank and pump. A quick-connect connection was created to facilitate efficient test setup and takedown. Outputs from this configuration are volumetric flow and temperature of the fuel. Figure 7 shows the connections for fuel measurement.

Figure 7. Fuel Measurement Connection

Engine Torque Measurement

The 2010 Prius was fitted with a torque sensor to monitor output torque of the engine following the damper and flywheel. This type of instrumentation and location allows for extremely accurate engine torque to be determined. The data are then used in conjunction with the fuel flow data and engine speed data to produce an accurate map of engine fueling versus speed and load. The engine torque sensor uses a fairly standard torque sensor inserted between the transmission input and the damper. Figure 8 shows the torque sensor and transmission-side flange that were mounted onto the Prius transmission.


Figure 8. Engine Torque Sensor Mounted to Transmission Input

The additional space occupied by the sensor and related mounting flanges was added through the inclusion of a spacer between the engine and the transmission. Adjustments to the engine mounts were also made to accommodate the additional space required by the torque sensor assembly. Figure 9 shows the spacer, prior to final machining, which fits over the torque sensor assembly and flywheel/damper.

Figure 9. Torque Sensor Spacer

Select Research Findings

The following sections discuss some of the noteworthy findings related to testing this vehicle. These discussion items represent a small fraction of the information and insight gained during the testing of this advanced hybrid vehicle.

UDDS and Highway Fuel Economy

Although a wide variety of drive-cycles were used in the evaluation of the MY 2010 Prius, of particular interest are the urban dynamometer driving schedule (UDDS) and highway cycles. Figure 10 shows the tested fuel economy of the MY 2010 (Gen 3) Prius compared to the previous generation. As seen in the figure, the current-generation vehicle shows improved fuel economy performance for each cycle, but the "cold" urban cycle shows the largest increase in fuel economy. This finding synchronizes with the vehicle's mission of improved real-world fuel economy, which is directly related to vehicle warm-up and "cold" performance.

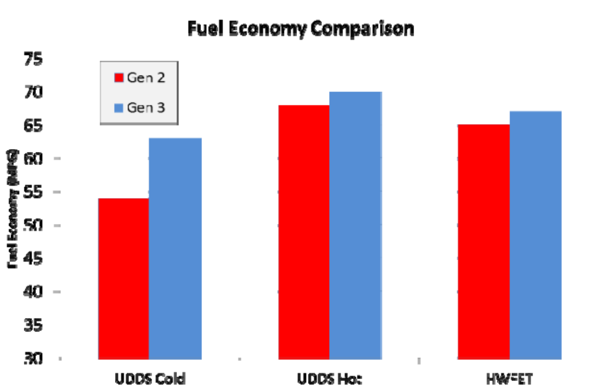

Figure 10. Gen 3 versus Gen 2 Fuel Economy Comparison

UDDS Catalyst Warm-up Strategy

One of the major reasons for the reduced fuel economy observed in Figure 10 relative to Cold versus Warm UDDS operation is the need for acceptable vehicle emissions for the initial engine start. Under this condition, the emissions system has not been warmed up, and so the vehicle seeks to quickly bring the catalysts to their activation temperatures and to stabilize the vehicle temperature. This is typically done through additional fueling during the vehicle/catalyst warm-up phase. The Prius uses an alternative approach.

As shown in Figure 11, the Prius uses a constant and low fueling rate for the initial 50 s of engine operation. Following this initial period, engine fueling begins to vary, but remains higher compared to the Warm UDDS fueling. During the initial 50-s warm-up, vehicle tractive power is provided mainly by the high-voltage battery, which allows the engine warm-up to occur somewhat offline from the vehicle requirements.

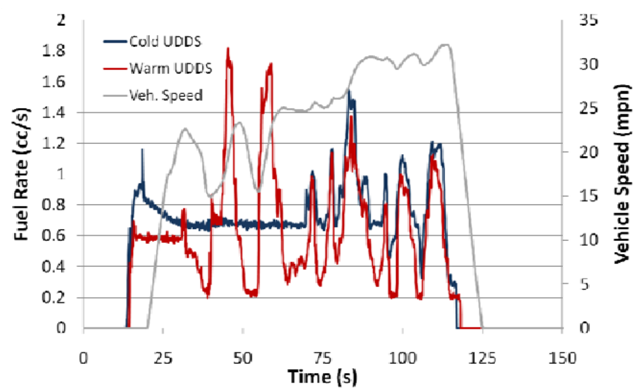

Figure 11. Cold versus Warm Engine Fueling at Engine Start

The initial 50-s period may be thought of primarily as a catalyst warm-up strategy, while the operation following this initial warm-up period may be considered as a more general vehicle warm-up strategy. This initial warm-up behavior allows the emissions system to quickly become active without using a large amount of additional fuel and is one of the major reasons for the improved Cold UDDS fuel economy relative to the previous-generation Prius. To exemplify the effectiveness of the catalyst warm-up strategy, Figure 12 shows the front catalyst temperature and fueling rate for a subsection of both the Cold and Warm UDDS cycles.

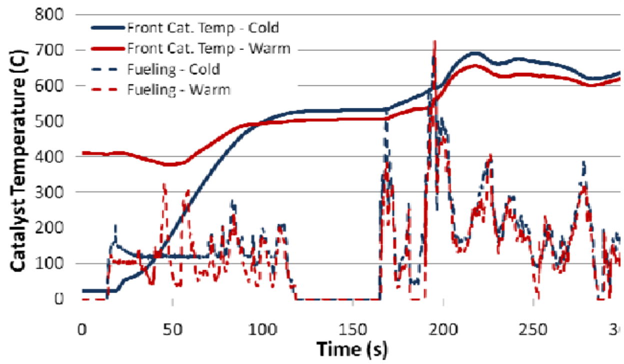

Figure 12. Cold versus Warm Front Catalyst Temperature and Fueling Rate

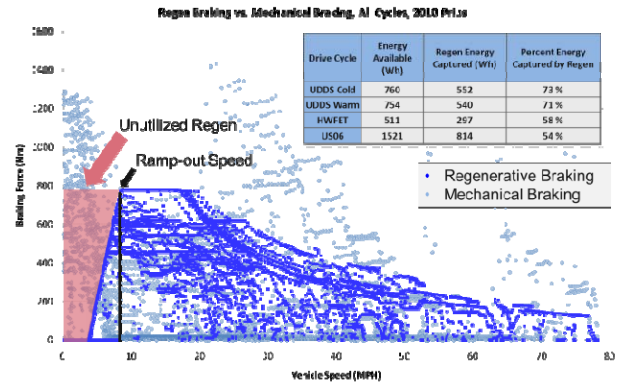

Figure 13. Estimated Regenerative Braking Envelope

Regenerative Braking

One of the major fuel economy enablers for any hybrid vehicle is the ability to capture energy that would be otherwise lost through vehicle braking. Several factors are incorporated in a vehicle's ability to capture regenerative braking energy. At lower vehicle speeds, regenerative braking is typically reduced to allow for acceptable drivability and vehicle feel. Once the vehicle has reached a suitable speed for smooth regenerative braking, a significant amount of vehicle braking can be done by using the regenerative braking system. As braking force and/or speed increase, the available regenerative braking power increases, and it soon increases above the regenerative energy system capability of the vehicle. This restriction is typically related to battery or electric machine power. Figure 13 shows an estimated regenerative braking envelope for the MY 2010 Prius. The low-speed ramp-out can be observed to begin at approximately 9 mph and is near zero around 4 mph. As braking power increases with speed and force, the system limits of the regenerative braking become visible. Figure 13 also shows the estimated energy capture efficiency for the Prius over various cycles. This table compares the available power at the wheels to the energy that was captured in the battery. As would be expected, cycles with higher braking loads and vehicle speeds (US06 and Hwy) show a reduction in the amount of energy captured relative to the total available.

Electric Machine Usage

As with previous generation Prius powertrains, the MY 2010 Prius hybrid transmission contains two electric machines. The larger of the two machines (MG2) is typically considered the tractive motor, since it often assists with vehicle propulsion and regenerative braking. The smaller electric machine (MG1) is typically considered to be a generator since its primary function is to act as a generator to absorb engine power. As discussed in the introduction, the newest generation of Prius transmission has a ratio between the transmission and MG2. This added ratio results in higher speeds compared to previous generations of Prius transmissions. Figure 14 shows the MG2 usage for the Urban, Highway, and US06 cycles. Similarly, Figure 15 shows MG1 usage for the same set of cycles.

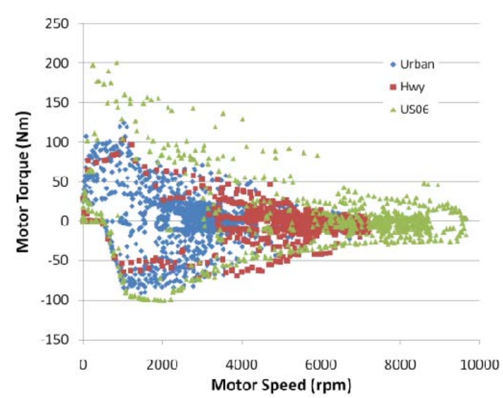

Figure 14. Electric Machine (MG2) Usage

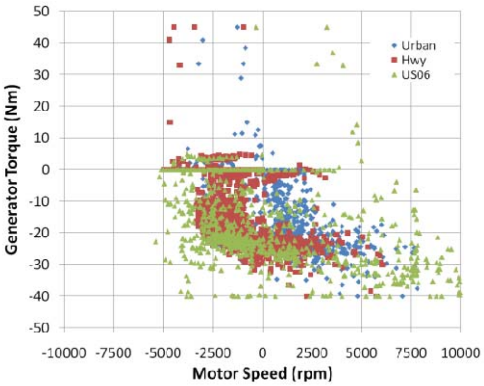

Figure 15. Electric Machine (MG1) Usage

Engine Usage and Efficiency

One of the most noteworthy features of the MY 2010 Prius is its larger 1.8L engine. This larger engine size allows for the engine to run at lower speeds during a significant portion of the regulatory cycles, which aids in increasing the overall system efficiency. Additionally, the engine efficiency is fairly high and consistent across a relatively large operating envelope. Figure 16 shows the engine speed and load usage points for the Urban and Highway cycles, as well as the estimated efficiency at a selection of relevant usage points. As expected, the larger engine exhibits a significant amount of lower speed engine usage — around 1200-1300 rpm. Additionally, the engine efficiency is fairly high for most portions of significant engine operation.

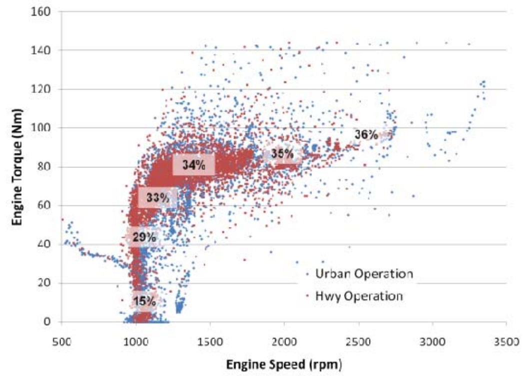

Figure 16. Urban and Highway Engine Usage and Efficiency

Conclusions

A significant amount of time and effort was spent on the instrumentation, testing, and analysis of the MY 2010 Toyota Prius. Specific instrumentation was developed to evaluate the most noteworthy aspects of this vehicle. Additionally, testing was tailored to the vehicle to efficiently and effectively benchmark and evaluate this advanced technology vehicle. The results and analysis included in this report represent a small, but important, subset of the entire project.

G. Comparing Performance Data from All PHEV Conversions Tested at ANL to Characterize PHEV Energy and Emissions Constraints

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Objectives

- Collect data and report to DOE on what has been learned to-date about PHEV conversions relative to most efficient approaches to use of stored energy, emissions compliance issues, configuration, and control strategy trends.
- Focus on the constraints that govern emissions control. (To-date, much of the analysis of PHEVs has been for energy efficiency and fuel displacement.)
- Find limits to blended depleting strategies in terms of thermal warm-up and temperature maintenance.
- Identify energy and emissions management strategies in PHEVs and HEVs tested over the past several years.

Approach

- Analyze the comparisons between conversion PHEVs and identify emissions certification hurdles.
- Mine data from ANL's extensive past PHEV test list and find the operational characteristics that caused high emissions. Identify trends in energy management, temperature, fuel consumption and resulting emissions.

Accomplishments

- Analyses of past HEV and PHEV testing at ANL were organized and presented at a major conference on engine control.

Future Directions

- ANL will make the analysis and the raw data more available on-line for a broad audience so that engineers in the field of engine control and systems will better understand the challenges and can arrive at successful solutions.

Background and Approach

Emissions control is most challenging for PHEVs that are constrained to "blended" operation during depleting mode. A blended PHEV type does not have the capability to drive electric-only during a given cycle. This means that the engine must be used during high-load portions of the cycle. However, the decisions made by the controls designer reflect choices in fundamental trade-offs of charge depletion rate (increased petroleum displacement) and high-emissions engine-on operation. ANL has tested a number of retro-fitted PHEVs, all with different approaches to engine operation. Enough data are available to observe some trends. The analysis approach includes looking at charge-sustaining operation with successful emissions control and closely comparing this to the depleting operation, where thermal state and engine-start conditions are different.

Charge-Sustaining Hybrid Engine-Start Analysis

Initial engine start and warm-up is the key strategy element of total-cycle engine emissions control. This is true for charge-sustaining and charge-depleting operation. The first data analyzed were from the initial hybrid Prius and its evolution from Gen 1 to Gen 2 based on cold-start testing using the urban dynamometer drive cycle [UDDS]. A conservative approach was taken in the 2001 (Gen 1) Prius. Advances were made in either the controls or the hardware for the Gen 2 Prius to facilitate engine shut-down after the first "hill" in the UDDS cycle, as seen in Figure 1.

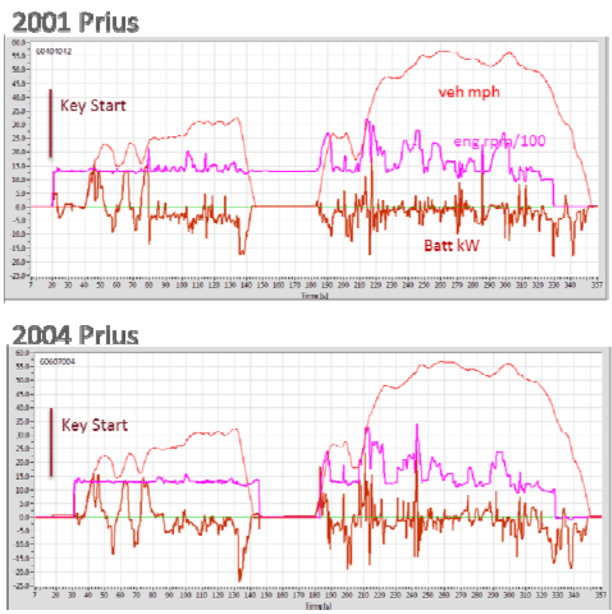

Figure 1. Gen 1 and 2 Prius Cold-Start UDDS Data Showing Initial Start Strategy

Further analysis of the hot-start UDDS in later-generation Prius hybrids shows the trend toward delaying the engine more and more after start-up in the interest of saving fuel. In Figure 2, the 2010 Gen 3 Prius data show that the engine does not start until after the vehicle starts accelerating. It appears that if the driver were only moving the vehicle around a parking lot, for example, it might be possible to do so without starting the engine.

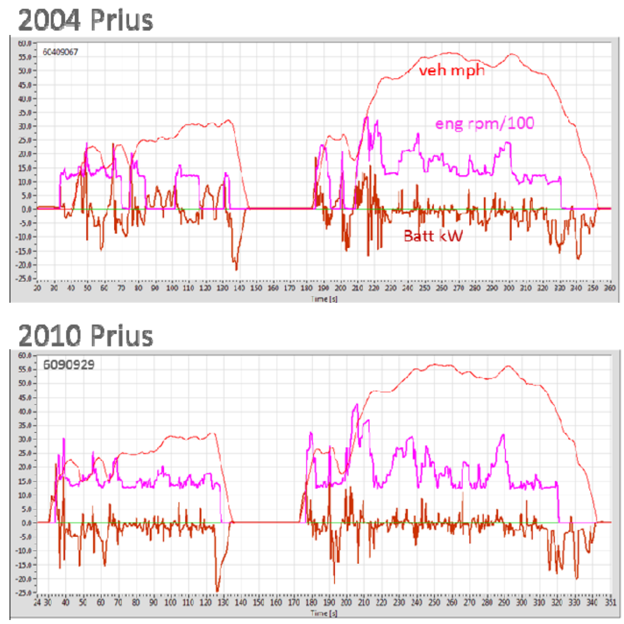

Figure 2. Gen 2 and Gen 3 Prius Comparison of Hot-Start UDDS Data Showing Initial Start Strategy Differences

Charge-Depleting Engine-Start Analysis

In depleting mode, the engine comes on to satisfy road or speed limitations of the electric-drive portion of the powertrain. Figure 3 shows data from city cycle testing of the Hymotion Prius conversion. The engine speed trace shows when the engine comes on. It starts in the beginning to satisfy warm-up, and it stays on during the second "hill" because the powertrain must run the engine during high-speed (>40 mph) operation, but for the remainder of the cycle, the engine only comes on to satisfy peak power demands. A solid red line on this chart estimates with some precision the "engine-on" periods.

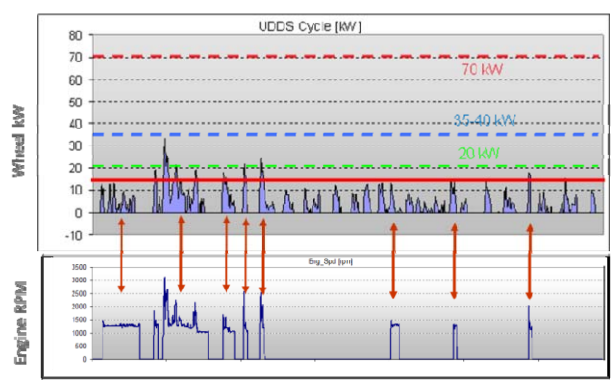

Figure 3. Hymotion Prius PHEV Depleting Operation

Charge-Depleting Emissions Analysis

Before PHEV emissions data were available, one of the major questions researchers had was whether the extended periods of engine-off would be periods of particularly high exhaust emissions. The hypothesis was that if the catalyst were cooling off for 10-12 minutes, the next engine start would produce emissions on the order of the initial engine start at the beginning of a cycle.

Figure 4 shows data from a depleting test where the engine was off for 12 minutes during the UDDS cycle. The emissions rate traces show that in fact, very low emissions are measured during this test. It appears that blended PHEV operation can keep emissions rates low.

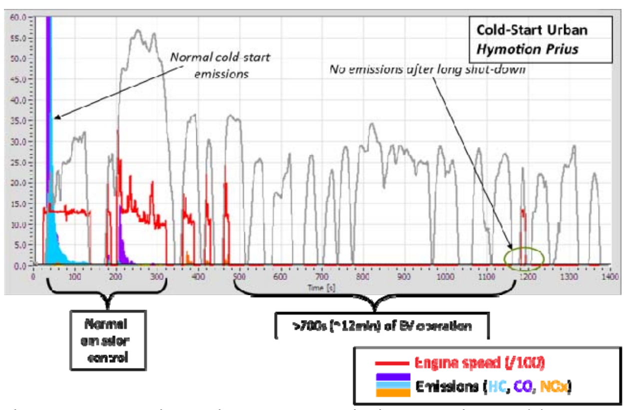

Figure 4. Hymotion Prius PHEV Emissions During Cold-Start UDDS Cycle

Figure 5 shows the different strategies taken by two different PHEV conversion companies. In the top graph, the engine start was suppressed until the power and/or speed limit of the electric drive was reached and the engine started during the highest-load part of the cycle. For in-use driving, this strategy may have kept the engine off more often than if the engine were invoked at lower speed and loads, as is seen in the lower graph.

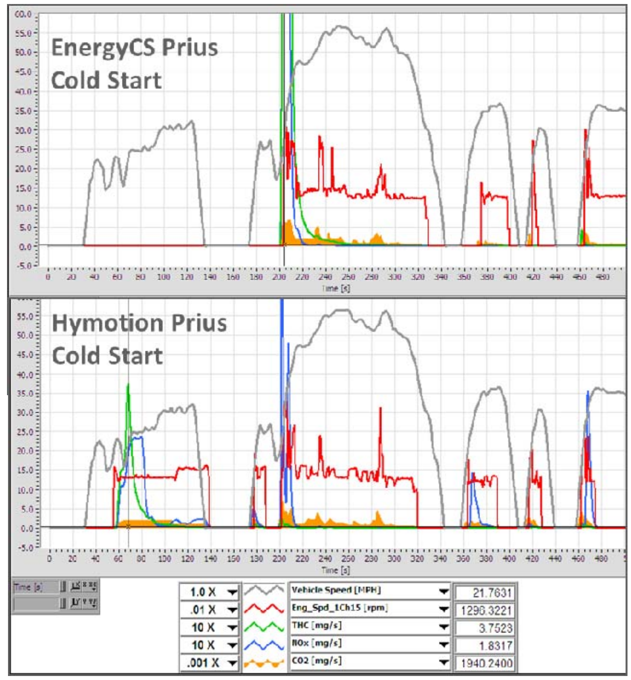

Figure 5.Comparison of Prius PHEV Initial Engine-Start Strategies in Cold-Start UDDS Cycle

However, looking at the total-cycle emissions levels throughout the charge-depleting test cycles (Figure 6), it can be seen that the emissions rates are significantly higher in the initial cold-start and in later cycles. Expected charge-sustaining emissions are shown to compare the depleting emissions data for both vehicles.

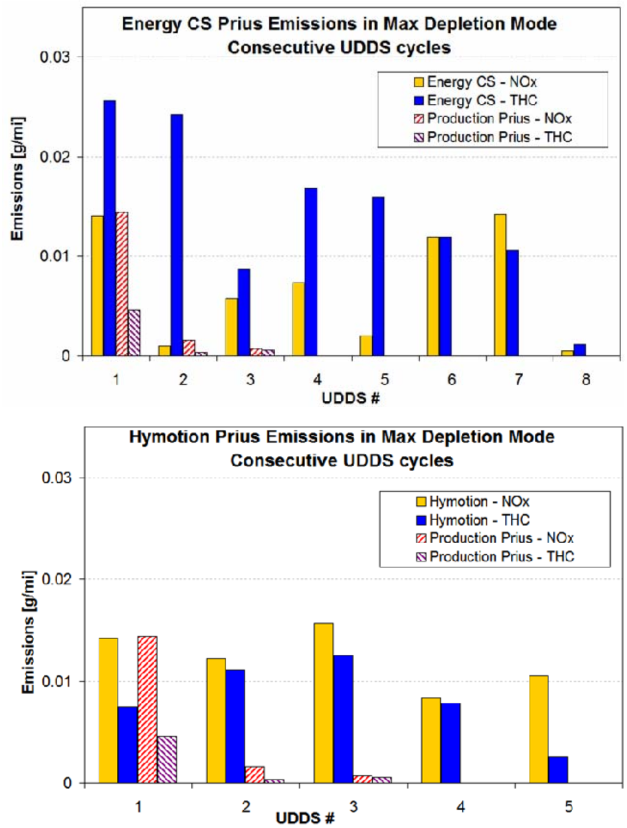

Figure 6. Cycle Emissions Levels for Charge-Depleting Operation Compared to Charge-Sustaining Operation

Conclusion

This investigation drew upon years of extensive and lengthy PHEV dynamometer tests and focused on the issue of emissions control. Conclusions were drawn based upon the various different Prius and Escape hybrid PHEV-conversion approaches. One of the major findings was that sensitivity of the initial cycle start was of much more importance than restarts throughout the remainder of the UDDS cycle. In fact, emissions levels from engine restarts even after extended periods of engine-off did not differ much from what is characteristic of charge-sustaining results. Although some conversions did not control emissions well, some calibrations were able to provide very low emissions when the initial engine-start was allowed to run through its normal warm-up strategy. This approach takes away from overall fuel savings; however, this trade-off is necessary in order to achieve emissions certification.

One curious speculation arises from the fact that the Gen 3 Prius includes an extensive thermal-management system to accelerate engine warm-up using exhaust heat. This system would significantly leverage fuel savings in a PHEV version of the Gen 3 Prius. Toyota has announced plans for a 2012 PHEV version of the Gen 3 Prius, which will undoubtedly take advantage of the novel thermal-management system.

Publications/Presentations

1. Duoba, M., "HEV/PHEV Operation for Engine Emissions Control," Advanced Engine Control Symposium, Tianjin, China, Nov 3, 2010.

H. Upgrade On-Line Database for Vehicle Testing Results

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Objectives

- Provide a user-friendly web-based database repository for the latest technology hybrid vehicle test data. Reports to include data summaries of all hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), electric vehicle (EV) and high-tech conventional vehicles tested at Argonne within the Vehicle and Systems Simulation and Testing (VSST) Program.
- Enable free access by industry, universities, and the general public. (Argonne has named it the **Downloadable Dynamometer Database, or D^3**. It is an easy-to-use research tool that allows for the transfer of Argonne's latest advanced vehicle data for analyses and education. The web address is https://webapps.anl.gov/vehicle_data/)

Approach

- Collect vehicle performance data from testing on Argonne's vehicle test facility — the 4WD and 2WD chassis dynamometer vehicle test facilities.
- Thoroughly review and perform critical analyses of the test vehicle results to verify data accuracy and quality control.
- Reduce the data for upload onto the publicly available Internet website, then link it into the database to provide search and reference capabilities.
- Upload new vehicle test data from Argonne's Advanced Powertrain Research Facility as available.

Accomplishments

- Redesigned the front-end of the database to provide a more attractive visual entrée to the database, with links to basic information on the VSST test program and information about the advanced vehicle testing facilities included at Argonne's Center for Transportation Research.
- Revised the database format from search-based to nested-folder-based, thereby allowing users to see all of the vehicles tested by scrolling through the list of folders. Every folder is identified by a picture of the vehicle, along with its make and model name, as an added feature to enhance the user experience and simplify access to the data desired.
- Improved a previous feature to provide a one-page executive summary of vehicle test results, enabling a simple-to-read overview rich in visual content and easy vehicle-to-vehicle comparisons. This feature has proven to be especially useful for reporting test results on PHEVs.
- Improved the advanced graphical/table calculation tool for PHEV test results calculations. This tool uses all of the new parameters for PHEVs addressed by California Air Resources Board (CARB) regulations and SAE J1711.

Future Directions

- Need to increase the visibility of D^3 to user communities through providing more linkages from the Argonne Center for Transportation Research website.
- Continue to evaluate the user demand to provide means for two-level access: (1) basic level for public access that delivers summary one-pagers, simple data sets, and reports and (2) controlled level, which

would require a login/password to gain access to extensive "Level 2" datasets and reports for DOE. We have received no requests for access to any raw datasets from original equipment manufacturers (OEMs), universities, or other national laboratories during the past two years.

Introduction

Vehicle benchmarking combines testing and data analysis to characterize efficiency, performance, and emissions as a function of duty cycle, as well as to deduce control strategy under a variety of operating conditions. The valuable data obtained from this effort have been placed in an Internet-accessible database that provides a unique resource not previously available to researchers, students, and industry. This website is available at https://webapps.anl.gov/vehicle_data/.

Vehicle performance and benchmarking data are useful to nearly all aspects of the FreedomCAR partnership, and the Tech Teams also benefit from the data collected by Argonne's Advanced Powertrain Research Facility (APRF). These data have also become important for test procedure and policy development for DOE, the Society of Automotive Engineers (SAE), the California Air Resources Board (CARB), U.S. Environmental Protection Agency (EPA), U.S. Department of Transportation (DOT), and the National Highway Traffic Safety Administration (NHTSA). Test procedures, label fuel economy, and Corporate Average Fuel Economy (CAFE) regulations all depend on these data for development. The importance of maintaining this database is paramount because no other government entity or company has such a data resource available.

Approach

For each of the vehicles tested at Argonne's APRF, a set of data is generated. Depending upon the level and depth of testing, a stream of 50–200 different data are collected at the facility standard of 10-Hz data rate.

After testing, all of the data must be inspected for quality control (QC) purposes, to determine if the data are complete, thorough, and representative of the vehicle being tested. Argonne uses a set of tools that compare and contrast data relative to time and use of the first law of thermodynamics. Because this is a repetitive process, a template is generated to define the time and first law relationships between data. Each new set of data is run against these predefined relationships and set up for visual analysis and comment (Figure 1).

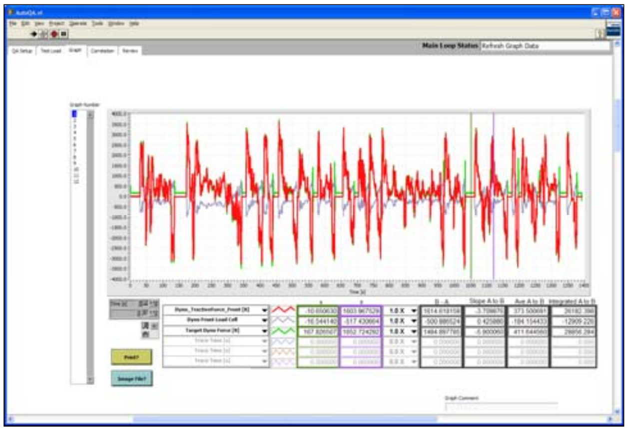

Figure 1. Standard APRF QC Analysis Tool

Once the data are thoroughly checked, they are saved and reduced to a predefined subset of data. Each set of data includes:

Phase Information: Summary data for each phase of the test; items include fuel economy and emissions (g/mi), for example.

Test Information: Summary of testing conditions needed to replicate the work at similar vehicle testing facilities; items include road load, dynamometer setting, and test cell environmental conditions, for example.

Main Summary: A one-page test summary with aspects of the phase information, test information, and 10-Hz data combined into a presentable sheet.

10-Hz Data: The raw 10-Hz data for each signal in the vehicle.

After the data quality control has been performed, data are uploaded to the D^3 website (Figure). The term D^3 is an abbreviation for **D**ownloadable **D**ynamometer **D**atabase. The html interface provides relational and searchable database functionality (the website is available at: https://webapps.anl.gov/vehicle_data/).

The current website interface is designed so that users can easily find data. Each vehicle's data are labeled with make and model identification and a small photo of the test vehicle, as shown in Figure 2. Users have the ability to search the entire database vehicle-by-vehicle.

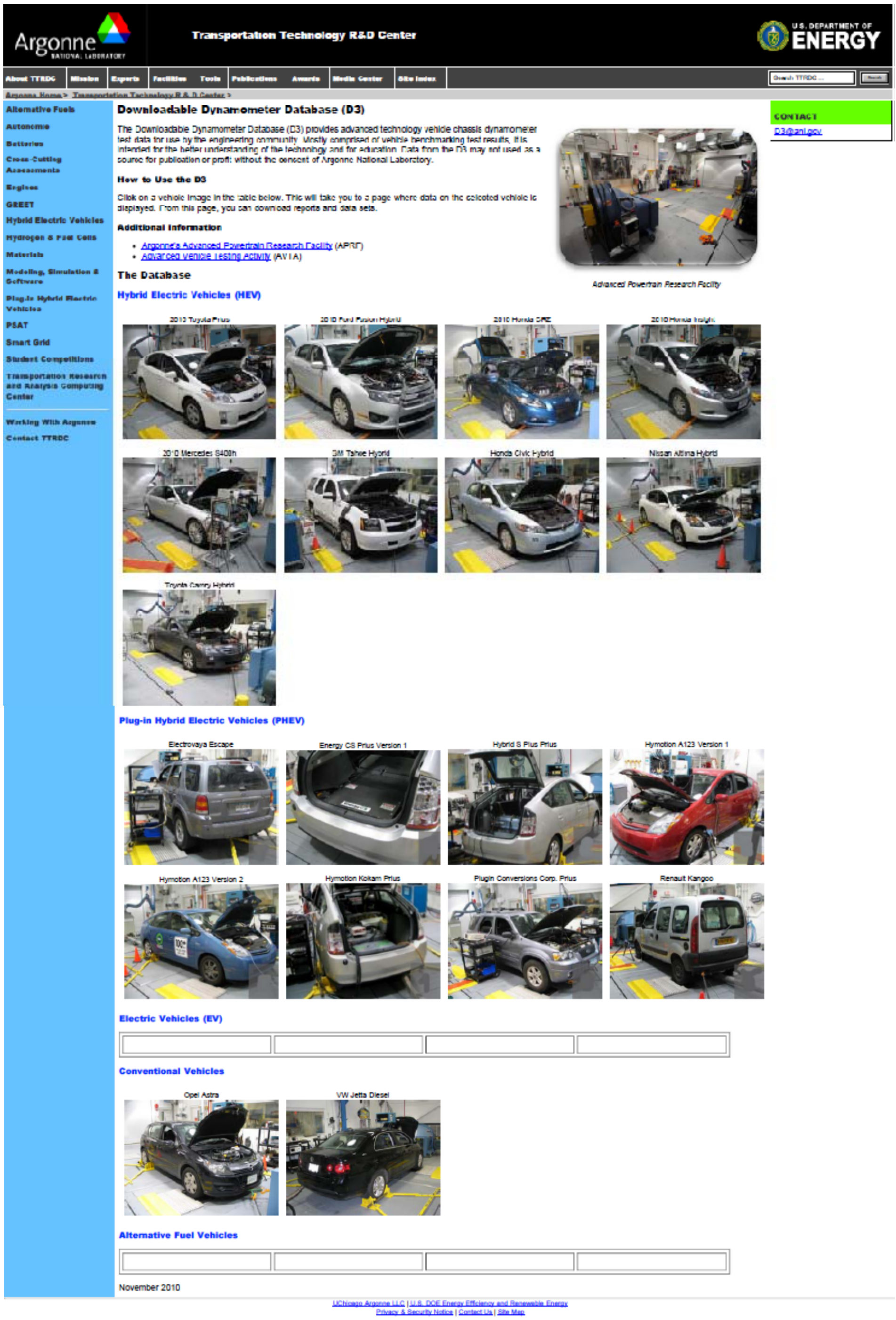

Figure 2. Downloadable Dynamometer Database (D^3) home page

Vehicles are grouped by the major types of powertrain configurations, with a newly added section for Alternative Fuel Vehicles. Each vehicle folder contains a one-page briefing that provides a synopsis of the test results, the full test report document, slides depicting selected data comparisons, and photos of the vehicle and instrumentation used. In addition, each vehicle folder contains the separate test data files identified by the test cycle performed. After the user has finished searching for the desired data, all of the data can be sent via http download in a single compressed data file (zip). As of October 2010, D^3 had 26 advanced vehicles with over 196 sets of data available for download.

This year, Argonne introduced an improved automatic one-page reporting tool that visualizes and runs the critical plug-in hybrid electric vehicle (PHEV) calculations. The SAE J1711 and CARB zero-emission vehicle (ZEV) mandate procedures involving new parameters unique to PHEVs. These relate to energy consumption rates, various definitions of the depleting range, and equivalent electric vehicle (EV) range. The reporting tool also uses Utility Factors to weight the results. Figure 3 shows an example printout.

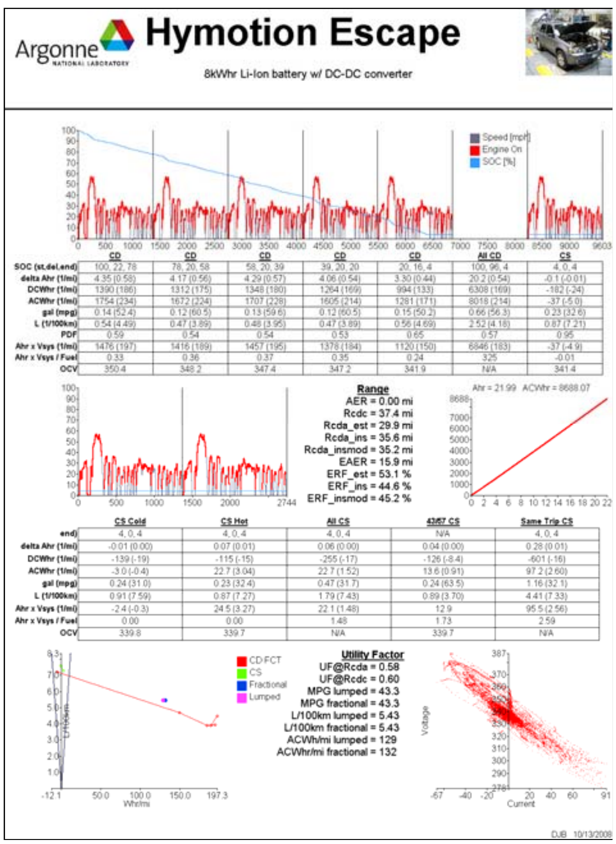

Figure 3. PHEV One-Page Calculation Printout

Conclusions

The Argonne D^3 allows industry, academic, and government partners access to high-quality vehicle chassis testing data. The D^3 is a simple and easy-to-use tool that allows for the transfer of useful data for analysis and education. Argonne will continue to develop the database, and promote its accessibility and easy-to-comprehend content.

Publications/Presentations

1. Keller, G., and Gurski, S., et al., "D^3 Website," September, VSATT (Vehicle Systems Analysis Technical Team) Review, 2007.

2. Keller, G., "Downloadable Dynamometer Database (D^3)," DOE Vehicle Technologies Merit Review, 19 May 2009.

I. Light-Duty Lean Gasoline Direct Injection Vehicle Technology Benchmark

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Objective

- To benchmark performance and emissions of advanced lean GDI and lean NO_x trap vehicle technologies and make information publicly available for vehicle simulations of advanced powertrains and after-treatment systems.

Approach

- Acquire a modern lean GDI vehicle with lean NO_x emission controls system from Europe (vehicle representative of the most advanced technologies on the market)
- Instrument vehicle and perform chassis dynamometer experiments to characterize performance, emissions, and after-treatment system for US drive cycles (UDDS, HFET, and US06) and steady-state experiments to establish performance/emissions maps for future vehicle simulations.
- Investigate modern production micro-hybrid performance attributes, such as Engine Start-Stop (MSA) and Intelligent Alternator Control (IGR)
- Make use of vehicle chassis dynamometer data to develop a model of the Lean GDI engine suitable for simulation with conventional and advanced powertrains

Major Accomplishments

- Obtained BMW 120i with 2.0l lean GDI engine on loan from General Motors
- Vehicle engine and after-treatment system were instrumented for engine out, tailpipe and Lean NO_x Trap (LNT) emissions characterization.
- Engine performance and emissions was characterized on chassis dynamometer over standard US drive cycles and steady state operation.
- Micro hybrid features were studied over the same drive cycles
- Data was analyzed and processed into look-up tables to generate a new engine component model in PSAT (Powertrain System Analysis Toolkit ©).

Future Direction

- Use newly created models to evaluate the potential of lean GDI engine operation and after-treatment systems with advanced (hybrid) powertrains.
- Focus on ethanol blends and potential opportunities presented by ethanol for lean combustion and emission control
- Use experimental data to commission a lean GDI engine on a dynamometer cell with a open source prototype controller.

Introduction

While stoichiometric gasoline direct injection engines are being introduced in the U.S market by both domestic and foreign car manufacturers, lean burn gasoline engines are yet to be commercialized for that market; whereas they were introduced in Europe in the late 1990. Lean burn engines tout further fuel economy relative to stoichiometric engines but require NO_x control exhaust after-treatment similar to diesel engines due to the high oxygen content exhaust gas which renders the conventional stoichiometric gasoline three way catalyst less efficient on NO_x conversion.

This project proposes to benchmark a state of the art lean gasoline direct injected engine on US drive cycles and steady state operation conditions in order to evaluate the technology. The test vehicle features two micro-hybrid functionalities that were evaluated as well.

The experimental steady state mapping data was compiled into a PSAT engine model in order to evaluate gasoline lean burn engine in advanced powertrains.

Approach

Procurement and Instrumentation

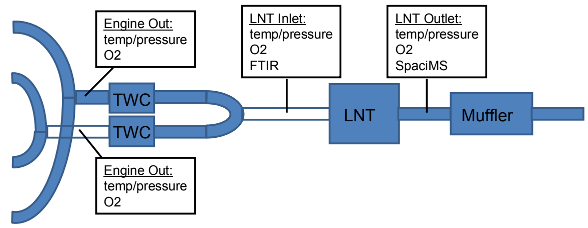
ORNL Fuels, Engines, and Emissions Research Center (FEERC) personnel obtained a MY2008 BMW 1 series 120i on loan from GM to carry out that study. Table1 lists the main engine specifications.

Table 6 Main Engine Specifications of the BMW120i BioPower Vehicle

Component	Specifications
Engine	2.0l 4 cylinder (N43B20)
Injection system	200bar lean burn direct injection
Max power	130kW (170hp) @ 6700rpm
Max Torque	210Nm (155lb.ft) @ 4250rpm

The exhaust system was instrumented in four locations as shown in Figure 1: two engine-out sampling points because of its dual manifold and three-way catalyst (TWC) configuration, and pre and post Lean NO_x Trap (LNT) sampling points.

Figure 1. BMW 120i exhaust system and instrumentation diagram



Engine out emissions (CO, CO_2, O_2, hydrocarbons and NO_x) were measured using emission analyzers. Another set of the same instruments were used to characterize tailpipe emissions diluted by the dilution tunnel. In addition to the exhaust analyzers, thermocouples, pressure transducers and universal exhaust gas oxygen (UEGO) sensors were mounted at various positions in the exhaust. Critical engine information was retrieved via the vehicle On-Board Diagnostic (OBD) link. Component currents and voltages were monitored by a power analyzer in order to characterize the powertrain micro hybrid features. All that data was centrally logged by the chassis rolls data logger.

Characterization Procedures

The vehicle was benchmarked over standard US drive cycles:

US Federal Test Procedure-75 (FTP)

Highway Fuel Economy Test (HFET)

US06 Supplemental Federal Test Procedure (US06)

In addition to those drive cycle, the vehicle was operated over extended combinations of speed and load conditions in order to characterize its emissions and fuel consumption in steady-state conditions. Both the drive cycles and steady state mapping exercises were performed three times to evaluate repeatability and potentially rule out outlier test results.

The vehicle commissioning used standard certification fuel (UGT96) which was suspected of contaminating the exhaust after-treatment LNT and preventing normal engine lean operation. Therefore subsequent tests were run with ultra low sulfur (<2ppm) similar to European gasoline that this engine was designed for. Earlier tests carried out in this study were discarded to ensure the after-treatment system was fully decontaminated and operating properly.

Operating Modes
The engine operates in two different modes:

- Lean: lean Air-Fuel mixture at low speeds and low loads and stoichiometric Air-Fuel mixture at higher speeds and loads
- Stoichiometric-only: stoichiometric Air-Fuel mixture for all engine speeds and loads

There are two micro hybrid features on this vehicle:

- MSA (German acronym for Automatic engine Stop-Start): the engine is shut down when the vehicle is stopped provided a set of enabling conditions are fulfilled.
- IGR (German acronym for Intelligent Alternator Control). It operates two different ways:

The alternator is deactivated during accelerations in order to dedicate the full engine power for traction purposes (Referred to as Alternator Deactivation)

The alternator is used to regenerate energy during coast downs (Referred to as Brake Regeneration)

Over the course of testing, the following operating modes were experienced:

- Stoichiometric-only without MSA and IGR
- Stoichiometric-only without MSA but with IGR
- Lean without MSA and IGR
- Lean with MSA but without IGR
- Lean with MSA and IGR

Because only MSA mode is driver selectable, and some operating modes (lean vs. stoichiometric-only, IGR vs. no IGR) appeared and disappeared without driver or staff intervention, not all operating modes were repeated three times for each test, some of them only have two instances and some only one instance.

Results

Fuel Economy
Lean operation consistently shows better fuel economy than stoichiometric-only operation even though improvements vary with drive cycles between 4 and 15%. Fuel economy results are shown in Figure 2. The more aggressive the drive cycle, the more occurrences of high speed and high load points where the engine will run stoichiometric (even in lean mode) and therefore the smaller the improvement (this is the case on the US06 cycle which only show 4% better fuel economy).

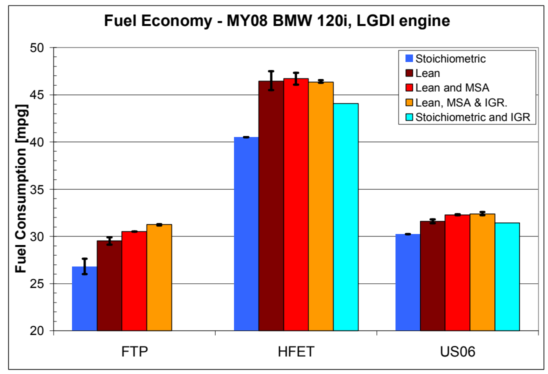


Figure 2. Fuel Economy and its Spread as a Function of Vehicle Mode and Drive Cycle.

MSA generates a 3.3% fuel economy improvement on the FTP cycle and 2.2% on a US06 drive cycle. IGR improved fuel economy by 2.5% on an FTP cycle whereas on the US06 drive cycle the fuel economy improvement is within the repeatability interval and therefore is inconclusive. Benefits of micro hybrid features (both MSA and IGR) could not be quantified on the HFET cycle because fuel economy variations related to each operating mode were within the repeatability interval. This was to be expected because the cycle features no stop and very few transients, and therefore very few opportunities for those fuel economy improvement techniques.

Because the powertrain features micro-hybrid functionalities, the battery state of charge (SOC) might not be balanced over a drive cycle as the battery might deplete or recharge un-evenly based on the cycle profile. This has the potential of biasing fuel economy results for hybrid vehicle applications. Therefore a correction factor was calculated to offset SOC imbalances on each drive cycle performed in this study. Revised fuel economy results are shown in Table 2.

Table 2. SOC Corrected Fuel Economy as a Function of Vehicle Mode and Drive Cycle

Drive cycle		Stoichiometric - only	Lean	Lean with MSA	Lean with MSA and IGR
FTP	Fuel economy [mpg]	28.18	30.31	31.78	31.93
	Improvement vs stoich. [%]	0	7.6	12.8	13.3
HFET	Fuel economy [mpg]	40.54	46.85	47.20	46.40
	Improvement vs stoich. [%]	0	15.6	16.4	14.5
US06	Fuel economy [mpg]	30.28	31.63	32.46	32.53
	Improvement vs stoich. [%]	0	4.5	7.2	7.5

All absolute fuel economy results have improved because the alternator was consistently overcharging the battery. Relative improvements demonstrate similar trends but different amplitudes. Lean mode now provides only 8% (compared to 10% previously) better fuel economy than stoichiometric-only on the FTP cycle, HFET and US06 improvements stay stable at 15 and 5% respectively. MSA now boosts fuel economy by 5% (up from 3%) but IGR improvements are less than 1% (down from 2%) on the FTP cycle.

Emissions

NO_x emissions were measured on standard US drive cycles (FTP, HFET and US06) for the same operating modes (stoichiometric-only, lean, lean with MSA and lean with MSA and IGR). NO_x emissions results are compiled in Table 3.

Table 3. NO_x emissions as a Function of Vehicle Mode and Drive Cycle

Drive cycle	Stoichiometric-Only	Lean	Lean with MSA	Lean with MSA and IGR
	[g/mile]	[g/mile]	[g/mile]	[g/mile]
FTP	0.03	0.11	0.10	0.13
HFET	0.002	0.11	0.13	0.11
US06	0.03	0.35	0.20	0.29

Lean operation NO_x emissions exceed US Tier II Bin5 NO_x level of 0.05g/mile (at 50000 miles) whereas stoichiometric-only operation emissions are within the limits. Emissions are worse (0.35g/mile) and more spread (0.16g/mile interval) on the US06 cycle which is the most aggressive of drive cycles tested in this study. Micro hybrid features did not have a significant effect on NO_x emissions: results with those features enabled are within the repeatability interval of the other tests run without them. One has to bear in mind that this vehicle is not sold in the US and therefore was not calibrated for US certification drive cycles. As such, emissions might not be optimized and could potentially be improved with a US specific calibration.

Other emissions were analyzed for the purpose of this study. Results for carbon monoxide (CO), total hydrocarbons (THC) and particulate matter (PM) emissions are shown in Figures 3, 4 and 5 respectively. The vehicle meets the US Tier II bin 5 regulation levels for all those components regardless of the engine operating mode.

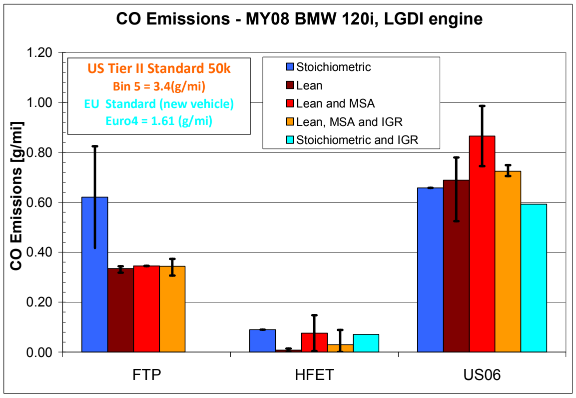


Figure 3. CO emissions as a Function of Vehicle Mode and Drive Cycle.

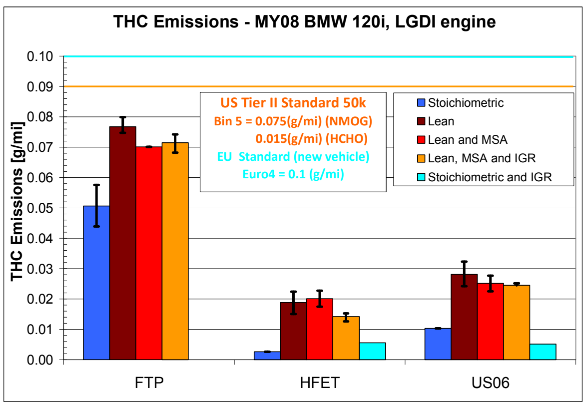


Figure 4. THC emissions as a Function of Vehicle Mode and Drive Cycle.

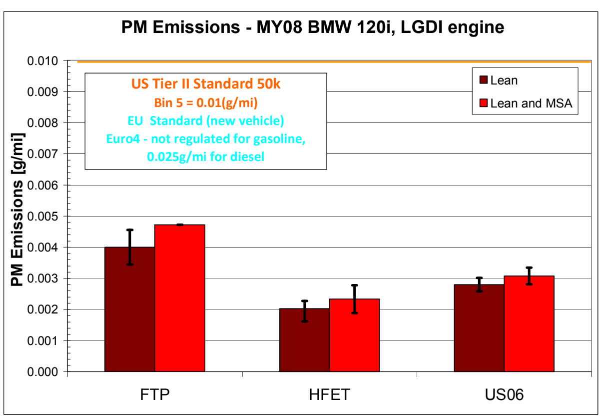


Figure 5. PM emissions as a Function of Vehicle Mode and Drive Cycle.

Steady State Mapping

Steady state data was collected to characterize the engine operation, performance and emissions. The vehicle was operated at a fixed gear ratio at various vehicle speeds chosen so that engine speed spans 1500rpm to 7000rpm in 500rpm intervals. For each vehicle speed, steady state engine and emissions data was collected for each engine load varying from 0 to 100% in 10% intervals. Results were post-processed and formatted into 2-D look-up tables as a function of engine speed and load. Figure 6 shows an example of such a table.

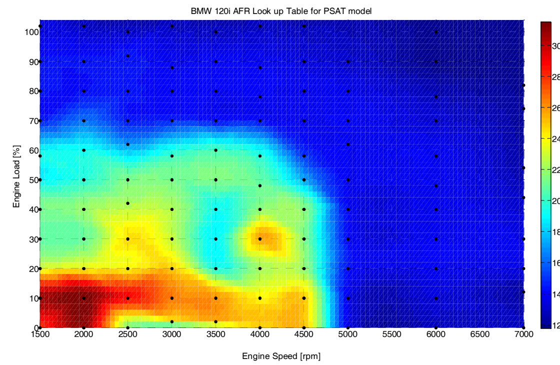


Figure 6. Steady state Air Fuel Ratio as a function of engine speed and load.

Engine out, Pre-LNT and tailpipe emissions (CO, CO_2, THC, NO_x) where characterized as well as engine operation (Air-Fuel-Ratio, Mass Air Flow, manifold pressure, exhaust line temperatures and pressures and wheel torque). This data was used to create a PSAT (Powertrain System Analysis Toolkit ©) steady state model of the lean burn engine and its after-treatment system. That component model will be available for future projects to assess the benefits of lean burn gasoline engines when integrated in different vehicle platforms or integrated with advanced powertrains like hybrid powertrains.

Conclusions

A European lean gasoline engine vehicle (BMW 120i) was tested on chassis rolls dynamometer. Fuel economy and emissions were measured for various engine and micro-hybrid operating mode combinations. Lean operation demonstrated fuel economy improvement of 4 to 15% over stoichiometric-only operation depending on the drive cycle. The more aggressive the drive cycle, the fewer opportunities to run lean and therefore the smaller the fuel economy improvement. Micro hybrid features were characterized as well. Engine Start-Stop demonstrated fuel economy up to 5% depending on the drive cycle and battery state of charge balancing correction. Brake regeneration showed fuel economy improvements as much as 2% on the FTP cycle. The more stops and deceleration phases in a drive cycle the more sizeable the benefits are for those features. When running lean, emissions were within US Tier II Bin5 thresholds except for NOx (0.11g/mile on FTP) which exceeded the regulation level of 0.05g/mile (at 50,000 miles).

J. Upgrade to APRF 4WD Vehicle Testing Facility to Provide Extremes of Cold/Hot Environment

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Objectives

- The objective of this project is to expand the capabilities of an existing 4WD test cell to allow vehicle testing at 20°F (-7°C) to 95°F (35°C) that includes installation of a solar load array system on the subject facility.
- This cold/hot testing capability is required by the new EPA "5-cycle" certification test method and will enhance our role of testing advanced vehicles and components for DOE.

Approach

- This project will design and build a structure to attach to the Building 371 High Bay exterior to accommodate the additional required utilities and work space. The enhanced refrigeration system will be located in the new addition, and duct work will be routed to the test cell to provide the necessary cooling, thereby allowing vehicles to be tested year-round at temperatures ranging from 95°F (35°C) down to +20°F (-6°C).
- The full solar spectrum array lighting panels will be mounted on the ceiling to simulate sunlight radiation conditions. The solar array's purpose is to duplicate the real-world temperatures induced by the sun's energy inside passenger compartments to exercise vehicles' air conditioning systems at maximum load.
- Total budget: $5,000,000. Breakdown: $3,500,000 for general plant project (GPP) construction and $1,500,000 for equipment.

Accomplishments

- Funding received and apportioned for equipment and construction segments: 6/29/10.
- Baseline agreement approved by DOE, and final PIP document submitted. Cost code assigned: 7/21/10.
- General contractor solicitation issued: 8/17/10.
- Construction contract awarded (to Linblad Construction): 10/6/10.
- Pre-construction meeting held and construction schedule discussed: 11/10/10.
- Anticipated date of construction completion established: 4/30/11.
- Anticipated date of facility commissioning and acceptance criterion validation established: 6/30/11.

Future Directions

- This facility will serve as a systems-based test bed for benchmarking the performance of vehicles' battery packs, driveline components, control strategies, and accessory load under a range of temperature conditions and duty cycles.
- This facility will contribute to Argonne's ongoing benchmarking and validation of energy consumption and emissions performance from advanced technologies.
- The enhanced capabilities of this test facility will provide data and operational characteristics, which will allow implementation of additional features into AUTONOMIE for cold and hot ambient conditions.

Introduction

The DOE advanced battery systems development program would benefit from an upgrade to Argonne's existing 4WD Advanced Powertrain Research Facility (APRF) to enable the in-vehicle testing of battery packs and their support systems in extreme environments of cold and hot temperatures. Design estimates have indicated that \$5 million in facilities expansion and equipment costs would be required to incorporate the thermal controls, air conditioning and refrigeration equipment, solar-load lamps, and speed-matched air handling equipment needed to provide a full-range of environmental conditions.

Approach

The overall size of the addition is approximately 3,000 ft^2 (1,500 ft^2 per level) and will be built on the south side of the existing APRF facility. The first floor will house a work area, and the second floor will house mechanical and electrical equipment, as shown in Figure 1.

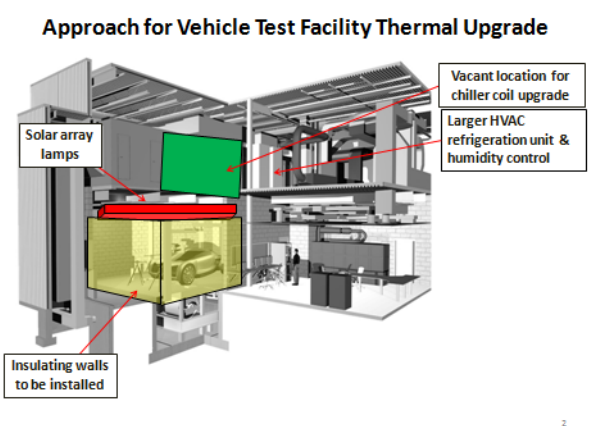

Figure 1. Proposed layout of APRF Upgrade.

The existing 4WD test cell will require some relocation of equipment in order to allow installation of the insulated walls and ceiling. The full solar spectrum array system will be mounted in the existing test cell area inside of the (added) insulated thermal chamber. A large air blower unit, regulated to match vehicle speed, will be included to simulate air movement across the vehicle as if it were driven on the road. A 480-vac, 800-A power service will be added to reinforce the new supporting equipment, along with facility-related requirements.

Required Test Cell Upgrades

- **Refrigeration coils in HVAC unit.**
- **Refrigeration and desiccant dehumidifier skids in upper mezzanine.**
- **Insulated- cell walls, doors, ceiling.**
- **Solar spectrum light array on ceiling.**
- **Air-flow blower that operates in proportion to vehicle speed.**

The cold/hot battery systems test facility and equipment would be capable of carrying out performance and life testing of high-power and high-energy battery cell systems for all-electric drive vehicles, as well as for PHEVs. DOE needs this environmental capability to measure vehicle performance degradation and battery system responses to the same extremes of in-vehicle temperature operation to which they will be exposed in the various climatic regions of the country. The future success of advanced electrified vehicle R&D will depend on studying the impacts of hot/cold environments and investigating the latest cooling and heating methods employed by the various battery packs to ensure both their longevity and satisfaction levels to customers. Such a facility would be instrumental to supporting the validation of advanced pack designs from battery manufacturing facilities, as well as from DOE's battery development activity. Furthermore, the upgrade will enable the collection of essential vehicle application data that includes the following:

- Impacts of hot/cold extremes on battery pack performance;
- Evaluation of battery cooling/heating system functions;
- Measurement of accessory power drains; and
- Overall impacts of the battery system parameters on vehicle fuel efficiency.

Second, the battery pack performance data collected at these environmental extremes will enable the addition of temperature effects to Argonne's development of the PSAT/ AUTONOMIE powertrain modeling and simulation tool. The data collection and modeling advances will enhance our ability to (1) improve electrified vehicle energy control strategies that improve battery energy delivery and (2) mitigate any conditions that might limit the useful life of the battery.

Moreover, the new EPA "5-cycle" certification test method requires the cold/hot testing capability to measure fuel efficiency down to cold temperatures of -7$^{\mathrm{o}}$C (20$^{\mathrm{v}}$F) and high temperature conditions of 35$^{\mathrm{o}}$C (95$^{\mathrm{o}}$F), with vehicle accessories and air conditioning operating, as per Figure 2. The results of these tests will be the foundation for an accurate standard mileage measurement that will provide a sound match between standard test conditions and real-world observations in fuel usage. With such a test facility, DOE can run the required EPA 5-cycle certification and official fuel economy measurement test requirements.

Major EPA 5-Cycle Test Specifications:

- **+20°F (Cold CO test)**
- **+95°F (Hot SC0$_3$ test)**
- **Solar Load (Hot SC0$_3$ test)**
- **Proportional Air Flow Control (Hot SC0$_3$ test)**

Figure 2. Photo of a test cell with solar spectrum array installed that is capable of running the EPA 5-cycle certification test.

It is important to note that the APRF and these upgrades do not duplicate any existing government facilities, as no DOE vehicle test facility is capable of replicating the temperature extremes required to perform the new light-duty vehicle fuel economy certification tests.

Conclusions

In order to remain a world-class advanced vehicle and battery systems testing laboratory, Argonne's APRF requires this upgrade of its air handling and refrigeration systems to enable testing of vehicle controls and battery systems in vehicles at the hot/cold temperature extremes found in various regions of the United States. Furthermore, this additional facilities capability is necessary to perform the required protocols for the new U.S. Federal fuel economy and emissions tests.

The total cost estimate to accomplish the upgrade is \$5 million and includes the following additions to the existing APRF test facility:

Purchase and installation of additional air refrigeration and dehumidification equipment to achieve a -7$^{\mathrm{o}}$C (20$^{\mathrm{o}}$F) ambient temperature.

Purchase and integration of a solar radiation array and heating/cooling and critical air handling controls to achieve 35$^{\mathrm{o}}$C (95$^{\mathrm{o}}$F) testing conditions.

Installation of insulation to test cell walls and ceiling to maintain these temperatures.

Extension of the building structure itself to provide space to house the additional refrigeration and air handling equipment.

Publications/Presentations

1. Keller, G., "Construction Project to Provide Climate Control to APRF 4WD Test Cell," presentation to VSATT (Vehicle Systems Analysis
2. Technical Team) Review, April 2010.
3. Keller, G., "4WD Test Cell Thermal Upgrade," poster for DOE Vehicle Technologies Merit Review, June 7, 2010.

K. Automotive X Prize Test Support for Validation Event

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Objectives

- Develop and implement safe and successful validation-stage testing of the finalists in the Automotive X Prize competition, in the controlled environment of a chassis dynamometer, using defined drive cycles, within a limited time period.
- Ensure safe testing and charging of the vehicles, taking into consideration their prototype nature.
- Ensure repeatable and accurate energy consumption results.

Approach

- Prepared two test sites, including additional calibration of instrumentation, to accommodate the anticipated volume of testing. Developed special dynamometer tie-down systems to accommodate the vehicles' unusual powertrain configurations that included three-wheel and two-wheel layouts.
- Set up outside charging tents at each test site with custom-built energy limiter boxes to reduce risk of overcharging and exercise of good safety practices during charging.
- Developed and practiced safe, consistent, and fair procedures to document and test Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), Battery Electric Vehicles (BEVs), and Conventional Vehicles (CVs).

Accomplishments

- Argonne provided the X Prize Foundation with validation-stage test results, which helped determine the eligibility of competitors to win the Automotive X Prize.
- The Argonne team successfully executed quality dynamometer testing for the validation stage of the Automotive X Prize Competition, within the limited time period allowed.
- The validation events ran safely and smoothly, thanks to the Argonne team's extensive preparations and dedication.
- Argonne increased its expertise in testing advanced vehicles in several areas, including:
- Acquisition of BEV testing experience,
- Production of data for standards development, such as for SAE J1634,
- Development of dynamometer tie-down experience with atypical vehicle set-ups, and
- Enhancement of insight into coast down matching with electric motors, with feeds into standard development.

Future Directions

- The project is completed and closed out.

Introduction

The Automotive X Prize (AXP) is a competition that requires its competitors to design, build, and test vehicles that achieve a 100-mile-per-gallon equivalent (MPGe). The competitors who achieve at least a 100 MPGe or greater in the on-road energy efficiency event during the finals stage combined with the dynamometer energy efficiency event in the validation stage are eligible to win the prize, which can be up to $5 million (US dollars), depending on the categories. A race event determines the winner in each category. More details are available at http://www.progressiveautoxprize.org/.

The AXP organizers approached the US Department of Energy (DOE) to find an advanced technology vehicle test facility with the expertise to test the unique vehicles participating in the competition. The goal of this project was to obtain high-quality and repeatable energy consumption dynamometer test data in a safe environment for the validation stage of the Automotive X Prize; Argonne's Advanced Powertrain Research Facility (APRF) had the expertise and capability to complete the required testing.

Approach

Test Process Preparation

Argonne's first step was to work with the AXP organizers to define the required test cycles. The result was a final validation-stage test cycle for energy consumption that combined the US Environmental Protection Agency (EPA) Urban Dynamometer Driving Schedule (UDDS) and Highway Schedule, repeated four times. This test was a cold-start test; the emissions test was a cold-start EPA Federal Test Procedure (FTP). The final test was a gradeability test, successful completion of which was one of the requirements for winning the prize money.

Argonne's second step was to develop a generic test flow. Figure 1 shows the validation stage workflow for each team.

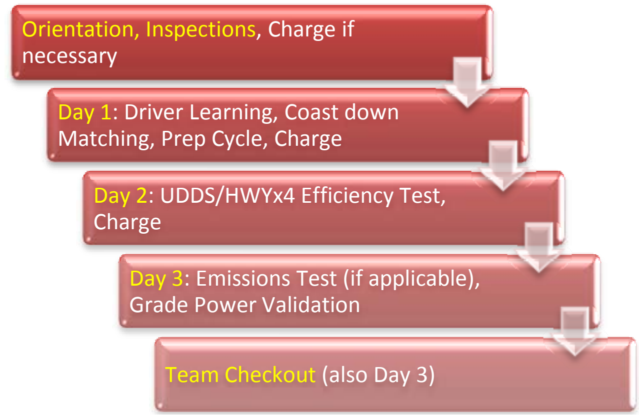


Figure 1. Test flow for the Validation Stage

After an orientation, the testing team put the vehicles through a safety inspection at Argonne to ensure that the vehicles and their chargers did not pose any risk to the staff or the facility during the testing.

The first test day started with setting up the vehicles in the test cell, which included restraining each vehicle on the dynamometer and connecting the vehicle instrumentation. Next, the Argonne drivers learned how to operate these unique vehicles. The driver training was essential, as each vehicle had different behaviors to control input and some vehicles had unconventional driver interfaces. Then, Argonne performed coast down matching on the dynamometer to match the track coast down data provided by the AXP organizers. A UDDS cycle served as a preparation cycle to condition the vehicle and provide final driver training. The final step for the first day was to charge the vehicle, if necessary, to ensure a full start of charge at the beginning of the efficiency test.

The second test day was dedicated to performing the actual validation-stage testing, to determine the energy consumption on the combined UDDS/ highway cycle, repeated four times. After the testing, the team returned each vehicle to the charging station, if necessary, to start the charging. The AC electric energy used to recharge the vehicle, along with any fuel used measured during the efficiency test on the dynamometer, counted toward the total energy consumption for the validation stage.

The third and last day of testing included the FTP emissions test for vehicles with internal combustion engines, as well as the gradeability test. The gradeability test required that the vehicle maintain 55 miles per hour (mph) on a 4% grade for 15 minutes (alternative classes) or for 30 minutes (mainstream classes). After a complete review of data from of all the tests by Argonne staff and the AXP officials, the vehicles and teams went through a check-out process.

Challenges

The powertrain architectures and vehicle types to be tested were unknown until a week before the testing, as the finalists participating in the validation stage at Argonne were determined during the AXP finals stage that was completed the week before the start of testing at Argonne. At the time, several vehicle architectures were still contenders, such as Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), Battery Electric Vehicles (BEVs), and Conventional Vehicles (CVs). Therefore, the preparations needed to include and accommodate these different technologies. In addition to the variety of potential powertrain architectures, most of the competitors built physically unusual vehicles in terms of size and layout, including three-wheel and two-wheel vehicles.

The high-profile and high-stakes nature of the competition required thorough preparation to minimize mistakes. An additional challenge was the compressed timeframe — the award ceremony was set for three weeks after the end of the testing.

The final and most important challenge for the Argonne team was maintaining safe test and charge conditions at all times. The prototype nature of the competition vehicles implied a higher level of risk compared to the risks inherent in testing standard production vehicles.

Preparations

Argonne prepared two independent test sites for the testing. Argonne's state-of-the art four-wheel-drive chassis dynamometer was the main test site. In addition, Argonne's two-wheel-drive chassis dynamometer was also ready to perform testing if needed. Each chassis dynamometer was tuned and calibrated to emulate vehicles with inertias down to 300 pounds. In order to address the vehicle tie-down challenge, Argonne procured special low-profile tie-down equipment, and implemented custom solutions for restraining three- and two-wheel vehicles on the chassis dynamometer.

Argonne set up tents at each test site for charging and soaking vehicles between test days. Charging the vehicles outside minimized the risk to the test facilities. To avoid overcharging the vehicles' energy storage systems (most of which were in experimental stages for the competition), Argonne designed and implemented energy limiter boxes. Limiter boxes terminate charge if a settable AC kWh energy level has been reached or a settable time limit has been reached. These limiter boxes also served as breakout boxes to feed the power analyzers with easy and safe current and voltage readings.

Additional safety precautions involved the continuous surveillance of the charge tents by the Argonne protective (security) force. Argonne's protective force staff, fire department staff, and safety staff were an integral part of the safety strategy. Everyone involved received training on the nature and risks of the different vehicle technologies involved in the competition, from the planning stage through to the execution phase.

Argonne staff developed many separate procedures and plans to ensure a safe validation event. The Argonne team developed the following plans and procedures to ensure the smooth, consistent, and fair flow of testing:

- Vehicle arrival plan
- Visitor guidelines and safety expectations
- Team arrival plan and orientation
- Media plan
- Vehicle and charger inspection plan and procedures

Charging plan and procedures

Instrumentation plan

Dynamometer test plans

Set-up, Progressive Insurance Automotive X Prize (PIAXP) tests, and gradeability test

Dynamometer procedures

Vehicle set-up and instrumentation

Vehicle removal

- Day 1: Driver training, coast down matching, prep cycles, and charging, if needed (including documentation)
- Day 2: Energy efficiency testing
- Day 3: Emissions and grade testing

Data and quality control (QC) plan

Team and vehicle checkout plan

All the plans and procedures were dry-run and refined using Argonne test vehicles before the official validation event started.

The team developed a high-resolution test schedule to allow for testing of four competitors per week. This required staff flexibility, with the potential for two test sites and 16-hour test cycles. The team prepared to have one driver per vehicle at all times, to ensure the best chance of completing the drive cycles. In addition, the team established clear roles for everyone involved. At least one AXP official was present at all times to witness all aspects of the testing and answer the teams' questions with respect to the competition rules.

Instrumentation and Measurements

During the tests, the team measured and recorded the AXP-mandatory Controller Area Network (CAN) messages and the main battery pack current. The tailpipe exhaust would have been measured if an internal combustion vehicle had been among the finalists. The team measured DC battery pack current using a power analyzer, which integrated the current used across all the tests. Argonne team members compared total Ah energy measurement to the total Ah charge energy as a measure of charge completeness.

The Argonne team measured charge energy during the charge events in the tent. The charge set-up involved two redundant power analyzers powered through back-up power supplies, which measured the line voltage and current feed to a vehicle charger. Two laptop computers recorded the charging time history from both power analyzers. This redundant set-up minimized the risk of data loss. The vehicle chargers were fed through the previously described energy limiter boxes. Finally, the team recorded the DC current to the energy storage system during the charge, to compare the total DC Ah discharged by the battery pack to the total DC Ah of charging. Figure 2 shows the full charge set-up.

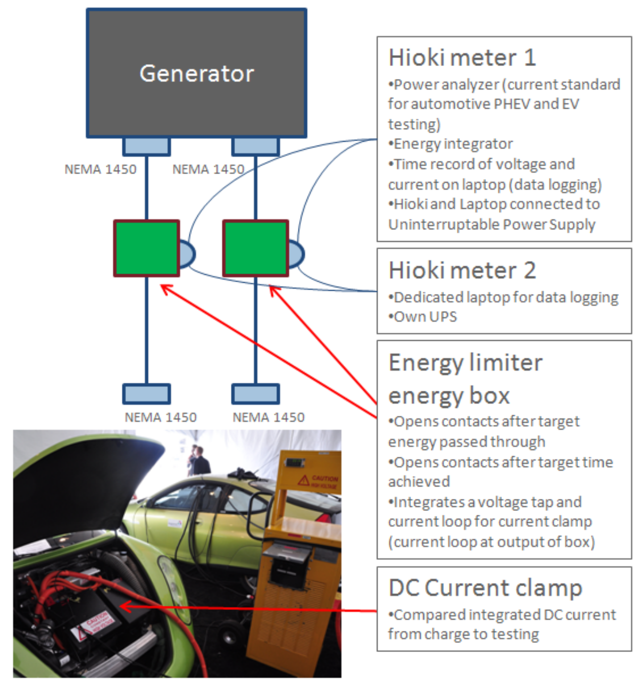


Figure 2. Charge set-up and instrumentation

Vehicle Testing

All the finalists tested at Argonne for the validation stage were BEVs. Figures 3 through 8 show the finalists being tested at the APRF.

Figure 3. Team Li-Ion (#27) testing on the dynamometer


Figure 4. Team RaceAbout (#10) testing on the dynamometer

Figure 5. Team TW4XP (#33) testing on the dynamometer

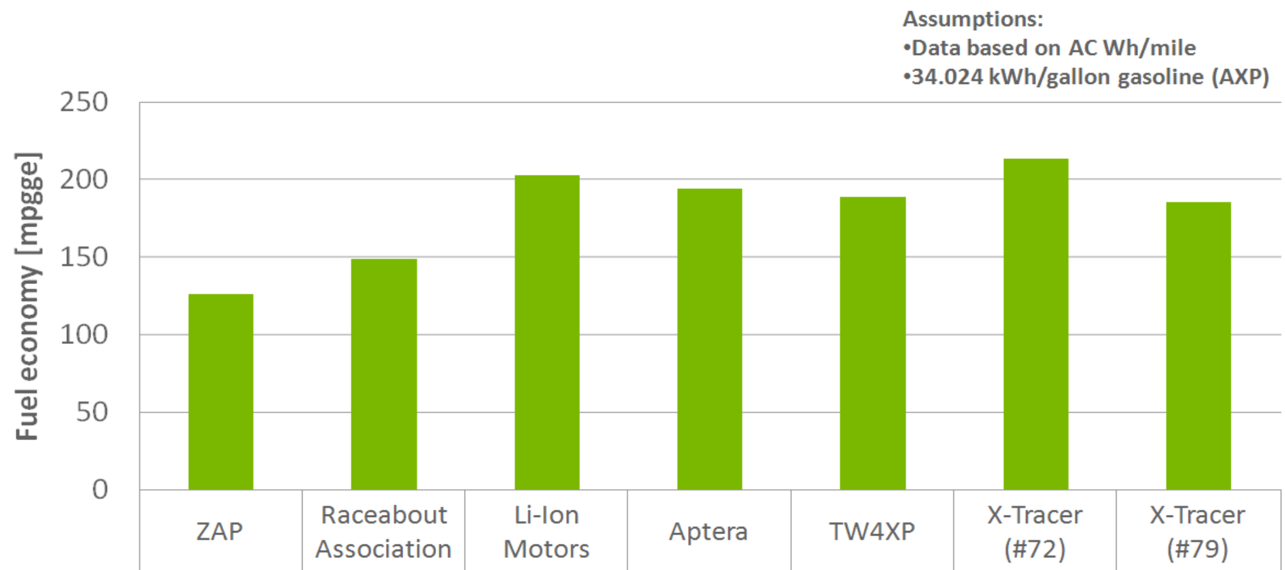

Figure 6. Team Aptera (#32) testing on the dynamometer


Figure 7. One of the two vehicles from Team X-tracer (#72 shown, #79 not shown) testing on the dynamometer

Figure 8. Team ZAP (#08) testing on the dynamometerTest Results

<u>Test Results</u>

The final energy consumption numbers ranged from 126 MPGe to 213 MPGe over the four pairs of UDDS and highway cycles. The results from the validation phase were combined with the on-track energy consumption results to determine which teams were eligible to win the prize money. All teams completed the gradeability test. Figure 9 shows the dynamometer energy consumption results for each vehicle tested in the validation stage at Argonne.



	ZAP	Raceabout Association	Li-Ion Motors	Aptera	TW4XP	X-Tracer (#72)	X-Tracer (#79)
Dyno	126.4	148.6	202.5	194.3	189.1	213.5	185.3
GHG	passed	passed	passed	passed	passed	passed	passed
Grade	passed	passed	passed	passed	passed	passed	passed

Figure 9. Dynamometer energy consumption results for the AXP validation stage

Lessons Learned from the Testing

Argonne gained more experience with vehicle tie-down set-up for unusual vehicle types. Three-wheel vehicles with the center wheel in the rear are especially difficult to restrain. During deceleration, the weight transfer tends to lift the rear center wheel and the front axle moves with respect to the rear axle, due to the geometry of the swing arms. This requires a full constraining of the rear wheel, which we achieved using a wheel clamp-beam constraint, as well as four chains, as shown in figure 10.

Figure 160. Three-wheel vehicle restraining system

The extensive testing of BEVs increased our knowledge about BEV instrumentation, the wide range of BEV behaviors, and most important, BEV charging events. We recorded many charge events during the validation stage, which provided insight to charge termination, repeatability of charge, and the value of Ah clamp from testing to charging. This information will contribute to development of standards such as the SAE J1634 “Electric Vehicle Energy Consumption and Range Test Procedure,” with which Argonne is actively involved.

Argonne also gained experience in coast down matching on the dynamometer for vehicles with electric motors. To protect power electronics from overvoltage that results when electric motors create electromagnetic fields (EMF) while spinning, the power electronics actively manage the bus voltage, creating torque at the wheel above certain speeds. The current coast down matching procedure does not account for this phenomenon. Therefore, the data obtained during the validation testing will be useful for revising the current recommended practice.

Conclusions

DOE and Argonne's APRF successfully executed a quality testing event for the validation stage of the Automotive X Prize competition, within the required timeframe. The events ran safely and smoothly thanks to the extensive preparation and dedication of the test team. In addition, the testing provided hard data to advance the development of automotive standards currently in revision.

Publications/Presentations

1. Henning Lohse-Busch, PhD, and Michael Duoba, "DOE Update of the Automotive X Prize Dynamometer Validation Testing Summary," Vehicle Systems Analysis and Technical Team Meeting, Aug. 25, 2010, Washington, DC.

2. Henning Lohse-Busch, PhD, and Michael Duoba, "VSATT Update of the Automotive X Prize Dynamometer Validation Testing Summary," Vehicle Systems Analysis and Technical Team meeting, Nov. 3, 2010, Detroit, MI.

3. Glenn Keller, "Argonne Provides Technical Support for Auto X Prize Competition," Argonne *TransForum*, Vol. 10, No. 3, Fall 2010, Argonne, IL. Available at www.transportation.anl.gov/publications/transforum/.

IV. LABORATORY AND FIELD TESTING (MEDIUM & HEAVY DUTY)

A. Medium Truck Duty Cycle Project

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Objective

- To collect and analyze real-world heavy- and medium-truck duty cycle (HTDC, MTDC) and performance data to support: PSAT/Autonomie modeling, DOE technology investment decisions, heavy- and medium-truck fuel efficiency research, and to outreach to other federal and private stakeholders for collaboration and joint project execution.
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Approach

- Identify relevant performance measures (e.g., location, speed, fuel consumption, gear, grade, time-of day, congestion, idling, weather, weight, etc.). Note: no emissions data is currently being collected.
- Design/test a data acquisition system to collect identified performance measures (i.e., field hardened and tested, able to interface with the test vehicle's on-board databus and other sensors, communicates data wirelessly/daily/securely).

- Find fleets willing to participate without direct funding (i.e., gratis partnerships). Incentives for partners include: better introspective data to improve fuel efficiencies, public exposure, and public goodwill.
- Instrument and "shake-down" test vehicles; i.e., six test vehicles per year in two vocations per year over two years
- Manage data in a cost effective and secure manner (e.g., automatic quality assurance programs to look for data that is out-of-range, missing data, etc.).
- Develop specialized data manipulation and analysis software; e.g., the prototype real-world-based duty-cycle generation tool – DCGenT will generate duty cycles of user specified duration based on user-selected duty cycle characteristics (e.g., grade, payload, type of roadway, weather, time-of-day, etc.).
- Outreach to other agencies/programs for cost leveraging. A recent major MTDC success involves a DOE/DOT partnership agreement for the collection of brake and tire performance data. DOT provided funding for all sensors and labor associated with their brake and tire interests and by doing this in conjunction with DOE's MTDC efforts reduced the amount of funding required to conduct this research. The benefit to DOE is that the brake and tire performance data adds to the DOE's data store of medium-truck performance data; already the largest known data store of medium-truck performance data from real-world operating environments, in the world.

Major Accomplishments

- Completed the MTDC Part-1 data collection effort on transit buses and local delivery trucks.
- Completed the brake and tire pressure data collection in partnership with DOT's Federal Motor Carrier Safety Administration (FMCSA).
- Completed the crosscutting analysis of MTDC Part-1 data.
- Completed the energy efficiency analysis of the use of wide-based single tires by Class-8 trucks in long-haul operations.
- Completed the draft MTDC Part-1 data analysis report.
- Initiated the MTDC Part-2 data collection effort on towing/recovery and utility trucks.

Future Direction

- Complete the MTDC Part-2 data collection effort
- Complete the MTDC final report
- Develop a MTDC and HTDC public website for summarized and analyzed data.
- Broaden the data collection suite to include aerodynamics, parasitic energy losses, rolling resistance measures, and emissions.
- Broaden the data collection efforts to include duty cycle data for heavy- and medium-truck hybrids.
- Complete the Duty Cycle Generation Tool (DCGenT) with the capability of estimating energy demand including truck-based energy demands involving real-world event such as idling, coasting, and congestion

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Discussion

The MTDC project, like the former Heavy-Truck Duty Cycle (HTDC) project is an important DOE Vehicle System Analysis Program effort. It is providing important data and information related to fuel usage, engine parameters, speed, direction of travel, time-of-day, geographic position, grade, and weather and road conditions for Class-6 and 7 vehicles operating in real-world environments. Through the use of the DCGenT users are able to generate, based on user-specified criteria, real-world-based duty cycles for use by vehicle fuel economy modeling development in support of the DOE Vehicle Technologies

Program, other modeling applications, private industry studies, and studies by the heavy-truck research community. For example, an analyst might be interested in duty cycles for metropolitan areas during peak travel times; or a duty cycle that is characteristic of rural freeways with steep grades. Upon completion of the DCGenT, analysts will be able to specify various performance shaping factors to generate customized duty cycles based on data collected from real-world experience. Lastly, with more than one year's worth of Class-8 data in DOE's Truck Performance Database, and Class-7 data being collected daily, specialized studies of energy efficiency are being conducted, and support for the development of a standardized heavy truck duty cycle for emissions studies can be provided, including possible collaboration with the Environmental Protection Agency (EPA). The parameters for which data have, and will continue to be collected are based on parameters of importance for vehicle fuel economy modeling development in support of the DOE Vehicle Technologies Program.

The MTDC effort is leveraging the prior HTDC work that has led to the development of a customized data acquisition suite, the collection of a significant database of Class-8 real-world performance data, and the development of DCGenT. MTDC, which involves an emphasis on Class-6 and 7 trucks, was initiated in the latter half of FY 2008. The MTDC effort involves designing and implementing a 36-month data collection, analysis and reporting effort for Class-6 and 7 trucks. The effort is further subdivided into two parts: Part 1 involved the data collection effort for transit buses and combination delivery vehicles which was just completed; and Part 2 will involve similar efforts for utility trucks and towing and recovery trucks. A list of the data channels gathered in the MTDC effort is provided in Table 1.

Table 1. MTDC Data Channels

No.	Description		No.	Description
1	Total Vehicle Distance		38	Barometric Pressure
2	Road Speed Limit Status (On/Off)		39	Latitude
3	Wheel-Based Vehicle Speed/Road Speed		40	Longitude
4	Front Axle Speed		41	Altitude
5	Engine Speed		42	Vertical Velocity
6	Current Gear		43	Velocity over Ground
7	Selected Gear		44	Longitudinal Acceleration
8	Actual Gear Ratio		45	Lateral Acceleration
9	Output Shaft Speed		46	Heading
10	Transmission Selected Range		47	Satellites
11	Transmission Current Range		48	Time UTC
12	Engine Oil Temperature		49	Distance
13	Intake Manifold Temperature		50	Steer Axle Weight
14	Engine Coolant Temperature		51	Drive Axle Weight
15	Boost Pressure		52	Wiper Switch Position (On/Off)
16	Fuel Rate		53	Brake Actuator Status - Left Front
17	Instantaneous Fuel Economy		54	Brake Actuator Status - Right Front
18	Actual Engine - Percent Torque		55	Brake Actuator Status - Left Rear
19	Percent Accelerator Pedal Position		56	Brake Actuator Status - Right Rear
20	Percent Load at Current Speed		57	Lining Status - Left Front
21	Driver's Demand Engine - Percent Torque		58	Lining Status - Right Front
22	Nominal Friction Percent Torque		59	Lining Status - Left Rear
23	Brake Switch		60	Lining Status - Right Rear
24	Clutch Switch		61	Brake Application Pressure
25	Cruise Control Accelerate Switch		62	Tire Pressure - Left Front
26	Cruise Control Active		63	Tire Pressure - Right Front
27	Cruise Control Coast Switch		64	Tire Pressure - Left Rear Outside
28	Cruise Control Enable Switch		65	Tire Pressure - Left Rear Inside
29	Cruise Control Resume Switch		66	Tire Pressure - Right Rear Inside
30	Cruise Control Set Switch		67	Tire Pressure - Right Rear Outside
31	Cruise Control Set Speed		68	Tire Temperature - Left Front
32	Power Takeoff Governor/Status Flags		69	Tire Temperature - Right Front
33	Power Takeoff Set Speed		70	Tire Temperature - Left Rear Outside
34	Total Power Takeoff Hours		71	Tire Temperature - Left Rear Inside
35	Battery Voltage		72	Tire Temperature - Right Rear Inside
36	Fan Drive State		73	Tire Temperature - Right Rear Outside
37	AC High Pressure Fans Switch			

The routes of the six test vehicles involved in the MTDC Part-1 effort are shown in Figures 1 and 2.

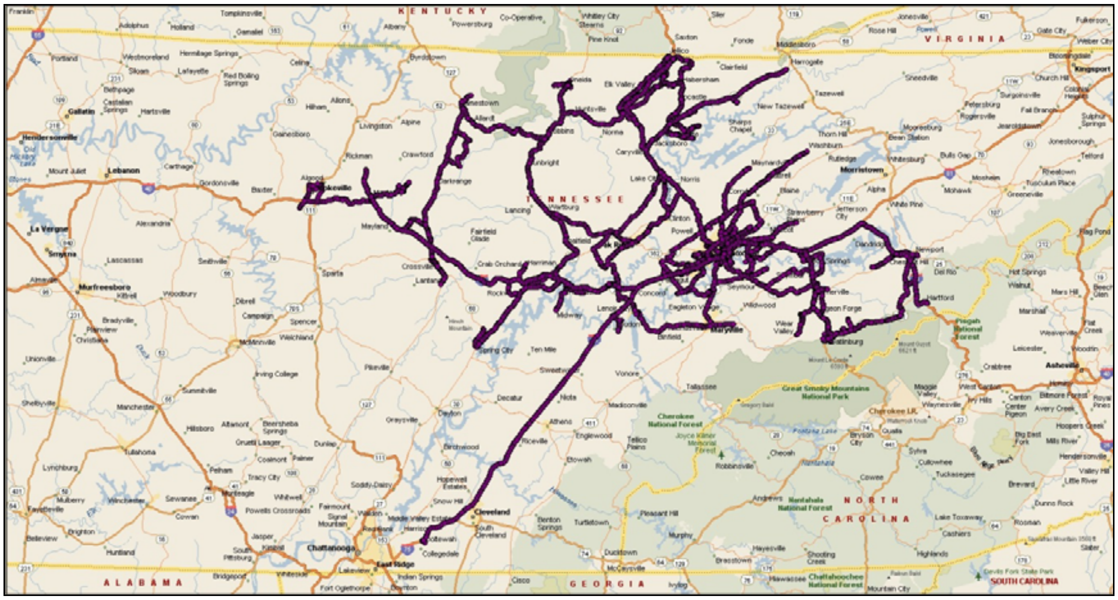

Figure 1. Routes of Participating H.T. Hackney Trucks

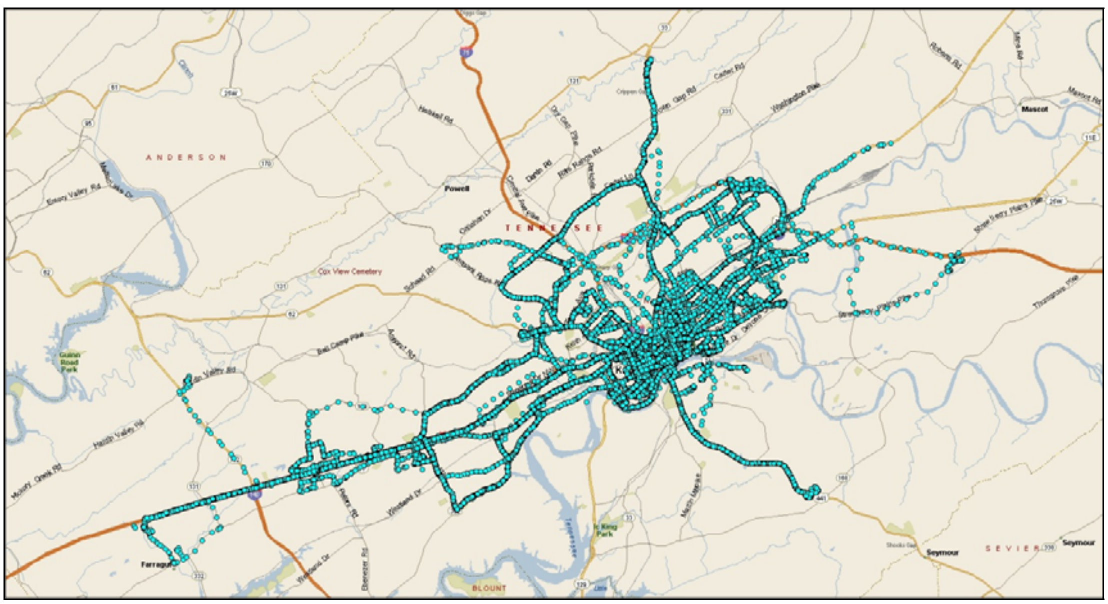

Figure 2. Routes of Participating KAT Buses

During the one-year MTDC Part-1 data collection period, the six participating vehicles logged over 95,000 miles (45,400 for the H. T. Hackney combination trucks and 49,400 for the transit buses) and consumed over 17,000 gallons of fuel (6,000 for the H. T. Hackney combination trucks and 11,300 gallons for the transit buses), while conducting business in the East Tennessee area.

General statistics related to the data collection effort for the H. T. Hackney and KAT vehicles are presented in Tables 2 and 3.

Table 2. General Statistics for the H. T. Hackney Combination Trucks

	MTDC Vehicle			Grand
	1	2	3	
Dist. Traveled	18,4	6,5	20,3	45,4
Total Time [hrs]	565	190	556	1,31
Avg. Speed	32.7	34.	36.7	34.7
Avg. Mov.	42.4	41.	42.7	42.4
Total Fuel [gal]	2,56	841	2,59	6,00
Overall Fuel	7.19	7.7	7.85	7.56

*Computed using vehicle data bus information on fuel consumption and integration of vehicle speed over time

Table 3. General Statistics for the KAT Transit Buses

	MTDC Vehicle			Grand
	4	5	6	
Dist. Traveled	23,1	7,73	18,5	49,4
Total Time [hrs]	2,48	847	1,87	5,20
Avg. Speed	9.3	9.1	9.9	9.5
Avg. Mov.	19.3	19.7	19.6	19.4
Total Fuel [gal]	5,43	1,76	4,17	11,3
Overall Fuel	4.26	4.38	4.43	4.34

*Computed using vehicle data bus information on fuel consumption and integration of vehicle speed over time

The collected MTDC data was used to generate distributions of idling time and idling fuel as a percentage of total time and total fuel consumed, respectively. Seven intervals of time were considered, ranging from 0-5 minutes (i.e., the vehicle was idling –vehicle static and engine running– for less than five minutes) to more than 240 minutes (4 hours); with the short intervals corresponding to idling due to traffic conditions (i.e., delays at traffic lights, congestion, and bus dwelling time) and the largest one to overnight parking and garage idling. The idling information is presented in Table 4 and Table 5, for the combination trucks and the transit buses, respectively.

For the H. T. Hackney combination trucks (Table), the largest proportion of idling time (61%) and fuel consumed (50%) while idling correspond to idling intervals that last between 0 and 5 minutes, that is, traffic congestion and delay at traffic signals. This is followed by intervals of 5 to 10 minutes of idling time (25% of idling time and 25% of fuel consumption while idling), and by the 15-60 minute time interval. The latter is mostly idling while stopping for a delivery. The 180-240 minute interval is proportionally low in terms of idling time (1.5%) but ranks third (12%) in terms of gas consumed while idling.

The KAT transit buses also spent most of their idling time (31%) in congestion and bus dwelling stops (0-5 minute idling interval) which also consumes the largest proportion of fuel spent while idling (see Table 5). However, as opposed to the combination trucks, the transit buses spent 26% of their idling time in intervals that are larger than 4 hours consuming also about 26% of the fuel spent while idling. These large idling times were observed mostly at the parking lot while the vehicles were waiting to start a trip.

Table 4. Distributions of Time Spend and Fuel Consumed while Idling (H. T. Hackney Combination Trucks)

Idling Interval [min]	Time			Fuel		
	[hrs]	% Total	% Total	[gal]	% Total	% Total
0-5	142.	61.4	10.	63.	50.1	1.1
5-10	59.1	25.5	4.5	32.	25.6	0.5
15-60	15.0	6.5	1.1	10.	8.4	0.2
60-	2.2	0.9	0.2	1.4	1.1	0.0
120-	9.6	4.2	0.7	3.0	2.4	0.1
180-	3.4	1.5	0.3	15.	12.3	0.3
240+	0.0	0.0	0.0	0.0	0.0	0.0
TOT	231	100		12	100	

Table 5. Distributions of Time Spend and Fuel Consumed while Idling (KAT Transit Buses)

Idling Interval [min]	Time			Fuel		
	[hrs]	% Total	% Total	[gal]	% Total	% Total
0-5	808	30.7	1.6	782	30.6	6.9
5-10	314	11.9	0.6	304	11.9	2.7
15-60	285	10.8	0.6	281	11.0	2.5
60-	277	10.5	0.6	251	9.8	2.2
120-	150	5.7	0.3	154	6.0	1.4
180-	116	4.4	0.2	111	4.3	1.0
240+	682	25.9	1.4	670	26.2	5.9
TOT	2,6	100		2,5	100	

The overall and moving fuel efficiencies of the test vehicles are presented in Tables 6 and 7.

Table 6. Overall and Moving Fuel Efficiency – H. T. Hackney Combination Trucks

MTDC Vehicle	Overall FE [mpg]	Moving FE [mpg]	% Diff
1	7.197	7.407	2.91%
2	7.794	7.925	1.68%
3	7.853	7.974	1.54%
All	7.565	7.727	2.14%

Table 7. Overall and Moving Fuel Efficiency – KAT Transit Buses

MTDC Vehicle	Overall FE [mpg]	Moving FE [mpg]	% Diff
4	4.267	5.488	28.64%
5	4.386	5.773	31.63%
6	4.437	5.698	28.41%
All Vehicles	4.348	5.609	29.01%

An example of duty cycles generated for the KAT transit busses operating on surface streets is shown in Figure 3. Other duty cycles and a detailed discussion of the characterization of the MTDC Part-1 data collection effort can be found in the MTDC Interim Report (Medium-Truck Duty Cycle Data from Real-World Driving Environments: Project Interim Report, ORNL/TM-2010/255, to be published in December, 2010).

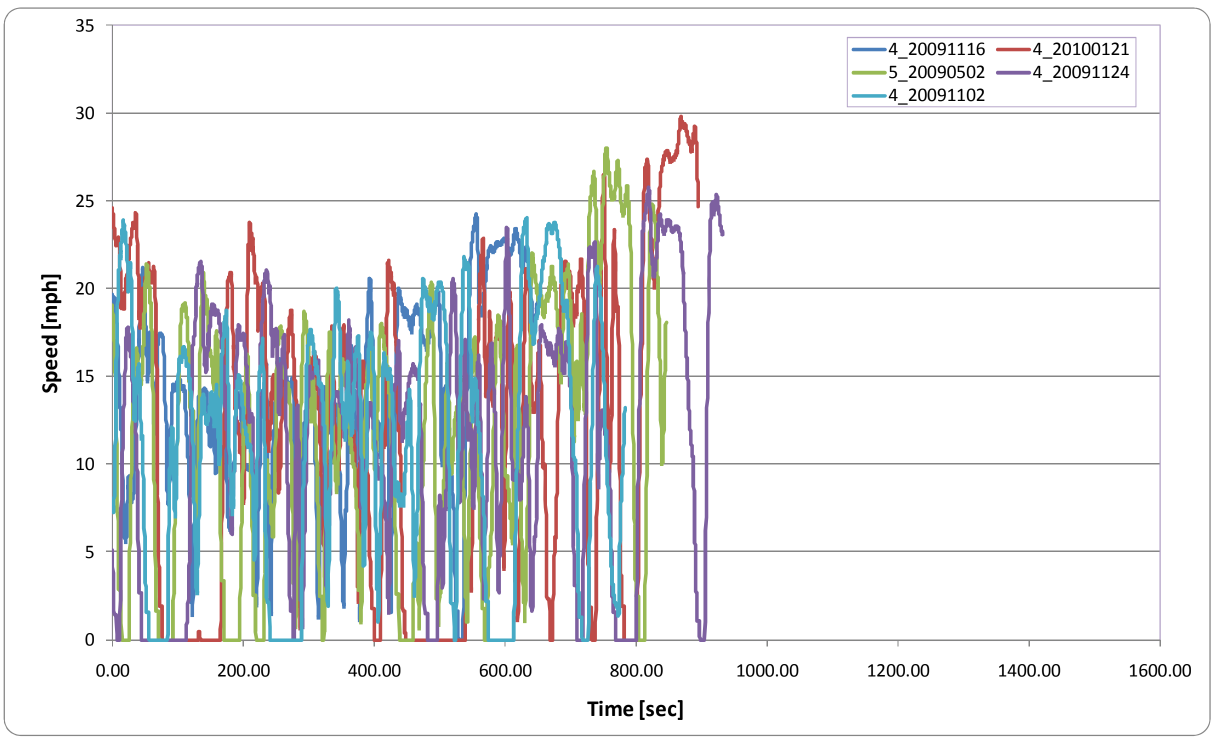

Figure 3. Transit Bus Highway Duty Cycles

The MTDC effort builds on the lessons learned in the HTDC Class-8 data collection effort. The Class-6 and 7 markets involve the second and third largest segment of fuel consuming heavy trucks in the US and consist of a number of vocational applications that operate in disparate topologies and in varying recurring congestion environments. Widely varying levels of vehicle miles traveled, degrees of stop-and-go operation, and load weight variability are expected, which provide an extra challenge for characterizing the duty cycles for this class of heavy vehicles. Assessment of the variability inherent in such duty cycles is the focus of a sister DOE project at ORNL entitled the Large Scale Duty Cycle (LSDC) project. The LSDC effort is currently in the conceptual design assessment phase and is reported on in a different section of this annual report.

Conclusion

The MTDC (and HTDC) efforts are producing a rich database of duty cycle and vehicle performance data that is available nowhere else in the world. To date, this duty cycle data has been provided to Argonne National Laboratory to support PSAT/Autonomie modeling efforts for class-7 and 8 trucks. The effort has demonstrated the ability and value of cross-agency cooperation and partnerships (DOE/VTP and DOT/FMCSA) which has produced a win-win situation for both agencies. More sand greater cooperation with DOT/FHWA in Part-2 of the MTDC effort and future duty cycle efforts is expected. This effort has shown the need for more data based on vocations within a given class in order to characterize the variability inherent within particular vocations. Currently, a feasibility study for a large scale, low-cost duty cycle effort is being conducted to assess within-vocation duty cycle variability. Additionally, methods for synthetically generating emissions data are being discussed and a potential partnership with EPA is being explored.

B. Large Scale Duty Cycle Project

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Objective

- Develop characteristic, application-specific duty cycles for trucks in those applications responsible for the greatest fuel consumption, and use the data to quantify the fuel savings that advanced efficiency technologies can provide in each application. This assessment of fuel savings potential will allow regulators and legislators to estimate both the fuel economy improvements possible in the future and the costs that will be incurred in achieving them. It will also enable trucking fleets to select technologies that are most relevant and cost-effective in reducing fuel use for each application. This research will therefore focus technology investment where it is most beneficial and promote market-driven efficiency improvements in the U.S. trucking fleet, which will reduce fuel use.

Approach

- Identify commercially available data acquisition technologies that can be used to inexpensively collect basic duty cycle data from trucks in a broad range of applications across the U.S. trucking fleet.
- Select vehicles among the trucking applications with the greatest vehicle miles traveled (VMT) and measure the duty cycles of 100-500 vehicles in each of these applications (participation from a total of 3000-7500 trucks is anticipated) during a period of approximately 12 months. The data collection for this number of vehicles must be highly efficient, using wireless data transmission from vehicles to a data server, and automated quality checking and database management of all incoming data will be used.
- Employ analysis methods developed at ORNL to create synthetic duty cycles from the measured datasets that are representative of the driving characteristics in each trucking application. Duty cycle variations within an application will also be evaluated so that the fuel savings potential evaluations for a selected application can be bracketed using data characteristic of that application.
- Perform analysis using the duty cycle data characteristic of each application to assess the fuel savings potential of advanced efficiency technologies, both individually and in combination. This

will be based on a tractive energy analysis for which only basic vehicle characteristics and the duty cycle data are needed.

- Create web-based tools to present the results of the analysis, allowing users to easily observe the predicted benefits for any combination of the technologies evaluated for individual truck applications.

Major Accomplishments

- This project is in an initial planning and feasibility study stage. Scoping of the complete research program was completed early in 2010.
- A partnership was established with the Technical Maintenance Council (TMC) of the American Trucking Association (ATA), who is collaborating with ORNL on a gratis basis to identify trucks for the data cycle collection effort.
- Established a methodology for obtaining road elevation data, which is important for the fuel economy evaluations, based on GPS position data as opposed to measuring elevation directly.
- Developed software that statistically evaluates duty cycles, in terms of the measured accelerations and speeds, and creates shortened duty cycles for modeling purposes that have similar acceleration and speed distributions as the original cycle.
- Completed a data acquisition system technology assessment to evaluate several candidate data collection options relative to criteria selected for the project.

Future Direction

- Complete the feasibility study: demonstrate the analysis approach using the same type and resolution of data that will collected for the project, identify participant trucks in the vocations of interest for the project, and obtain cost information from telematics suppliers for performing the duty cycle measurements.
- Perform Proof of Concept testing with a limited number of trucks to validate the data acquisition systems.
- Develop software for data integrity checking/verification that efficiently manages and stores the incoming data measured from the trucks in a database with minimal user interactions required.
- Perform a full system pilot test with a larger set of vehicles to verify and refine the data automation and analysis functions.
- Develop web application tools that are linked with the database for comparing and assessing the effectiveness of fuel efficiency technologies and combinations of technologies.
- Conduct the complete Field Operation Test with 3000-7500 trucks.
- Develop representative duty cycles for each truck application and complete the fuel savings potential analysis for each application.
- Write a final report for the project describing the research and all results obtained.

Discussion

Medium- and heavy-duty trucks are responsible for about 25% of the energy used and emissions generated in highway transportation in the U.S. The VMT for trucks is expected to increase at a rate significantly outpacing passenger VMT growth, which will result in a steady rise in the percentage of energy consumption (and emissions) attributable to trucks over the coming decades. These facts have sparked significant recent interest in truck fuel efficiency in the transportation community.

Accurate, representative duty cycle information is critical for properly assessing the impacts that advanced vehicle technologies can have on fuel economy for a particular type of vehicle. However, clear and detailed duty cycle data is presently unavailable for most applications of medium and heavy trucks in the U.S., and no detailed statistical analyses of duty cycles for a large number of vehicles among the diverse trucking applications that operate on American highways have been conducted in the past. Without this application-specific duty cycle data to characterize how trucks are used in the real world, advanced technologies aimed at improving fuel efficiency cannot be optimized for individual applications and users do not know which technologies can provide the greatest fuel savings and are most cost-effective.

Assessment of fuel efficiency technologies using duty cycles

Detailed vehicle performance models can be used to predict the fuel consumption of a particular vehicle design for any given duty cycle, and if adequate data is available to accurately characterize a vehicle, very accurate fuel consumption predictions can be made. By including sub-models that represent the behavior of different fuel efficiency technologies in a model, it is possible to quantify the benefits of these technologies and assess their fuel economy benefits. Such models require a very complete description of the vehicle's drive train so that energy losses associated with the various drive train components and other parasitic energy losses (engine, transmission, tires, aero losses, accessories, etc.) can be accurately accounted for at each instant in time. These models can very effectively be used to estimate the fuel savings that can be achieved when a technology that reduces the parasitic losses acting on the vehicle (such as aerodynamic drag reduction devices, or low rolling resistance tires) is employed for a particular vehicle design. However, a new model needs to be developed for each different type of vehicle, and this approach can be very time consuming.

As an alternative to such complex models that represent a specific vehicle configuration, first order models that focus on the energy provided to the wheels (referred to as the tractive energy) can be used to evaluate the fuel savings potential of fuel efficiency technologies, even without detailed knowledge of specific drive train components of individual vehicles. This approach may not provide a high fidelity prediction of the benefits expected for a given technology for a particular vehicle, but it can be used to identify significant opportunities regarding the energy savings potential of different technologies that act on one particular physical effect or those that provide fuel savings during some portion of a duty cycle. A tractive energy analysis also allows the benefits of combinations of technologies to be quantified without developing very detailed vehicle models that incorporate many complex sub-models. Accurate duty cycle information is the key to such an analysis, which also requires some general vehicle and technology parameters (mass, aerodynamic drag coefficient, average rolling resistance, etc.). There are, of course, limitations to such a model, but for evaluating which vehicle applications will benefit from individual technologies or technology combinations, such a model can be very effective at identifying "low hanging fruit" and determining that particular approaches will not be effective in improving fuel economy for some applications. In short, this type of simplified analysis will provide an order of magnitude ranking of the effectiveness of advanced fuel efficiency technologies for each vehicle application.

The representative duty cycle data that will be developed in this project will be analyzed using a tractive energy analysis, and the fuel savings and emissions reduction potential of individual technologies and combinations of technologies will be evaluated. Those technologies that show the greatest potential for reducing fuel consumption and emissions will be highlighted for all of the truck applications measured in the project.

Variations in truck duty cycles:

Different vehicles are driven in very different manners—as measured by the duty cycle—depending on the type of roads that are used (e.g. freeways vs. urban or suburban roads), individual driver behavior, frequency of stops that are required, and elevation changes along the way, among other things. Figure 1

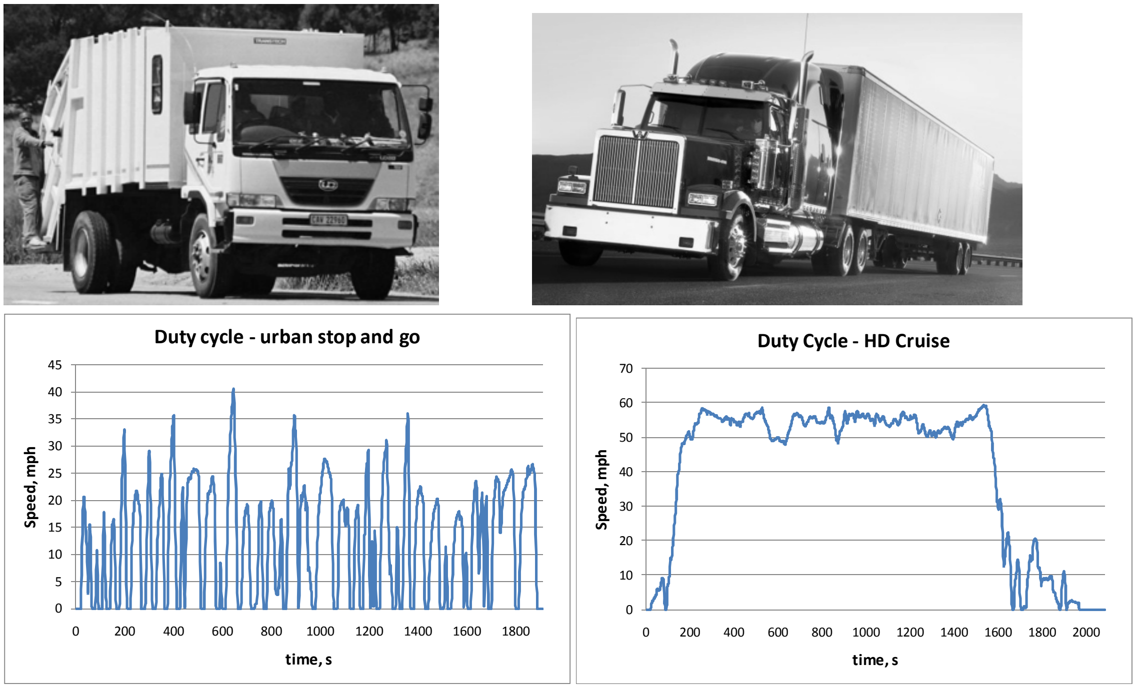
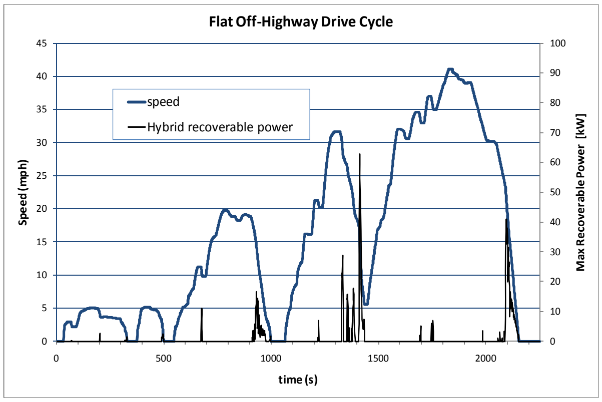


Figure 1. Comparison of typical speed cycles for two trucking applications

compares two extremes of duty cycles, corresponding to very different truck applications.

Differences in duty cycles among different applications play a very significant role on fuel economy, and also strongly influence the fuel savings that can be achieved when using advanced fuel efficiency technologies (such as aerodynamic drag reduction devices, low rolling resistance tires, hybrid technologies, etc.). As an example, regenerative braking, which recovers the kinetic energy that would otherwise be lost with traditional friction brakes and converts and stores the energy for later use, can be very beneficial for a vehicle used in an urban setting with frequent stops and starts, such as the garbage truck's duty cycle shown above. However, regenerative braking would be activated rather infrequently for long drives on the freeway at nearly constant speeds. As a result, it can be expected that regenerative braking would have a much smaller impact on fuel economy for a truck that is used mainly in continuous, long-haul operation than for a truck that experiences frequent start-stop cycles. These two applications perhaps represent the broadest extremes of truck use in terms of the differences in duty cycle, but there is a nearly continuous spectrum of vehicle uses in the trucking industry. Typical duty cycles among the many truck applications are not well characterized, and even what might be considered minor differences in duty cycles can strongly affect the energy savings potential for particular technologies in some cases. The graphs in Figure 2 show two duty cycles for off-highway use that might be typical of a local delivery operation.



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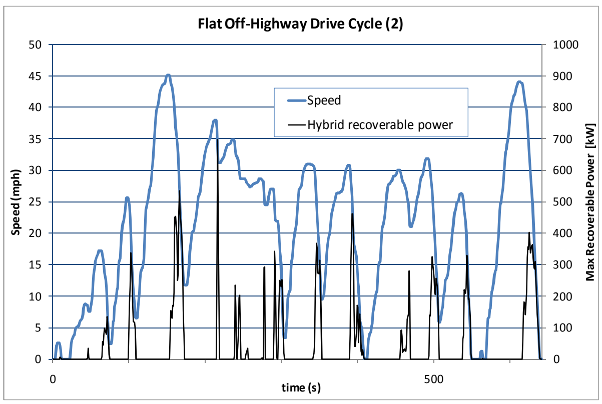
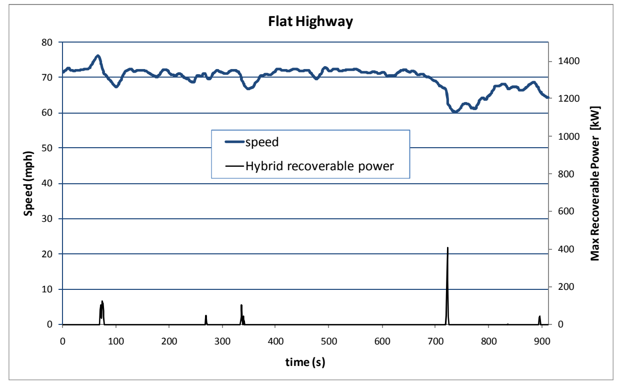


(2b)

Figure 2. Off-highway speed cycles, with average speeds of (a) 15.6 mph and (b) 21.0 mph. Also shown in the figures is the maximum recoverable power during deceleration events if regenerative braking were used.

While both duty cycles are characterized by moderate speeds and periodic stopping, a tractive energy analysis shows that the first cycle could achieve a maximum of 6.2% energy savings if regenerative braking were employed, whereas the second cycle has a potential 61.4% energy savings with regenerative braking. With such large differences in predicted energy savings, very different conclusions could be reached depending on which duty cycle was analyzed. Another factor that can be important to the energy savings potential for some technologies is the importance of road grade. Very frequently, the grade is not considered in the analysis for the sake of simplicity, but this can be just as important as the speed differences between two duty cycles. Figure 3 show two highway duty cycles, one for which the grade is negligible and a second for which there are significant elevation changes along the route.



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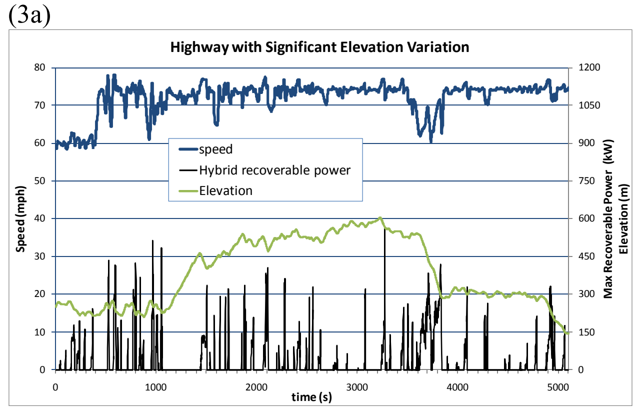

(3b)

Figure 3. Duty cycles for travel along a flat highway and a highway with significant elevation changes. For (a), the average speed is 69.8 mph while it is 71.8 mph for (b)

The average speed only differs by 2 mph between the two cases. With the large elevation variations in cycle (b), however, the tractive energy analysis shows that the difference in the maximum energy savings for regenerative braking is quite significant: for cycle (a), the energy savings potential is only 1.8%, while for cycle (b) it is 19.9%. If the elevation changes are not included in the analysis for cycle (b), the predicted maximum energy savings for regenerative braking is only 2.7%, which shows that the effect is predominantly due to the elevation and not a difference in the two duty cycles.

These two examples clearly demonstrate the importance of using fully appropriate duty cycles for characterizing the energy savings potential of a technology. This underscores the significance of developing characteristic duty cycles for the various trucking applications and using them to assess the benefits that advanced efficiency technologies can provide for that application. These examples also demonstrate the utility of the tractive energy analysis for providing a relatively simple means to evaluate the energy savings potential of advanced vehicle efficiency technologies.

Conclusion

The LSDC project represents an extension of previous duty cycle collection and analysis activities at ORNL that will allow researchers to better understand the driving behaviors of trucks throughout the U.S. Whereas prior research has focused on collecting very detailed information from a few trucks in selected applications, the direction for this project is to broaden the set of vehicles evaluated, providing statistically significant truck samples, while collecting a reduced number of data channels so that only those data essential to evaluating fuel efficiency are collected. The trucks to be measured will cover trucking applications responsible for over 90% of truck VMT, and with the number of vehicles that will be measured the data will allow variations in duty cycle both within and across applications to be critically evaluated using statistical analysis. The results of this research will provide a comprehensive understanding of truck usage, filling a considerable knowledge gap that currently exists. Furthermore, the analysis of the fuel savings potential for advanced efficiency technologies will allow truck owners and decision makers to make informed decisions and select those technologies that will provide the greatest reductions in fuel use for a given application. Developing this understanding is critical in advancing the national goal of reducing fuel consumption from trucks and can help define improved truck efficiency goals and strategies such as those contained in new regulations addressing medium- and heavy-duty truck fuel economy. The results of this research will lead to reduced fuel consumption in the U.S., reducing our dependence on foreign oil, in addition to providing economic savings through reduced expenditures on fuel and reductions in the emissions of greenhouse gases.

C. Advanced Technology Medium and Heavy Vehicle Testing Activity (AVTA)

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Objective

- Validate the performance and costs of advanced technologies in medium- and heavy-duty applications
- Feedback results to interested parties to further optimize and improve the systems
- Facilitate purchase decisions of fleet managers by providing needed information.

Approach

- Work cooperatively with fleets to collect operational, performance, and cost data for advanced technologies
- Analyze performance and cost data over a period of one year or more
- Produce fact sheets on advanced heavy-duty vehicles in service
- Provide updates on new, advanced technology to DOE and other interested organizations, as needed

Results in FY10

- Completed a 12-month study of ‘Gen I’ Eaton hybrid system in Phoenix, AZ and published a final report in December 2009
- Initiated a ‘Gen II’ study of the Eaton hybrid system vehicles being operated in a UPS fleet in MN
- Completed a final report on Azure gasoline hybrid delivery vans operating in Los Angeles, CA
- Initiated a field study of class 8 tractor trailers equipped with Eaton’s hybrid system in Miami, FL
- Collected and analyzed drive cycle and vehicle data to support a PHEV school bus being developed as part of Technology Acceleration and Deployment Activity (TADA)

Future Activities

- Complete evaluations on current fleet vehicles, initiate new evaluations
- Coordinate modeling and testing activities with other DOE projects such as 21CT as well as other DOE laboratories
- Monitor and evaluate promising new technologies and work with additional fleets to test the next-generation of advanced vehicles

Introduction

Understanding how advanced technology vehicles perform in real-world service, and the associated costs, is important to enable full commercialization and acceptance in the market. AVTA works with fleets that operate these vehicles in medium- and heavy-duty applications. AVTA collects operational, performance, and cost data for analysis. The data analyzed typically covers one year of service on the vehicles to capture any seasonal variations. Because of this, evaluation projects usually span more than one fiscal year. The AVTA team also works on shorter term projects designed to provide updates on current applications to DOE and other interested organizations.

Approach

The AVTA activities for 2010 included:

Fleet evaluations

Drive cycles assessment for PHEV school bus

Fleet Evaluations

In FY 2010, AVTA worked with 3 commercial fleets to evaluate the performance of advanced technologies in service. These fleet evaluations are discussed here as well as NREL's work to evaluate school bus drive cycles:

1) Gen I and Gen II Package Delivery Truck Evaluation - Eaton/UPS

In FY10 (December 2009) NREL completed and published an evaluation of the first generation of Eaton's hybrid electric delivery vehicles operating at a UPS facility in Phoenix, AZ.

UPS obtained new Eaton 'Gen 1' equipped HEV delivery trucks in their fleet in 2007. AVTA initiated an evaluation for these MD package delivery vehicles equipped with an Eaton's parallel hybrid systems (with lithium battery) to assess the performance and feasibility of this technology in Phoenix, AZ A group of 10 vehicles from both the new and conventional technology was selected for the study. The intent of the project was to compare the lithium battery parallel hybrid trucks with conventional diesel powered trucks.

The 12 month study period was identified to be Jan 2008- Dec 2008. Highlights of the final 'Gen I' report are as follows:

Gen I Delivery Van Use and Duty Cycle: The hybrids had a usage rate that was 20% less than that of the diesel vans. The hybrids consistently were driven a fewer number of miles throughout the evaluation period and experienced some downtime at the end of the evaluation. The hybrids spent more time idling and operating at slower speeds than the diesels did, and the diesels spent slightly more time operating at greater speeds; this resulted in the hybrids' fewer monthly miles (see Figure 1).

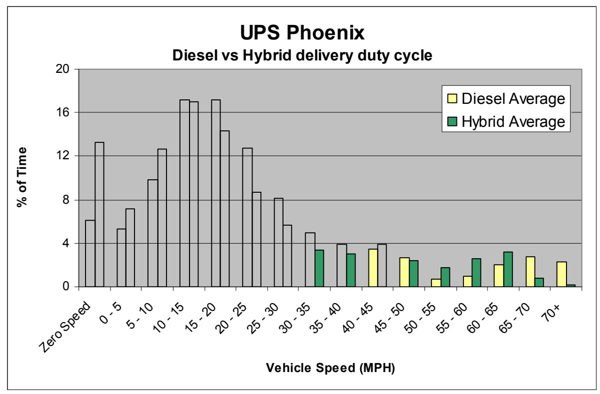

Figure 1. Hybrid and diesel drive cycle statistics

Gen I In-Use Fuel Economy: The 12-month average fuel economy for the hybrid vans is 13.1 mpg; 28.9% greater than that of the diesel vans 10.2 mpg (two-tailed P value = 0.0002). Table 1 shows the fuel consumption for each van group and the cumulative average mpg as well.

Table 1. Hybrid and Diesel Fuel Consumption

Hybrid Vehicles			
Van	Miles	Gallons Consumed	Miles per Gallon
666131	12,397	989	12.5
666132	19,286	1,395	13.8
666133	19,236	1,455	13.2
666139	17,003	1,357	12.5
666142	16,012	1,281	12.5
666145	17,091	1,237	13.8
Hybrid Total	101,025	7,714	13.1
Diesel Vehicles			
Van	Fuel Economy Miles	Fuel Economy Gallons	Miles per Gallon
663982	15,590	1,463	10.7
665020	23,275	2,203	10.6
665044	19,052	1,819	10.5
665086	20,204	2,322	8.7
665087	21,537	2,181	9.9
665150	19,135	1,706	11.2
Diesel Total	118,793	11,694	10.2

Gen I In-Use Operating Costs: The hybrid vehicles in this study exhibited a cost per mile reduction of 18%. Hybrid operational costs were $0.43/mile and the diesels were $0.53/mile. This was mainly due to the greater fuel economy of the hybrids as there was no statistically significant in maintenance costs between the two groups (see Table 2)

Table 2. **Hybrid and Diesel Operational Costs**

Total Cost per Mile Comparison						
Car	PWRTRN	Mileage Total	Non-Prop Mnt ($/mile)	Prop Maint ($/mile)	Fuel Cost ($/mile)	Total Cost ($/mile)
663982	Diesel	18,594	$0.142	$ 0.077	$ 0.357	$ 0.576
665020	Diesel	23,275	$0.077	$ 0.032	$ 0.360	$ 0.468
665044	Diesel	20,844	$0.119	$ 0.038	$ 0.363	$ 0.519
665086	Diesel	23,163	$0.141	$ 0.023	$ 0.437	$ 0.601
665087	Diesel	21,537	$0.140	$ 0.017	$ 0.385	$ 0.542
665150	Diesel	19,135	$0.077	$ 0.038	$ 0.339	$ 0.454
Total	**Diesel**	**126,548**	**$0.116**	**$ 0.036**	**$ 0.374**	**$ 0.526**
666131	Hybrid Diesel	12,397	$0.112	$ 0.061	$ 0.303	$ 0.476
666132	Hybrid Diesel	19,286	$0.064	$ 0.020	$ 0.275	$ 0.358
666133	Hybrid Diesel	19,236	$0.087	$ 0.020	$ 0.287	$ 0.394
666139	Hybrid Diesel	17,003	$0.089	$ 0.024	$ 0.303	$ 0.416
666142	Hybrid Diesel	16,012	$0.145	$ 0.067	$ 0.304	$ 0.515
666145	Hybrid Diesel	17,091	$0.149	$ 0.029	$ 0.275	$ 0.453
Total	**Hybrid Diesel**	**101,025**	**$0.106**	**$ 0.034**	**$ 0.290**	**$ 0.430**

Gen I In-Use Reliability: The cumulative uptime was calculated for each group during the study period and is shown in Figure 2. For the study period, the diesels missed a total of 10 operational days for propulsion-related issues while the hybrids missed a total of 68 days of operation (55 days of this missed operation were due to troubleshooting and repairs related to a prototype parking 'pawl' on three of the hybrid units in October and November).

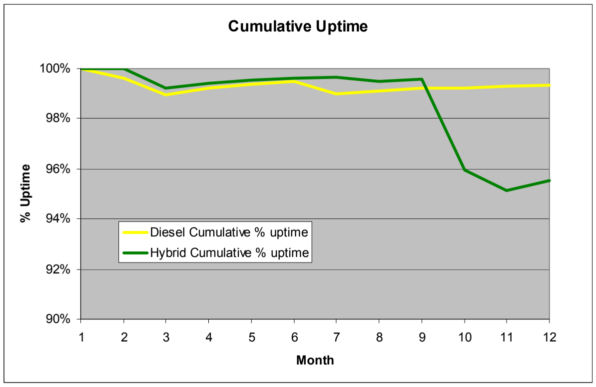

Figure 2. Cumulative uptime of hybrids and diesels

In June 2009, NREL and UPS kicked off a new 'Gen II study' aimed at evaluating the next generation of the Eaton hybrid system in a UPS fleet located in Minneapolis, MN. AVTA initiated this evaluation in July 2009 with a data logging effort from the groups of 10 new and 10 conventional technology vehicles that were selected for the study. The intent of this new evaluation in Minneapolis was to compare the lithium battery parallel hybrid trucks with conventional diesel powered trucks and also obtain years two and three from the hybrids operating in Phoenix, AZ.

The 12-month study period for the MN fleet study was identified to be July 2009-June 2010. The Phoenix study will include data from January 2009 through December 2010. Some highlights of the on-going work include:

<u>Gen II Delivery Van Use and Duty Cycle</u>: Initial GPS and CAN data collection to evaluate the driving characteristics of the hybrids as well as the conventional vehicle groups, show that the hybrids average driving speed of 15.0 mph was 24% lower than the diesels' 19.7 mph. The hybrids' averaged 35 miles per day, 38% lower than the diesels' 56 miles per day and the hybrids averaged 213 stops per day, 16% less than the diesels' 257 stops. The hybrids averaged 6.2 stops per mile, similar to the diesels' 6.5. From this preliminary data, it was evident that the vehicle groups are being operated differently enough that it was determined that the vehicle groups should be changed after six month's time to acquire operation data on both sets of routes. Figure 3, shows the sample data collected as it relates to average driving speed of the vehicles. A complete analysis of the drive data and a selection of appropriate chassis dynamometer testing will be completed in FY11 to test and assess vehicle performance.

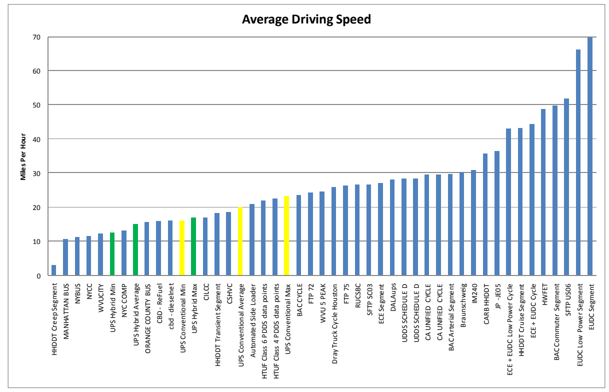

Figure 3. UPS II (MN) drive cycle analysis

2) Gasoline Hybrid Package Delivery Truck Evaluation – Azure/FedEx.

In FY09, the NREL AVTA team partnered with FedEx Delivery to evaluate FedEx's purchase of 20 pre-production gasoline hybrid electric parcel delivery vehicles (gHEVs) in their operations in Southern California. AVTA-funded activities were completed in FY10 and a final report has been issued documenting the results of this study which include:

- Drive cycle data collection and analysis results
- Chassis dynamometer testing of a FedEx gHEV at NREL's ReFUEL laboratory
- 12-month in-use evaluation results that include reliability, costs and fuel economy

Eight FedEx vehicles were instrumented with GPS-based data loggers, and over 62-route days of operation were collected. This data was used to confirm daily route consistency (hybrid group vs. conventional group), and to characterize each route according to 55 drive cycle metrics. From this data, three hybrid study vehicles were selected for a 12 month in-use study. Highlights from this study include:

<u>FedEx Drive Cycle Data Analysis</u>

Calculated kinetic intensity as well as average speed and stops per mile were used to compare the collected drive cycle data to existing stock drive cycles, and select chassis dynamometer test cycles.

The results of the drive-cycle/route study also showed that the two groups operated on slightly different routes; therefore, it was determined that the groups should be switched on the routes after 6 months. A summary of the route data analysis is shown in Table 3.

Table 3. **FedEx gHEV and diesel drive cycle statistics**

Drive Cycle Characteristic	Route and Group Statistics									
	A1	A2	A3	Mean A	CoV A	B1	B2	B3	Mean B	CoV B
Average Driving Speed (mph)	16.8	16.9	16.3	16.7	2%	18.9	20.9	18.8	19.5	6%
Daily VMT (miles)	43.8	47.3	21.4	37.5	37%	38.7	36.1	49.3	41.4	17%
Stops per Mile	3.85	3.79	4.22	3.96	6%	2.97	2.66	3.38	3.00	12%
Average Acceleration (ft/s^2)	2.27	2.11	2.09	2.16	4%	2.26	2.13	2.03	2.14	6%
Average Deceleration (ft/s^2)	-2.59	-2.55	-2.52	-2.55	1%	-2.44	-2.31	-2.56	-2.43	5%
Accelerations per Mile	20.80	20.78	22.82	21.46	5%	21.37	18.12	18.32	19.27	9%
Decelerations per Mile	20.26	19.71	22.63	20.87	7%	20.13	18.21	18.03	18.79	6%
Kinetic Intensity (ft^{-1})[1]	0.00059	0.00055	0.00074	0.00063	16%	0.00037	0.00030	0.00039	0.00035	14%

<u>FedEx Fuel Economy Analysis</u>: Based upon observed drive cycle kinetic intensities, the Orange County Bus cycle was selected as a cycle that best approximated the average routes driven by three study vehicles, while the NYCC and HTUF4 cycles were selected as upper and lower boundaries for vocational kinetic intensity. These cycles were subsequently used in the laboratory fuel economy testing at NREL which were previously reported in FY09. It was found that fuel economy improvements (on an energy/volume equivalent comparison) were possible on the NYCC cycle (~21%) but showed no statistical difference for the HTUF4 and OC Bus cycle. This comparison (gasoline HEV vs. diesel) was used to illustrate the fleet options available in Los Angeles. Emissions of NOx and PM were considerable less for the gHEV as compared to the diesel (~75-90% reduction in NOx and a ~90% reduction in PM).

Three gHEVs and three similar diesel parcel delivery trucks were evaluated for fuel economy during the 12-month in-use evaluation. In-use fuel data were collected via retail fuel data supplied by FedEx, and via on-board fuel logs completed by vehicle drivers and faxed to NREL as well as on-board loggers that recorded vehicle fuel use as measured by the on-board engine controller. For data obtained over the 12 months utilizing the retail fueling records, it shows that there is no statistically significant difference in the diesel equivalent fuel economy of the gHEV group at 7.54 mpg vs. the diesel group at 7.91 mpg (see Table 4).

Table 4. Twelve-month FedEx in-use fuel economy

Vehicle Type	Asset #	Start Date	End Date	Miles	Fuel Volume (gallons)	Fuel Economy (mpg)	Diesel Equivalent FE (mpg)	Fuel Cost ($)	Fuel Cost per Mile ($/mile)
gHEV	242292	04/21/09	04/12/10	10,693	1,540.8	6.94	7.54	4,468	0.42
	242294	04/21/09	04/14/10	11,843	1,744.7	6.79	7.38	5,119	0.43
	242295	04/23/09	04/22/10	7,214	1,001.5	7.20	7.83	3,010	0.42
	Total			**29,750**	**4,287.0**	**6.94**	**7.54**	**12,597**	**0.42**
Diesel	239670	04/21/09	04/23/10	13,099	1,822.43	7.19	7.19	5,254	0.40
	239830	04/22/09	04/26/10	11,344	1,321.50	8.58	8.58	3,893	0.34
	239896	04/28/09	04/26/10	11,124	1,350.82	8.23	8.23	3,899	0.35
	Total			**35,567**	**4,494.8**	**7.91**	**7.91**	**13,046**	**0.37**

Azure personnel worked in partnership with NREL and FedEx and conducted ISAAC data logger CAN downloads during scheduled visits. This data consists of distance traveled and fuel consumed since the last download and was collected from the gHEVs during the first 6 months of the study period. NREL compared fuel economy values calculated using the ISAAC data with values calculated using retail fuel logs during the same 6-month period. It should also be noted that Azure reported a ± 3% error in CAN-derived fuel consumption during simultaneous chassis dynamometer testing. A similar difference between CAN-derived and in-use data is shown in the Table and reinforces the in-use fuel economy being reported. Results are shown in Table 5.

Table 5. In-use CAN vs. retail fuel log data

Vehicle Type	Asset #	Start Date	End Date	CAN Miles	CAN Fuel Volume (gallons)	CAN FE (mpg)	Retail Fuel Log FE (mpg)	% Difference
gHEV	242292	04/22/09	09/03/09	4,507	650.0	6.93	6.78	2.2%
	242294	04/22/09	09/03/09	3,180	423.3	7.51	7.29	3.0%
	242295	04/22/09	09/03/09	2,410	345.8	6.97	6.78	2.7%

<u>FedEx In-Use Maintenance Costs:</u> In-use maintenance data were supplied by FedEx and transmitted to NREL for analysis. NREL removed warranty items and associated costs from this comparison. During the study period, the gHEVs had labor and parts warranted, while the diesels did not. Had warranty costs been included, the total gHEV maintenance costs for the study period would have been $6,815, or $0.229/mile (graph on left shows $6,136 or $0.206/mile without warranty costs). Maintenance data for the 12-month study period are presented in Figure 4. Maintenance costs are dominated by preventive maintenance activities and tire replacements. These two dominant maintenance categories have been removed in Figure 5, allowing for better visualization of lower-tier maintenance costs for each study group.

There are several obvious differences between the gHEV and diesel groups. Some of them (AC and HVAC, body, lighting, and various expendable items used to engineer solutions to minor problems) are likely due to "shakedown" activities when integrating the pre-production gHEVs. Key vehicle systems for comparison are the electric propulsion system, exhaust, power plant, brakes, and fuel system; these systems exhibit design or usage differences between the study groups.

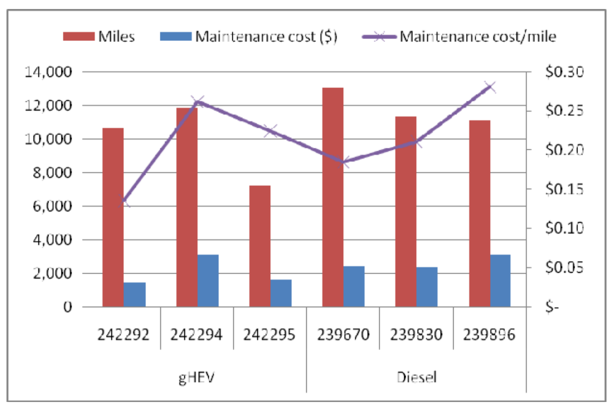

Figure 4. Maintenance costs for both FedEx groups

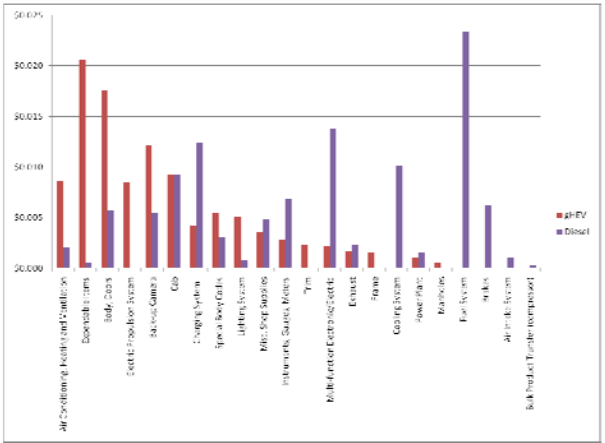

Figure 5. Maintenance costs details FedEx study

FedEx Vehicle uptime: Vehicle uptime was logged and analyzed as part of this project to help determine overall reliability of the new technology vs. the conventional. Vehicle uptime in this study is calculated as:

[Days in Service] /[Days in Service + Unplanned Days Out of Service]

Vehicle / study group uptime percentages for the study period are presented in Figure 6 and represents both warranty and non-warranty–related maintenance. The uptime goal of 98% is shown as a red dashed line. It is important to note that only four of the 46 unplanned days out of service for the gHEVs were related to hybrid propulsion system-related maintenance issues. These four days were specific to vehicle number H295, due to the replacement of an integrated starter generator (ISG) and digital motor operational controller (DMOC). Thus, the vehicle uptime related to hybrid system performance was 99.6%.

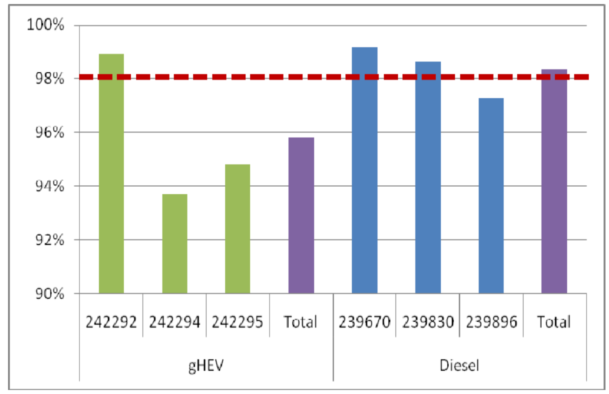

Figure 6. Vehicle uptime for FedEx study

FedEx Total Operational Costs for the Study Period: Total operational costs including fuel cost per mile and maintenance costs per mile were calculated for both diesel and gHEV groups and is shown in Table 6 and Figure 7. The gHEV group exhibited a slightly higher operating cost per mile at \$0.63 per mile versus \$0.59 per mile for the diesels. This was mainly due to the higher fuel costs for the gHEVs.

Table 6. Total operational costs for FedEx study

Vehicle Type	Asset #	Miles	Fuel Cost ($)	Maintenance Cost ($)	Total Operating Cost ($)	Total Operating Cost per Mile ($/Mile)
gHEV	H292	10,693	4,468	1,451	5,919	0.55
	H294	11,843	5,119	3,065	8,218	0.69
	H295	7,214	3,010	1,620	4,630	0.64
	Total	29,750	**12,597**	6,136	18,767	**0.63**
Diesel	D670	13,099	5,254	2,422	7,676	0.59
	D830	11,344	3,893	2,386	6,279	0.55
	D896	11,124	3,899	3,126	7,024	0.63
	Total	35,567	**13,046**	7,933	20,979	**0.59**

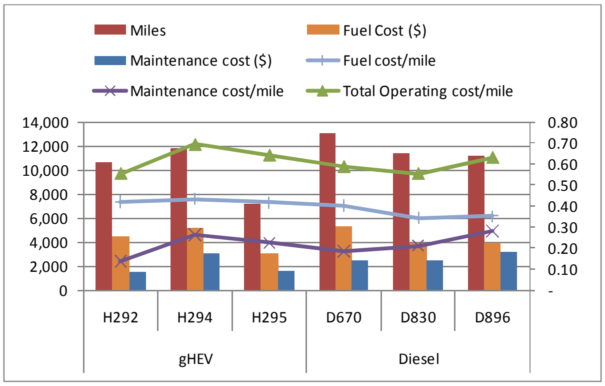

Figure 7. Total operational costs for FedEx study

The gHEVs experienced a smooth integration and deployment into commercial service. During the study period, the gHEVs performed well, experienced a minimum of unscheduled maintenance, and met the expectations of FedEx Express.

3) Class 8 HEV Beverage Delivery Truck Evaluation – Coca Cola / Eaton Gen II

In FY10, AVTA began to work with Coca Cola Enterprises (CCE) to evaluate the Eaton Gen II HEV tractors operating in their fleet in Miami, FL to evaluate HEV vs. diesel operation. CCE currently operates the largest heavy-duty HEV fleet in North America and many of these hybrids are equipped with the Eaton hybrid system. NREL initiated a project with CCE and Eaton to evaluate five HEV tractors and compare their performance to five diesel counter parts operating in similar service. This work began with a May 2010 kickoff meeting in Miami along with a drive cycle data logging activity. Once the data was analyzed, twoCCE vehicles were shipped to NREL to be tested on drive cycles derived from this on-road data at NREL's ReFUEL laboratory. The 12 month study period was identified to be May 2010- April 2011. Some highlights of this on-going work include:

<u>CCE Drive Cycle Collection and Analysis:</u> For a two-week period beginning on May 13th, GPS and CAN data was collected on 10 study tractors in the Miami/South Dade Coca-Cola Enterprises fleet. The study vehicles consisted of five Kenworth T370 single axle tractors equipped with a PACCAR PX-6 diesel engine, and Eaton Fuller UltraShift transmission and the Eaton Hybrid System, as well as five Freightliner M2 106 single axle tractors equipped with a Cummins ISC engine and an Eaton Fuller 7-speed manual transmission. Both the Kenworths and the Freightliners were 2007 EPA emissions certified. Additional vehicle details can be found in Table 7.

Table 7. Description of vehicles in CCE Miami Study

Vehicle Information	HEV Tractor	Diesel Tractor
Asset Numbers	643879 643880 643881 643882 643883	644024 644025 644079 644081 644082
Chassis Manufacturer/Model	Kenworth T370	Freightliner M2106
Chassis Model Year	2010	2009
Engine Manufacturer/Model	PACCAR PX-6 260	Cummins ISC-285
EPA Emissions Certification	2007	2007
CARB Emissions Certification	2008 (Clean Idle)	2008 (Clean Idle)
Engine Ratings Max. Horsepower Max. Torque	 280 HP @ 2300 RPM 660 lb-ft @ 1600 RPM	 285 HP @ 2000 RPM 800 lb-ft @ 1300 RPM
Fuel Capacity	56 gallons	80 gallons
Transmission Manufacturer/Model	Eaton Fuller UltraShift Automatic	Eaton Fuller T-14607 Manual 7 speed

Processing the data collected in Miami with a MATLAB based drive cycle tool provided several key drive characteristics of the Miami routes. Using this data and initially considering three duty-cycle characteristics (average speed while driving, percent idle time, and kinetic intensity), the library of heavy-duty standard duty cycles was reviewed to find cycles that most closely represent the CCE fleet data. Data were compared to existing cycles for kinetic intensity, and all data were added to the drive-cycle library. Using these three parameters, the Heavy Heavy-Duty Diesel Truck (HHDDT), Composite International Truck Local Cycle Commuter (CILCC), and the West Virginia University City (WVU City) cycles were chosen for testing on the chassis dynamometer. Figure 8 illustrates how these three cycles appear to be bracket the field data and can be used to characterize the variation observed in the field.

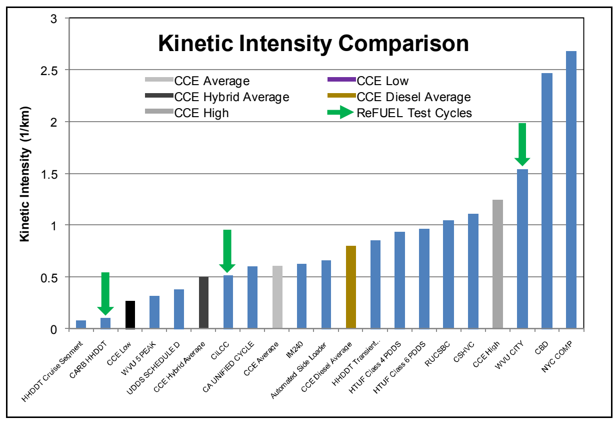

Figure 8. Comparison of CCE field data

To verify that these chosen cycles were the correct selection, a HD Truck model was used to run these three standard cycles and the 27 delivery days of CCE data to compare fuel economy. Figure 9 further illustrates how the prediction from these three chosen cycles bracket the CCE data.

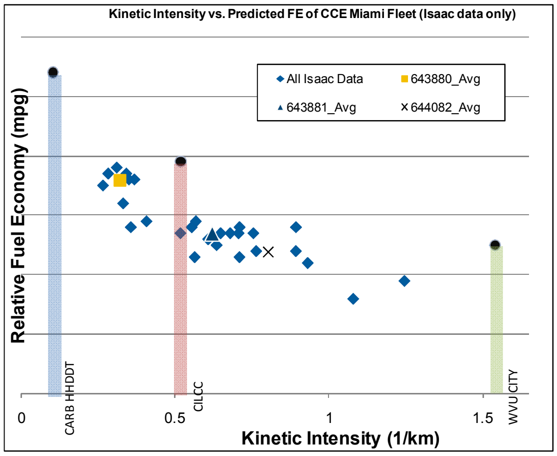

Figure 9. Simulated fuel economy of in-use and standard cycles for CCE vehicles

Laboratory Testing of CCE Tractors: One vehicle from each of the study groups would be needed o test these duty cycles at NREL's heavy duty chassis dynamometer facility in Denver, CO. Rather than transport both vehicles from Miami, CCE searched their fleet inventory for similar configuration vehicles closer to Denver. A Kenworth hybrid tractor was located in the Denver CCE fleet and the conventional diesel was located in Omaha, NE. These vehicles were exact matches to the tractors in the study fleet. The testing began in August with the Kenworth hybrid first up on the dynamometer. The first cycle to be tested was the WVU City cycle followed by the CILCC and then the CARB HHDDT cycles. This pattern was followed again for the conventional diesel tractor until testing was completed.

The emissions results were as expected for Carbon Monoxide (CO), Total Hydrocarbons (THC) and Carbon Dioxide (CO2). The HEV produced fewer of these emissions on each of the three selected duty cycles as detail in Table 8. However, Nitrogen Oxides (NOx) increased for the HEV over the conventional vehicle for each of the tested duty cycles. In fact for the HHDDT cycle, the HEV produced more than double the NOx emissions when compared to the conventional vehicle. This is presented in Table 9 as a percent reduction in emissions for the hybrid over the conventional vehicle. That said, while both engines were 2007 EPA emissions certified they were certified under different NOx emissions limits. The conventional vehicle with the 8.3 L Cummins ISC engine was certified at 1.25 g/bhp-hr and the HEV equipped with the 6.7 L PACCAR PX-6 engine was certified at 1.95 g/bhp-hr. The higher NOx emissions certification is thought to be the major contributor to the increase NOx observed on all three duty cycles tested.

Table 8. CCE Emissions

Drive Cycle	Vehicle	NOx (g/mile)	CO (g/mile)	THC (g/mile)	CO2 (kg/mile)
WVU City	HEV	9.94	1.64	-0.09	1.77
	Conventional	7.70	1.70	0.07	2.31
CILCC	HEV	7.53	0.35	-0.03	1.36
	Conventional	7.16	0.93	0.06	1.66
CARB HHDDT	HEV	5.75	0.49	-0.01	1.66
	Conventional	2.86	0.71	0.03	1.66

Table 9. CCE Hybrid Emissions Reductions

Drive Cycle		NOx	CO	THC	CO2
WVU City	HEV % reduction	-29.1	3.6*	222.7*	23.3
CILCC	HEV % reduction	-5.1	62.3	147.5	18.1
CARB HHDDT	HEV % reduction	-101.3	31.3*	141.9	-0.2*

The fuel economy results were as expected. The HEV demonstrated improved fuel economy on all three tested duty cycles with the lower average driven speed and higher kinetic intensity WVU City cycle producing the most significant difference between the two vehicles with a 34% increase in fuel economy, as seen in Table 10.

Table 10: CCE Laboratory Fuel Economy

Drive Cycle	HEV Fuel Economy (mpg)	Conventional Diesel Fuel Economy (mpg)	HEV Percent Increase (%)
WVU City	6.03	4.5	34.0
CILCC	8.2	6.35	29.1
CARB HHDDT	6.46	5.95	8.56

Table 10 further confirms the relationship between kinetic intensity and hybrid advantage. As such the hybrid advantage, indicated here as percent increase in fuel economy, increased with an increase in the kinetic intensity of the duty cycle. This is illustrated in Figure 10.

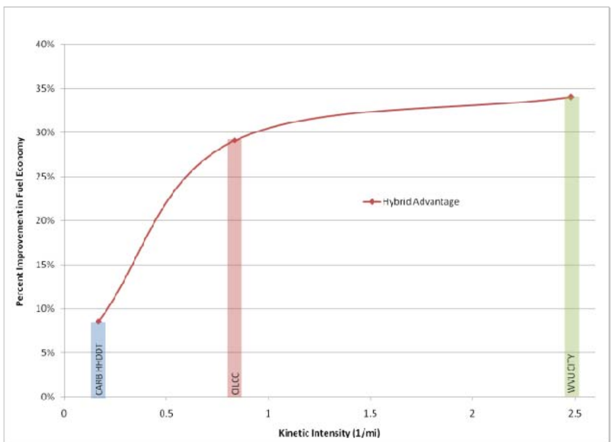

Figure 10. CCE Hybrid Advantage vs. KI

<u>CCE In-Use Data Collection</u>: A 12-month study of the CCE South Dade fleet started in May 2010 and will continue into May 2011. Fuel consumption data will be collected and correlated among three sources:

- CAN data recorded with the Isaac data loggers during the two-week study (an integration of the message "EngFuelRat," which will provide cumulative fuel used for each day of the two-week study period)
- Data coming from Quick Fuel, CCE's fueling contractor. Quick Fuel will provide CCE with a monthly record of the fuel delivered to each vehicle for each day of the month
- Engine Control Module (ECM) image downloads provided to NREL by the local CCE ECM service contractor. These images will contain a total cumulative fuel used value and will be compared month to month to determine monthly fuel usage.

Data from the CCE fleet evaluation activity will be next reported in an interim reported expected to be published in early 2011.

4) School Bus Drive Cycle Data Collection:
The AVTA team was asked to provide DOE VTP and industry with independent 3rd party analysis of Navistar's IC Corporation's next generation PHEV school bus operating in commercial service and collect comparative data to demonstrate to VTP and industry the commercial viability of the technology as compared to traditional technology

In FY10, technical evaluation and analysis provided to DOE included drive cycle and route evaluation and analysis to fully understand the targeted application of the PHEV school bus. Initial data collection plan for drive cycle analysis included considerations of:

- Drive cycle and driver behavior data
- Utilization of previous data collected from North Carolina route study; Austin, Texas; GPS data logging and Adams County, Colorado; bus fleet to build data set of school bus drive characteristics
- 3rd party analysis of driver behavior and route data of Navistar implemented Gen I buses in Schenectady, New York - compare to NYSERDA/NYPA study.

Aggregated analysis of bus data collected was completed and resulted in five areas that were analyzed for the complete set of 861 operational vehicle shifts (AM shift and PM shift for each vehicle):

- Total data set analysis
- Large bus set analysis (71+ passenger)
- Medium bus analysis (65-71 passenger)
- Total data set vs. NYPA study
- Total data set vs. existing MD/HD cycles
- Driver behavior analysis

Statistics for each operational day were calculated via 178 Different metrics. Well-known statistics such as average speed, distance, stops per mile were calculated and data set also includes more advanced statistics such as:

- Kinetic intensity (KI): Measures the energy consumption of the vehicle
- Characteristic acceleration (CA): Measures the intensity of vehicle acceleration

Statistical distributions by bus type were analyzed and histograms were created to visualize statistical spread and data distribution for average driving speed, distance traveled, stops per mile, etc. Scatter plots were also created to assist visualization of data trends. Trend lines within each data set were added to make projections within a data set easier. Overall aggregated data set statistics are shown in Table 11.

Table 11. Overall School Bus Data Set Metrics

Metric	Aggregate Data Average	Aggregate Data Standard Deviation
Distance Traveled (miles)	34.61	15.05
Average Driving Speed (mph)	25.34	4.26
Zero mph Time (%)	44.88	14.01
# of Stops per Mile	1.62	0.55
Maximum Driving Speed (mph)	58.38	9.01
Kinetic Intensity (1/mile)	1.23	0.64
Standard Deviation of Speed (mph)	16.02	2.71

A sample of the scatter plot analysis of the overall aggregated set is shown in Figure 11.

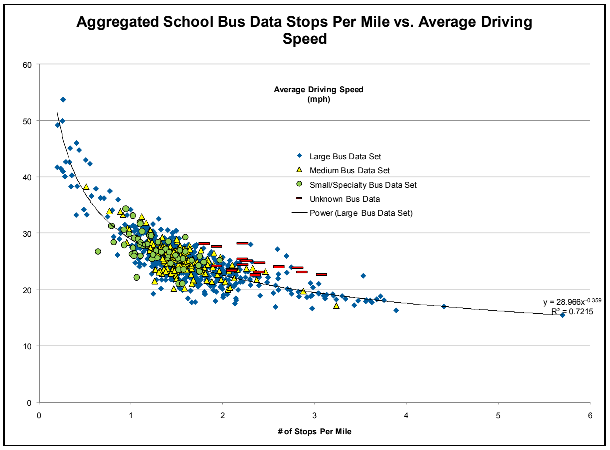

Figure 11. Overall School Bus Data Set

Statistics were reported on in a similar manner for both the large bus and medium bus data sets. A comparison of the entire data set was then compared to test cycle data used to evaluate a bus fleet in Schenectady, NY. This comparison was valuable to see how the test cycles used in that study compared to average values obtained in other bus fleets. A plot showing the values used in the ‘urban’, ‘suburban and ‘rural’ test cycles as compared to some standard bus cycles such as the RUCSBC, UDDS, and OCTA cycles as well as compared to data collected by the AVTA team is shown in Figure 12.

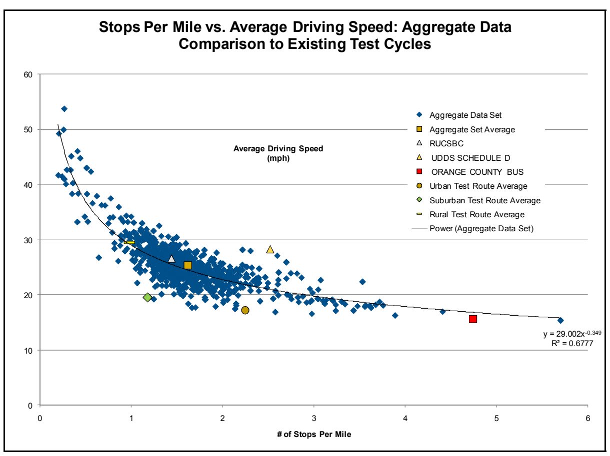

Figure 12. Overall School Bus Data Set Compared with NY School Bus Test Routes

In FY10, NREL and Zonar Corporation, one of the largest providers of school bus telematic equipment in the United States, agreed to collaborate to obtain large amounts of data from U.S. school districts. This agreement will allow NREL to access data collected wirelessly via Zonar’s systems and to provide an analysis of school bus operations from a variety of routes and regions across the United States. Colorado’s Adams County provided access in FY10, and three other districts in Utah and California are currently in negotiations for FY11 collection. This process allows for data gathering at a fraction of the cost of traditional methods of manually instrumenting vehicles and further data analysis will continue into FY11.

Overall AVTA Results

Results from AVTA fleet evaluations have been anticipated and well-received by the industry. Specific results for each evaluation are described in the project sections above. Unbiased, 3rd party assessments of performance and analysis of barriers to implementation are valuable to the MD and HD industry to help move petroleum saving technology into widespread commercial use.

Future Plans

The team will continue working with fleets to investigate the latest technology in medium-duty and heavy-duty vehicles. The team will track the latest developments in advanced vehicles and select those with the most promise for further study. Future plans include working with simulation & modeling teams at the DOE labs to ensure that relevant vehicle data are collected to verify and enhance the various simulation models and also to obtain more in-depth system data.

FY2010 Publications / Presentations

1. Walkowicz, K. (October 2009). *Drive Cycle Analysis & Tools. 18* pp.; Presented at Hybrid Truck Users Forum (HTUF), Atlanta, GA.

2. Walkowicz, K. (October 2009). *NREL and DOE Activities 8* pp.; Presented at Hybrid Truck Users Forum (HTUF), Atlanta, GA.

3. Lammert, M. (December 2009). UPS: Final Evaluation of Diesel-Electric Hybrid Delivery Vans. 37 pp.; NREL/TP-540-44134.

4. Walkowicz, K. (March 2010). *NREL’s Biodiesel Fleet Evaluation Experience* 20 pp.; Presented at Green Truck Summit, St. Louis, MO.

5. Barnitt, R.A. (May 2010). Interim Report on Fed Ex HEV Evaluation Project. 25 pp.; NREL/TP-540-47693

6. Walkowicz, K. (June 2010). *Medium and Heavy Duty Vehicle Field Evaluations* 20 pp.; Presented at 2010 DOE Annual Merit Review, Washington, DC.

7. Walkowicz, K. (September 2010). *Interim Status Report – In-Use Advanced Technology Evaluations* 48 pp.; FY10 DOE Program Milestone.

8. Walkowicz, K. (September 2010). *Interim Status Report – PHEV School Bus Activities and Evaluation* 69 pp.; FY10 DOE Program Milestone.

V. VEHICLE SIMULATION AND MODELING

A. Quantifying Thermal Effects on the Efficiency of Plug-in Powertrains

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Objectives

- Develop a simplified methodology to predict ambient thermal effects on advanced powertrains that ultimately may be used in modeling.
- Utilize the modeling techniques to quantify magnitude of thermal inefficiencies so that engineered solutions may be applied.

Approach

- Collect cold-weather vehicle testing data on a multitude of vehicles and architectures. Apply response surface methodologies to develop brake-specific fueling maps as a function of engine temperature.
- Develop a simplified lump capacitive thermal prediction model that does not require detailed and complex thermal modeling tools and techniques.

Accomplishments

- First simplified model was developed and applied to a 2008 Toyota Hymotion Prius plug-in hybrid.
- Technique and results were published and presented.

Future Directions

- To quantify this temperature effect and the magnitude that seasonal variations play in fuel consumption, an ambient independent model needs to be integrated into the technique.
- A test vehicle needs to be thermally instrumented and more complex thermal data acquired.
- These data will serve to refine the ambient temperature independent model, the results of which may be integrated into vehicle simulation modeling.

Introduction

A critical part of the DOE R&D plan is to develop and support technologies that displace petroleum usage. A portion of that work entails researching and benchmarking advanced powertrains, understanding their energy paths and usage, and researching methodologies to address inefficiency. For this work, a methodology of modeling and predicting fuel consumption in a hybrid vehicle as a function of the engine operating temperature has been developed for cold ambient operation (-7°C, 266 K).

This methodology requires two steps: (1) development of temperature-dependent engine brake-specific fuel consumption (BSFC) maps, and (2) data-fitting techniques for predicting engine temperature to be used as inputs to the temperature-dependent BSFC maps. We used response surface methodology (RSM) techniques to analyze fuel consumption as a function of thermal state across a broad range of engine operating conditions. This technique allows for prediction of fuel consumption of a vehicle as a function of the engine's power output and temperature.

Testing Description

Data for this work were collected at a 266 K ambient test-cell temperature at Environment Canada's Emissions Research and Measurement Section (ERMS). The ERMS is a division of the Canadian federal government that takes a lead role in measuring and analyzing air quality and exhaust emissions in Canada. The ERMS chassis dynamometer emissions testing laboratory is capable of conducting comprehensive emissions measurements from a variety of sources under controlled conditions at temperatures as low as −25°C (248 K). The facility is used to evaluate the emissions performance of advanced technology powertrains, emission control systems, and alternative fuels in light- to heavy-duty vehicle applications.

For this work, we selected a 2008 Toyota Prius Hymotion Hybrid conversion for testing, shown at Environment Canada in Figure 1. As shown in Table 1, we investigated engine coolant and oil temperature as metrics for engine thermal state. For engine oil temperatures, K-type thermocouples were fixed to the oil dipstick, measuring sump oil temperature. For coolant, the production sensor recorded temperature. Select Controller Area Network (CAN) data was collected via a KVASER Memorator. Vehicle speed, engine speed, brake load, and oil and coolant temperature, in conjunction with fuel flow rate, were recorded and used to develop the brake-specific fuel consumption (BSFC) maps. Algorithms were developed to both time-align and reduce the frequency to 1 Hz for analysis. Greater frequency was not shown to increase the modeling accuracy. However, for this work, analysis was not conducted to determine the lowest sampling rate to achieve acceptable results.

The vehicle was soaked at the ambient test temperature of 266 K for 12–36 hours prior to testing. The urban dynamometer driving schedule (UDDS) was used to capture engine data under low-speed urban driving conditions and the US06 drive cycle was used to simulate high-speed aggressive driving conditions. Drive cycles are shown in Figure 2. Testing began with a cold-start cycle, followed by three hot-start cycles. A 10-minute engine-off soak period proceeded each hot-start cycle. Abbreviated specifications for the test vehicle are listed in Table 2.

Figure 1. 2008 Toyota Prius Hymotion conversion plug-in hybrid vehicle at Environment Canada’s Emissions Research and Measurement Section test facility.

Table 1. 2008 Toyota Prius data acquisition instrumentation. List is partial and does not include all data collected during tests; only data required for modeling development are included.

Signal	Description	Notes
Vehicle Speed	Dynamometer/ CAN measured	Drive trace measurement
Engine RPM	CAN/spark frequency	Model input
Brake Torque	CAN	Flywheel torque, model input
T_oil	Dipstick thermocouple	Model input
T_coolant	CAN	Model input
Fuel Flow	Emissions bench carbon count	Model input

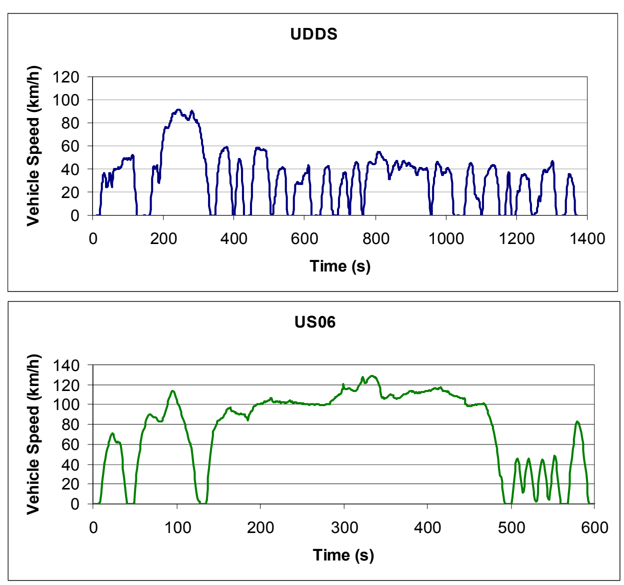

Figure 2. Speed vs. Time Trace for the UDDS and US06 Drive Cycles.

Table 2. 2008 Toyota Prius Hymotion PHEV conversion test vehicle specifications.

Parameter	2008 Toyota Prius Hymotion PHEV conversion
Type of vehicle	Sedan
Vehicle weight [kg]	1815
Battery	1.3 kWh (NiMH) + 5 kWh, 220 V, (Li-ion)
Motor	Permanent magnet, 50 kW (2)
Engine	1.5L, Atkinson cycle
Hybrid configuration	Blended mode

Brake-Specific Fueling Map Development

Response surface methodology (RSM) is "a collection of statistical and mathematical techniques useful for developing, improving, and optimizing processes." In this case, we applied least squares regression fitting of fueling rate as a function of engine speed/load/temperature from the experimental datasets listed in

Table . For this work, RSM techniques were applied to experimental vehicle data collected over several cycles while operating in a 266 K ambient temperature test cell over both UDDS and US06 Federal Test Procedures. Using the data collected, engine speed, load, engine oil/coolant temperatures were selected as input variables, and the fuel consumption measured at each value of the input variables during the cycle. These data were then used to generate the response surface output of BSFC.

Two back-to-back 266 K cold-start UDDS and four back-to-back US06 cycles were combined to develop the BSFC fueling model. Engine speed/load test points from testing are shown in Figure 3. Note that due to increased friction and heat transfer losses at cooler temperatures, the loading at 266 K is greater than that of the 20°C (293 K) cold starts. Also, the loading for the higher speed, higher acceleration US06 cycle is greater than the UDDS points.

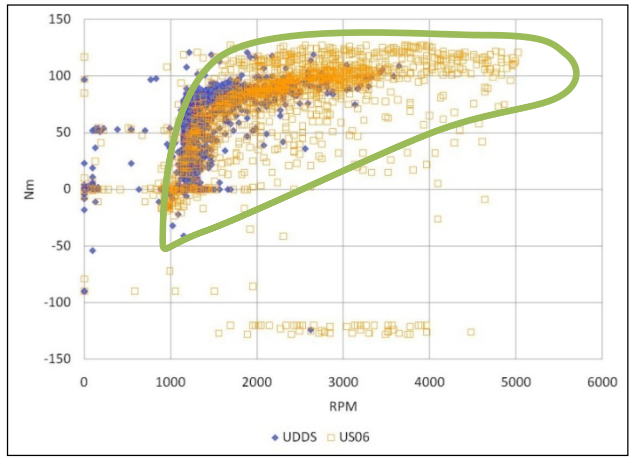

Figure 3. 2008 Toyota Prius Hymotion PHEV conversion 266 K cold-start UDDS and US06 cycle cold-start speed/brake load test points used as RSM model inputs.

Figure 3 shows that broad engine operational design space has been included within the data sets and response model. Associated with each speed load point is a unique measured engine oil temperature that was used as an input to the RSM model.

Using RSM techniques, the response of engine fueling rate as a function of the engine speed, load, and coolant temperature was best-fit modeled as a quartic polynomial including interaction terms.

An example of the modeled BSFC fit is included here and is of the form shown in Equation 1.

Equation 1. Quartic BSFC map format, 266 K cold, modified interactive terms (low-level interactive terms removed).

[fuel(RPM, Nm, T_{engine}) +x_i]$^{1/2}$ =
+a_0+a_1 * RPM+a_2 * Nm+a_3 * Tcoolant+a_4 * RPM * Nm
+a_5 * RPM * Tcoolant+a_6 * Nm * Tcoolant+a_7 * RPM^2
+a_8 * Nm^2+a_9 * Tcoolant^2+a_{10} * RPM * Nm * Tcoolant
+a_{11} * RPM^2 * Nm+a_{12} * RPM^2 * Tcoolant+a_{13} * RPM * Nm^2
+a_{14} * RPM * Tcoolant^2+a_{15} * Nm^2 * Tcoolant
+a_{16} * Nm * Tcoolant^2+a_{17} * RPM^3+a_{18} * Nm^3
+a_{19} * Tcoolant^3+a_{20} * RPM^2 * Nm^2
+a_{21} * RPM^2 * Tcoolant^2+a_{22} * RPM * Nm^2 * Tcoolant
+a_{23} * RPM * Nm * Tcoolant^2+a_{24} * Nm^2 * Tcoolant^2
+a_{25} * RPM^3 * Nm+a_{26} * RPM^3 * Tcoolant+a_{27} * RPM * Nm^3
+a_{28} * RPM * Tcoolant^3+a_{29} * Nm^3 * Tcoolant+a_{30} * RPM^4
+a_{31} * Nm^4+a_{32} * Tcoolant^4

In Equation 1, fuel refers to engine BSFC, RPM is engine speed, Nm is engine brake torque, Tcoolant is the engine coolant temperature, and the variables a_i serve as the polynomial coefficients. Note that not all of the interaction terms are included in this estimation of fueling rate. After analysis, certain interactions are removed, as they have little to no effect on the overall modeling accuracy. This depends solely upon the engine design and calibration, and is uniquely determined from the experimental data for each particular vehicle.\

Model-predicted values versus actual values were plotted and compared for general model accuracy, the results of which may be seen in Figure 4. For a perfect model, predicted values would fall on a 45° diagonal line vs. actual data. As shown, a relatively tight and evenly distributed spread of data falls along this line. Although small outliers are present, both the positive and negative outliers show a mean distribution and will be shown to have minimal impact on the overall cycle-predicted integrated fuel consumption, correlating extremely well with the predicted fuel rate. Details of the model correlation vs. actual data may be seen in Figure 5, in which the model-predicted fueling rate is compared to the actual test data for a UDDS cold start. The first 400 seconds of the tests are illustrated in order to better show detail; however, results throughout the test remain similarly accurate.

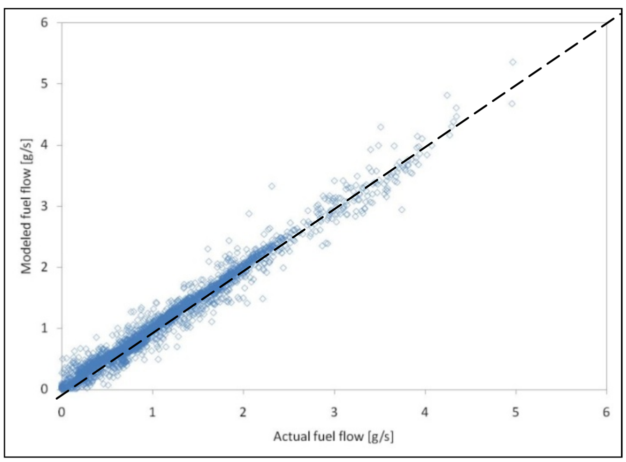

Figure 4. RSM BSFC model, predicted vs. actual data. R-squared values for the model = 0.98.

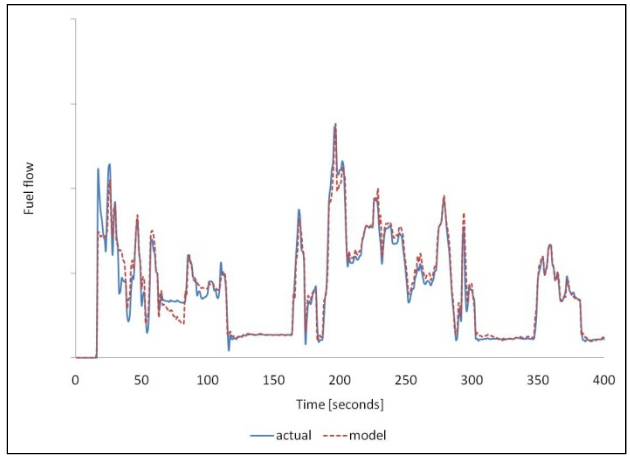

Figure 5. Cold-start model vs. actual fueling detail, initial oil temperature = 20°C, UDDS cycle. Tcoolant = model input for engine temperature.

In comparing the model-predicted fuel rates for the UDDS cycles, it can be seen that the models very closely detail the engine behavior using either oil or coolant temperature as the thermal metric.

Results of the integrated model fueling rate vs. actual data for a 266 K cold-start UDDS cycle are shown in Figure 6, comparing both oil and coolant temperatures as model inputs. Using oil or engine coolant as the temperature input, the modeled deviation from the actual measured fuel consumed, in grams, is less than 0.1%. This suggests that both oil and coolant are sufficient input variables to the BSFC response surface model to determine fuel consumption.

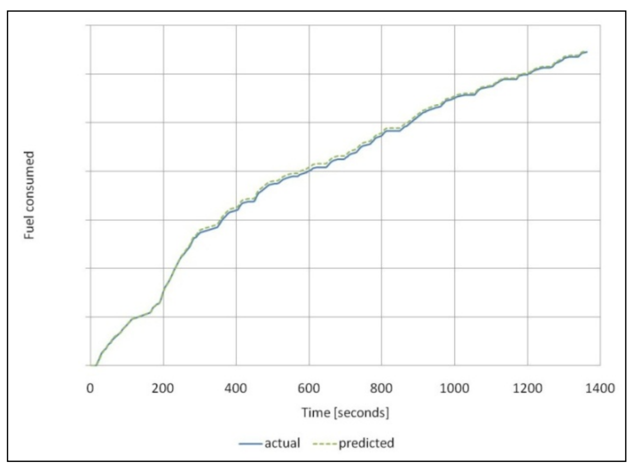

Figure 6. Model-predicted fuel consumed, 266 K UDDS cycle vs. actual recorded fuel consumed. Model < 0.4% predicted integrated value from actual data.

This methodology was shown to predict fuel consumption from datasets other than those used to develop the model. Deviation between the model predicted and actual integrated fuel consumption was shown to be 2%. Therefore, we anticipate that this model may be used accurately with a variety of speed/load/temperature inputs, and still remain relatively accurate.

Issues Relative To Accuracy For Modeling

In order to ensure model accuracy for a broad operating range, it is important that the data used to generate the fueling rate response surfaces sufficiently fill the design space. Inaccuracies could occur if the response model was used in regions in which not much data existed. We developed histograms of the model inputs RPM, engine load, and engine coolant temperature to quantify the areas of model strength and weakness with regard to design space. Figures 7, 8, and 9 show the modeling histograms for RPM, load, and engine temperature (coolant), respectively.

Analysis of the RPM histogram shows that engine load is relatively well distributed, with the exception of the 1500-RPM range. Review of Figure 3 shows that a significant number of operating points were recorded at this engine speed for a variety of loads. Application of the model in much higher RPMs would result in greater inaccuracy; however, since those speeds result in higher fuel consumption (due to increased friction), they most likely would not be encountered in modeling exercises. The same behavior occurs with regard to engine load, shown in Figure 8. With the exception of the 10Nm loading, there is a relatively decent balance of points throughout the load range. This would result in relatively accurate predictability. However, in reviewing Figure 9, one finds that a relatively small number of points exist at the cooler engine temperatures. If one were to use this response surface in modeling, an effort should be made to collect more data at the cooler temperatures to ensure better modeling accuracy. This is a simple matter of testing cycles of various loads and combining the datasets appropriately. The methodology would only change in the range of data collected.

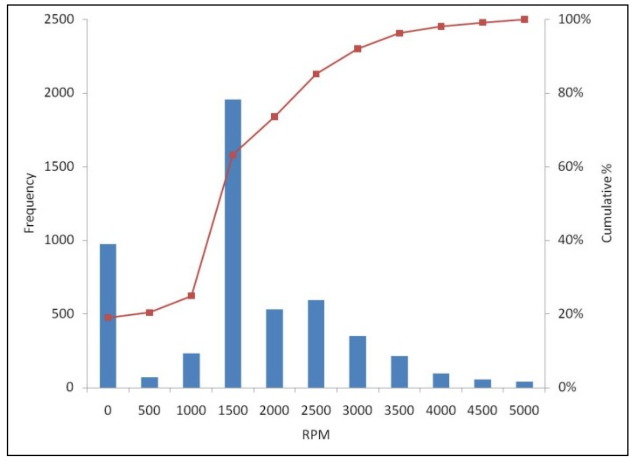

Figure 7. RPM histogram, UDDS cycle, 266 K cold start.

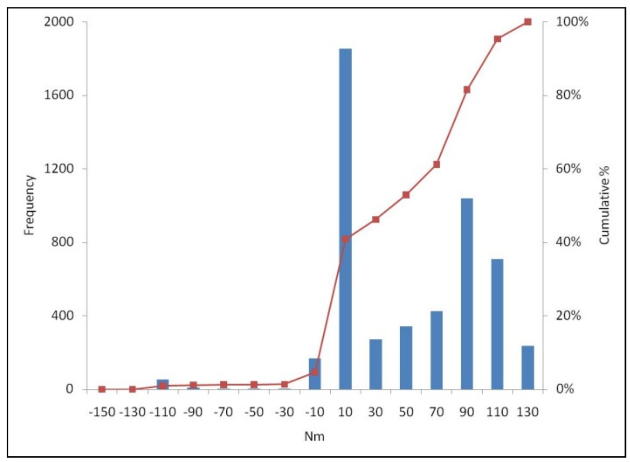

Figure 8 Brake load histogram, UDDS cycle, 266 K cold start.

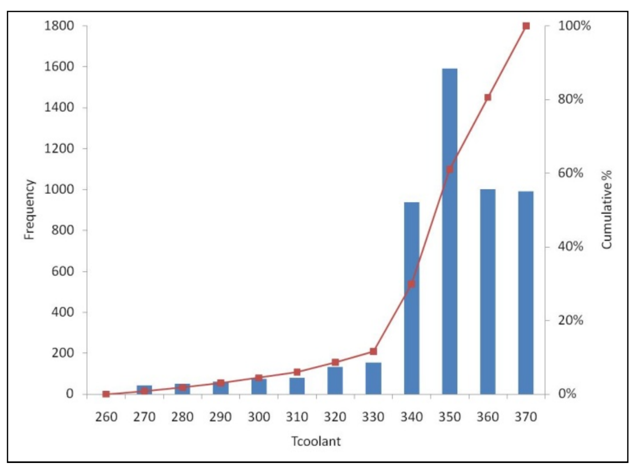

Figure 9. Engine coolant temperature (Tcoolant) histogram, UDDS cycle, 266 K cold start.

Importance Of Including Temperature Effects Into Estimating Vehicle Fuel Economy

To exemplify the importance of including temperature into the estimation of BSFC, Figure 10 shows the estimated fuel rate for several representative engine operating points at a range of temperatures. As can be seen, the engine thermal state is a significant factor in determining engine fueling rate at cold temperatures.

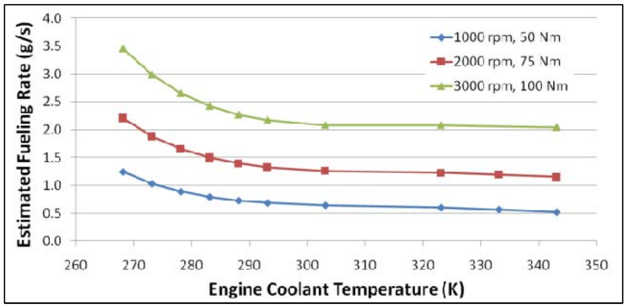

Figure 10. Estimated fuel rate for several representative engine operating points at a range of temperatures.

To further illustrate the importance of incorporating engine thermal state over a cycle, we provide analysis regarding the accuracy of the total fuel estimation for the first UDDS cycle starting from a cold-soaked vehicle in the 266 K ambient temperature. Figure 11 shows the engine coolant temperature over the cycle. While the vehicle eventually reaches stable coolant temperatures, there is a significant amount of operation at colder temperatures, where the engine operates with significantly increased fueling rates.

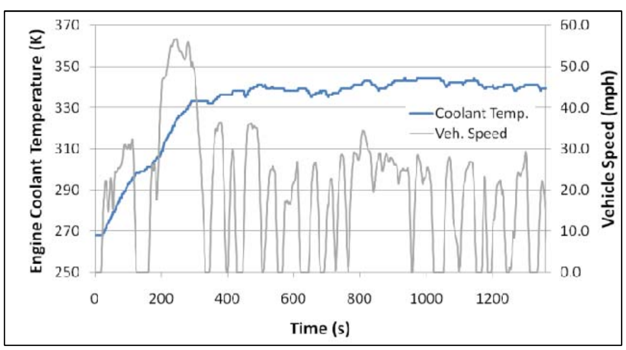

Figure 11. Plot of the engine coolant temperature over the UDDS cycle.

Using the BSFC response model, we estimated fuel usage at both a single coolant temperature and using the entire coolant time trace from the experimental data. The single coolant temperature used in this comparison, 328 K (55°C), was chosen to minimize the error compared to the actual fuel usage and represents a point in between the stabilized coolant temperature and initial starting coolant temperature. As expected, incorporating the entire range of coolant temperature significantly decreased the error of predicted vs. actual fuel used. Figure 12 shows the error relative to total grams of fuel used for both the single temperature- and time-series temperature-based evaluations at various time segments of the first UDDS cycle. This figure clearly shows that the single temperature estimate significantly underestimates the fuel used for the first three time segments, and over-predicts fuel usage for the entire cycle. The absolute error of the single coolant temperature estimate decreases over time as more of the engine operation occurs closer to the chosen temperature of 328 K. If a colder temperature is used for the single temperature fuel estimate, the error for the entire cycle is larger, since a significant portion of the operation still occurs at warmer temperatures.

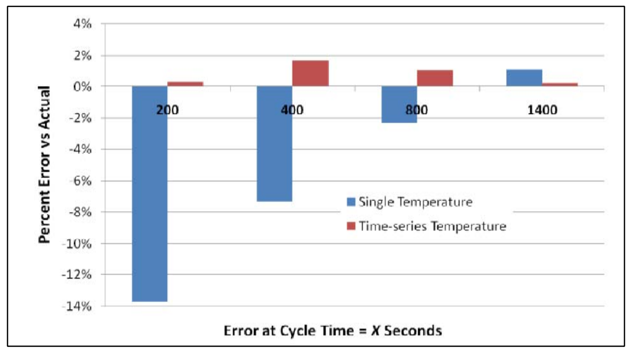

Figure 12. Chart showing amount of error relative to total grams of fuel used for both the single temperature- and time-series temperature-based evaluations at various time segments of the first UDDS cycle.

To better illustrate the error introduced by excluding proper thermal estimation, Figure 13 shows the error of the predicted fuel rate using the single and time-series temperature estimates over the UDDS cycle. As shown in Figure 13, the single temperature fuel rate is significantly underestimated during the initial vehicle warm-up period. Additionally, the fuel rate for a large portion of the cycle following warm-up is over-predictive. This is due to the compromise required in using a single temperature that must cover both the initial warm-up and the warm operating temperatures. As is expected for a least squares-type fit, the time-series-based temperature has a balanced amount of error both in the positive (under-prediction) and negative (over-prediction) directions.

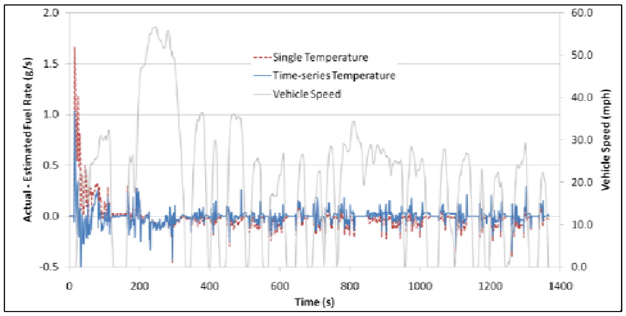

Figure 13. Plot illustrates the error of the predicted fuel rate using the single and time-series temperature estimates over the UDDS cycle.

Given the demonstrated importance of including engine thermal state into the estimation of fuel use while operating at cold temperatures, a natural follow-up question relates to how closely engine thermal state must be estimated. To investigate this issue, we repeated the previously discussed single coolant temperature analysis with increasing resolution until the cumulative fuel error at each time segment was less than 1%. In this analysis, the coolant temperature at each time-step would be set to the closest possible option and this temperature would then be evaluated using the developed BSFC fit. Using this setup, we optimized varying numbers of bins to provide minimal error relative to the BSFC fit as evaluated using the actual coolant temperature trace. Interestingly, only four coolant options were required to estimate the fuel used adequately within 1% for each of the analysis segments. Since the US06 cycle uses higher power and more frequent engine operation, we would expect that the four-temperature estimate would work suitably well for this cycle as well, given a faster warm-up and thermal stabilization. For certain analysis scenarios, this suggests that while it is important to incorporate thermal state into the estimation of fuel use, the estimated temperatures do not necessarily need to be exceedingly precise in order to develop suitable overall fuel usage estimates. If vehicle thermal operating state is spread over a much larger range of temperatures or if an engine's fueling rate is much more sensitive to temperature, this analysis will likely need to be revisited.

Figure 14 shows the optimal four-coolant temperature options relative to the actual coolant temperature trace. This figure shows that the temperature may be under- or over-estimated to a fairly large degree without significantly affecting the estimated cumulative fuel usage. As would be expected given the previously demonstrated increased temperature sensitivity at colder temperatures, most of the optimal temperature selections for the four points estimated are clustered during the warm-up period.

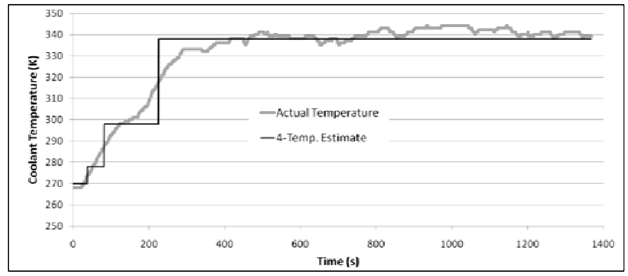

Figure 14. Plot shows the optimal four-coolant temperature options relative to the actual coolant temperature trace.

Engine Temperature Data Fit Development

As discussed previously, we seek through this work to create a streamlined thermal data fit that is tuned using experimental vehicle test data. While we aim to match the fit to the experimental data as closely as possible, our intent is to keep the fit fairly simple and easy to implement. The following section discusses the basic structure of the simplified model and the improvements needed to match the test data suitably, and shows the resulting model fit over repeated UDDS and US06 cycles. While engine coolant is the temperature variable of interest in this analysis, similar modeling could be done using engine oil temperature or any other alternative thermal state that is representative of engine warm-up behavior.

The preliminary structure of the coolant temperature model is a simple lumped capacitance model that tracks coolant temperature as a function of the estimated heat into the coolant from the engine fueling loss and the heat lost to the cold ambient temperature. Figure 15 shows the basic structure of the preliminary model.

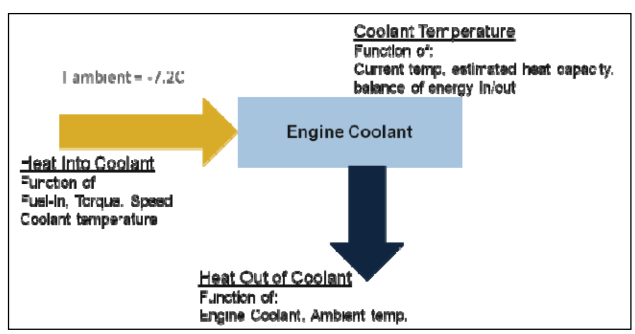

Figure 15. Preliminary coolant model overview.

The resulting model requires tuning three parameters to match the experimental data, which we did by minimizing the mean-square error (MSE) between the estimated temperature and the data collected in the test cell.

The majority of the model fitting was performed using four back-to-back urban cycles run with a 266 K ambient temperature setting. In order to give a better overview of the engine warm-up behavior, Figure 16 provides both the coolant and engine oil temperature trace of the four UDDS cycles. Note that the 10-minute soak period has been removed from the time-series data and thus, the large drop in temperature is due to the soak period between UDDS runs.

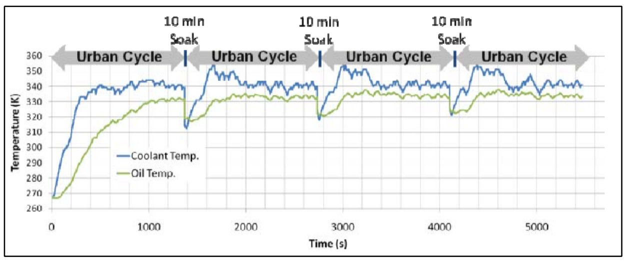

Figure 16. Coolant and oil temperature recorded over repeated UDDS cycles.

As shown in Figure 17, engine coolant increases in temperature much faster than the engine oil temperature. The engine oil temperature has a fairly significant lag in warm-up time due to mixing factors and the more complicated dynamics of the engine oil moving through the engine.

The first adaptation to the coolant temperature model was the inclusion of an exponential weighting factor to incorporate the observed delay between engine usage changes and a change in coolant temperature. Figure 17 highlights this issue on a section of the urban cycle.

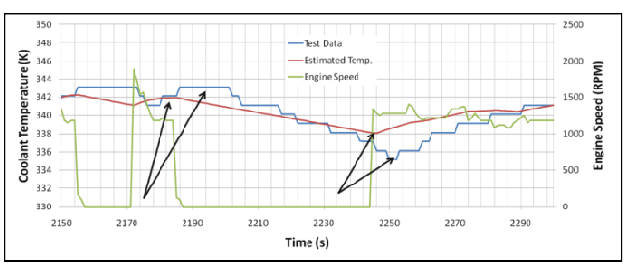

Figure 17. Delay between estimated and actual temperature.

The first set of arrows in Figure 17 highlights the delayed response of coolant temperature when the engine enters engine-stop mode. The decrease in engine coolant temperature coincides directly with the engine shutting down, whereas there is a significant lag observed in the actual test data. Similarly, the second set of arrows highlights the lag in temperature as the engine begins to operate and temperatures begin increasing. In order to better emulate this behavior, an exponential weighting factor was included in the model, which operates on the amount of heat reaching the coolant from the engine fueling losses. This factor incorporates previous engine usage rates into the heat transfer rate for a given time-step, allowing the lag observed in the experimental data to be incorporated into the model. The amount of influence given to previous operation (the alpha of the fit) is included in the set of variables optimized by the minimum MSE routine.

The second addition to the thermal model is the incorporation of a simplified oil temperature model, given the significant and slow oil warm-up observed during the initial vehicle warm-up. In conjunction with a rough estimate of oil temperature, we included a temperature differential-based heat-transfer coefficient between the engine oil and coolant. Figure 18 illustrates the issue that this simple oil warm-up model attempts to correct. Without including the oil temperature dynamic in the temperature prediction, the minimum MSE fit over all four cycles matches the later cycles very well, but over-predicts the coolant temperature for the first cycle.

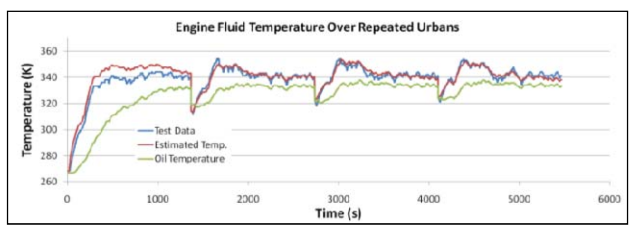

Figure 18. Over-prediction of initial coolant temperature.

To predict the coolant temperature more accurately, a very simplified oil temperature estimate was included into the model-fitting. The oil temperature estimate was created using the basic structure of Figure 18, along with the inclusion of an exponential lag term. The four terms of the oil temperature estimate were also solved using a minimum MSE approach.

With the inclusion of these new tuning variables, the coolant temperature estimate now requires five tuning variables to match the temperature profile observed during testing. In addition to the new tuning variables, we also created a similar engine oil temperature model, but this model needs to represent just the oil warm-up behavior and does not need to be particularly accurate. Furthermore, other thermal states such as engine block temperature could be used to model the preliminary lag as opposed to engine oil. Figure 19 shows an overview of the updated coolant temperature estimate.

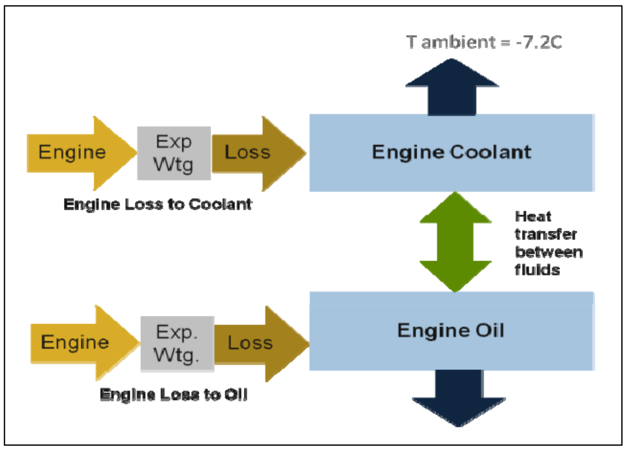

Figure 19. Updated engine coolant estimate.

Employing the minimum MSE fitting technique to these data shows a reasonable match in temperature over the four back-to-back UDDS cycles. Figure 20 shows the final model fit relative to both oil and coolant temperature. Figure 21 shows the error between observed and estimated coolant temperature.

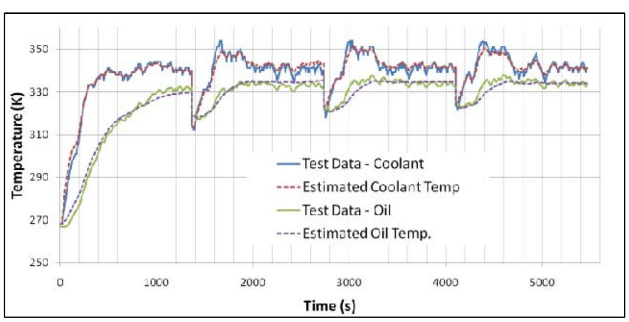

Figure 20. Estimated oil and coolant model vs. actual data.

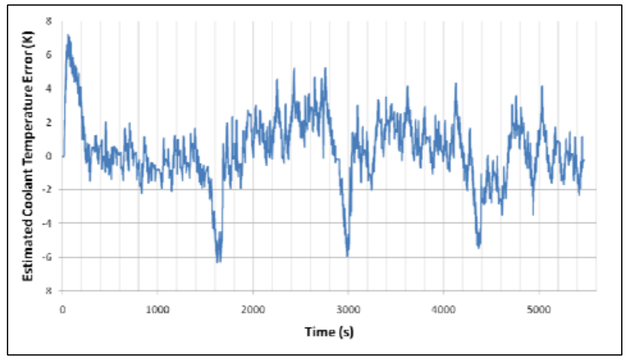

Figure 21. Estimated coolant temperature model error.

Once the coolant model was complete for the UDDS cycle data, we tested the model using the US06 cycle data. Based on these data, we included an additional component to represent the opening of the radiator above a certain coolant temperature. This model uses an activation temperature and maximum temperature for the thermostat valve, as well as an increased heat transfer coefficient to the ambient that scales linearly between the activation and maximum temperature. For temperatures above the maximum thermostat temperature, the heat transfer coefficient remains the same, since the thermostat valve cannot open any more. Below the activation temperature, the heat transfer is the same value from the previous UDDS analysis. The thermostat activation temperatures were obtained from the Toyota Prius Service Manual.

After incorporating these additional variables into the optimization procedure, estimated coolant and oil temperature for the US06 cycle is shown in Figure 22 for two back-to-back cycles with a one-minute pause in between. Additional US06 cycles were not included in this analysis, since the vehicle reached a stabilized temperature quickly.

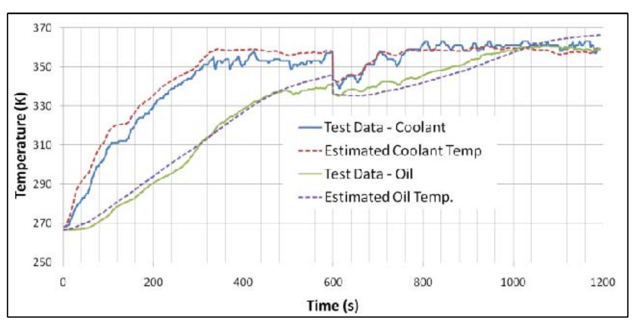

Figure 22. Estimated temperature for repeated US06 cycles.

Figure 23 shows the error of the US06 coolant fit relative to the experimental data. While the fit is still reasonably good, it is clear that the US06 cycle does not fit as well as the UDDS cycle. This suggests that some additional optimization may be needed to better fit both the UDDS and US06 cycle data. Furthermore, this also suggests that the lags and warm-up of other components may need to be assessed more thoroughly to better estimate temperatures for cycles with more engine usage and thus, both a faster warm-up as well as a larger temperature differential between coolant and engine oil.

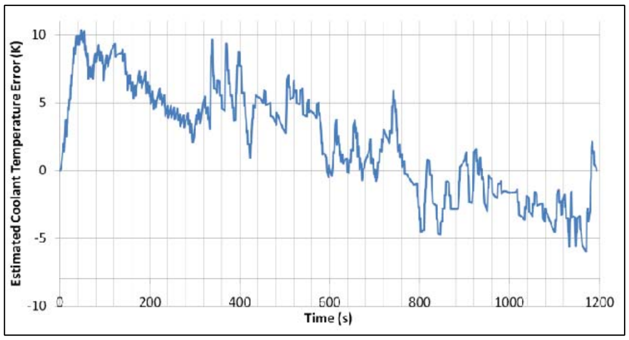

Figure 23. Error of the US06 cycle coolant fit relative to the experimental data.

Application of Methodology

Since a response model for the fueling rate as a function of the engine's speed/load/temperature has been developed in conjunction with an engine temperature predictive model, these results may be used in engine modeling programs to predict the fuel consumption of a modeled vehicle over any number of drive cycles/calibration strategies to predict optimal settings.

Conclusion

Using experimental data from a 2008 Toyota Prius tested on a chassis dynamometer, response surface methodology techniques have been applied to develop engine brake-specific fuel consumption maps, in conjunction with engine temperature predictive models through a simplified lumped capacitive technique. The UDDS and US06 drive cycles were investigated, with testing conducted at test cell temperatures of 266 K. Inputs to the maps were engine speed, load, and engine temperature, as indicated by either engine coolant or engine oil temperature. To summarize the results of this work:

- Response surface methodology techniques can quickly and accurately model engine brake-specific fuel consumption over a wide range of engine operating temperatures.
- Results of the model show that engine fuel consumption significantly decreases with an increase in engine temperature.
- Using a modified and tuned simplified lumped capacitance thermal model, an engine coolant temperature response fit technique has been developed and implemented for the 2008 Prius operating at cold ambient conditions.
- The predictive engine temperature model is shown to be relatively accurate for the both the UDDS and US06 cycles. Variations from the US06 cycle may be addressed with additional experimental data coupled with other optimizations.

These techniques may be readily applied to vehicle fuel economy estimation, which traditionally does not address thermal effects on consumption. Moreover, the developed response surface techniques should be streamlined generally enough to aid in the evaluation of a broad range of vehicles and technologies.

Publications/Presentations

1. Jehlik, F., Rask, E., and Christenson, M., Simplified Methodology for Modeling Cold Temperature Effects on Engine Efficiency for Hybrid and Plug-in Hybrid Vehicles, SAE Powertrains and Fuels Conference, San Diego, CA, Oct. 25–27, 2010.

2. Jehlik, F. and Rask, E., Development of Variable Temperature Brake Specific Fuel Consumption Engine Maps, SAE Powertrains and Fuels Conference, San Diego, CA, Oct. 25–27, 2010

B. Advanced Vehicles Validation

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Objectives

- Validate the latest conventional, hybrid, and plug-in hybrid vehicles in Autonomie.

Approach

- Gather component and vehicle assumptions.
- Develop the vehicle-level control strategy.
- Validate the model by comparing with available test data.

Accomplishments

- Validated heavy-duty conventional vehicles.
- Validated hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) using proprietary data.

Future Directions

- Continue to validate models of the latest powertrain technologies.
- Improve models for accessory loads for medium and heavy duty applications

Introduction

The objective of this project is to validate the latest vehicle powertrain configurations and component technologies to ensure the accuracy of the component data and vehicle-level control strategies used to evaluate fuel consumption benefits. The information obtained will support DOE research and development guidance.

Since no vehicle test data are available within DOE for validation of medium- and heavy-duty applications, test data from partnerships with West Virginia University and the U.S. Environmental Protection Agency (EPA) were utilized.

Vehicle Test Data Analysis

ANL used a generic process shown in Figure 1 to validate the vehicle model. First, the test data from a text file were imported into a Matlab environment following Autonomie format. Each parameter is then analyzed, the redundant signals are compared, and the missing signals are calculated.

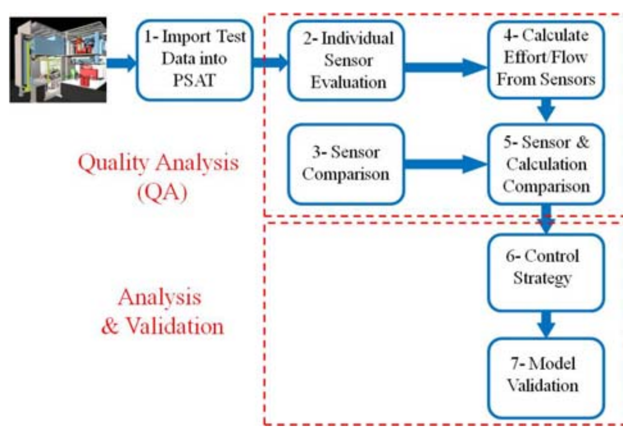

Figure 1. Test Data Analysis Process

The same process was implemented for the various validations detailed below.

Ford PHEV Escape

The latest pre-production version of the Ford Escape PHEV was tested at ANL's Advanced Powertrain Research Facility. A previously validated Ford Escape HEV model was used as a starting point. The battery model and data were provided by ANL's Battery group. The vehicle control strategy was analyzed and reproduced in simulation. The engine ON/OFF and its operating conditions were matched with the test data. Because of the proprietary nature of the vehicle application, detailed information is unable to be provided in this report.

Class 4 Parcel and Delivery (P&D) Conventional

A class 4 P&D vehicle was tested at SwRI under contract from the U.S. EPA. (Figure 1). The test was performed on three drive cycles: transient, HSC and SCL.

Figure 1. Class 4 P&D Vehicle

The main vehicle specifications are shown in Table 1.

Table 1: Main Vehicle Specifications

VEHICLE NAME	W/C700
VEHICLE TYPE	2008 FedEx Diesel Delivery Van
VEHICLE MANUF AND MAKE	Model Year 2008 FCCC MT45 Chassis with Utilimaster Body
TRANS TYPE AND # OF GEARS	Allison 1000 series 5-speed Automatic
Gross Vehicle Weight	16000 lbs
TEST WEIGHT	12900 lbs
ENGINE MODEL	Cummins ISB07 6.7 Liters
HP RATING ON LABEL	200 hp – 150kW
HP RATED SPEED	2600 rpm
TORQUE RATING	520 lbs-ft
TORQUE SPEED	1600 rpm
MAX AMOUNT OF PAYLOAD	4,600 lbs.
TOTAL WEIGHT OF VEHICLE	10,800 lbs
FUEL DESCRIPTION	Diesel
FINAL DRIVE RATIO	4.1

Working with truck manufacturers and suppliers, the component data were implemented to accurately represent the vehicle. Then, the driver characteristics were tuned to follow the trace similarly to the driver.

The gear information from testing was constructed based on an algorithm. The shifting algorithm was then developed to match test data as shown in Figure 2.

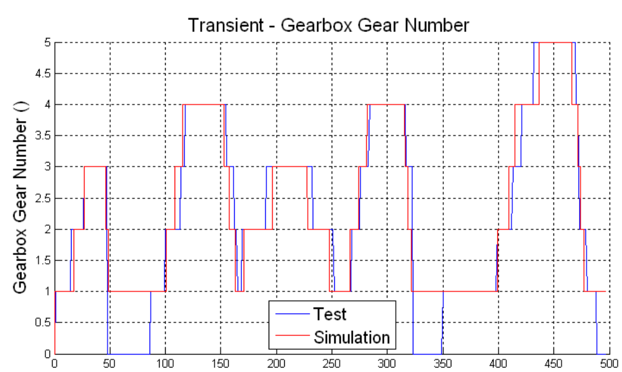

Figure 2: Gear Number Comparison on the Transient Cycle

The component operating conditions were then compared in further details. One way to evaluate the accuracy of the driveline losses in a conventional vehicle is to compare the engine torque. Figure 3 shows a comparison for the LSC drive cycle. Even if one should take into account the uncertainties from the measured data (i.e., CAN has slow rate) and the simulated component efficiencies, both signals show good correlation.

The fuel economy and distance of simulated vehicle was then compared with the test data. As shown in Figure 4, the results are within the test-to-test variability.

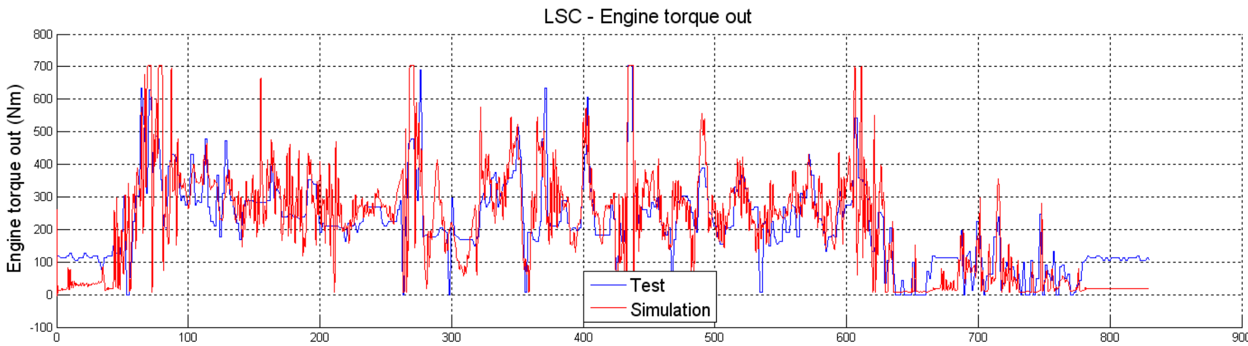

Figure 3: Comparison of Engine Torque on LSC Cycle

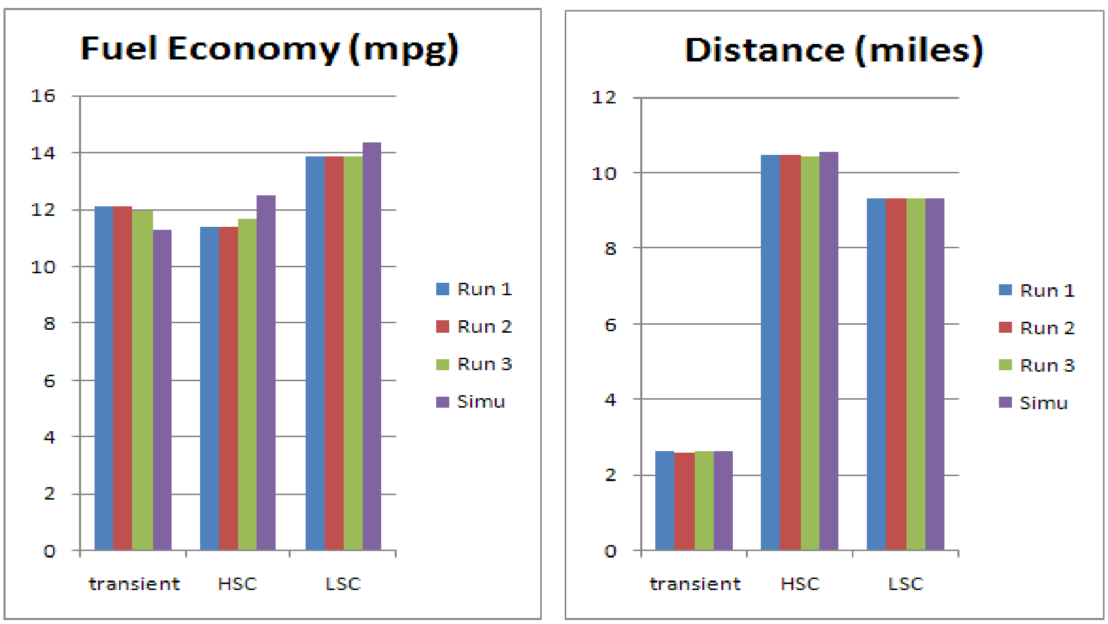

Figure 4: Comparison of Fuel Economy and Distance

Conclusion

Several vehicles were validated by using ANL's Advanced Powertrain Research Facility and test data from government agencies (EPA) and universities. The validation of the Ford Escape PHEV and a class 4 Parcel & Delivery vehicle demonstrated good correlation between tests and simulation.

The validation and correlation exercises demonstrate that Autonomie is now ready for use in assessing the fuel consumption benefits of medium- and heavy-duty vehicles.

C. Simulation Runs to Support GPRA

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Objectives

- Simulate multiple vehicle platforms, configurations, and timeframes to provide fuel economy data for analysis in support of the Government Performance and Results Act (GPRA).

Approach

- Validate component and vehicle assumptions with DOE national laboratories and FreedomCAR Tech Teams.
- Use automatic component sizing to run the study.

Accomplishments

- Simulated and sized more than 2,000 vehicles both for light and heavy duty applications
- Simulated new vehicles when assumptions or platforms were revised or when additional configurations or timeframes were requested.

Future Directions

- Continue to provide analytical data to support GPRA in 2011.

Introduction

Through the Office of Planning, Budget, and Analysis, DOE's Office of Energy Efficiency and Renewable Energy (EERE) provides estimates of program benefits in its annual Congressional Budget Request. The Government Performance and Results Act (GPRA) of 1993 provided the basis for assessing the performance of federally funded programs. Often referred to as "GPRA Benefits Estimates," these estimates represent one piece of EERE's GPRA implementation efforts — documenting some of the economic, environmental, and security benefits (or outcomes) that result from achieving program goals. The Powertrain System Analysis Toolkit (PSAT) was used to evaluate the fuel economy of numerous vehicle configurations (including conventional, hybrid electric vehicles [HEVs], plug-in HEVs [PHEVs], electric), component technologies (gasoline, diesel, and hydrogen engines, as well as fuel cells), and timeframes (current, 2010, 2015, 2030, and 2045). The uncertainty of each technology is taken into account by assigning probability values for each assumption.

Methodology

To evaluate the fuel efficiency benefits of advanced vehicles, the vehicles are designed on the basis of component assumptions. The fuel efficiency is then simulated on the Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Test (HWFET). The vehicle costs are calculated from the component sizing. Both cost and fuel efficiency are then used to define the market penetration of each technology to finally estimate the amount of fuel saved. The process is highlighted in Figure 1. This report focuses on the first phase of the project: fuel efficiency and cost.

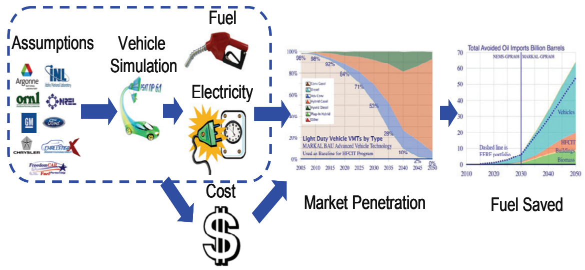

Figure 1. Process to Evaluate Fuel Efficiency of Advanced Technology Vehicles

To properly assess the benefits of future technologies, the following options were considered, as shown in Figure 2:

- Different vehicle classes: compact car, midsize car, small sport utility vehicle (SUV), medium SUV, pickup truck, as well as medium and heavy duty applications
- Four timeframes: 2010, 2015, 2030, and 2045
- Five powertrain configurations: conventional, HEV, PHEV, fuel cell HEV, and electric vehicle
- Four fuels: gasoline, diesel, hydrogen, and ethanol

Overall, more than 2,000 vehicles were defined and simulated in Autonomie. The current study does not include micro- or mild hybrids and does not focus on emissions.

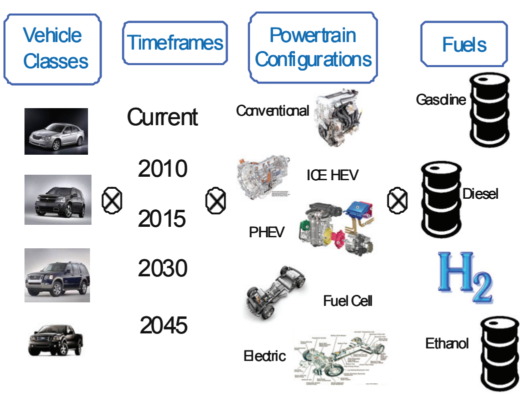

Figure 2. Vehicle Classes, Timeframes, Configurations, and Fuels Considered

To address uncertainties, a triangular distribution approach (low, medium, and high) was employed, as shown in Figure 3. For each component, assumptions (e.g., regarding efficiency, power density) were made, and three separate values were defined to represent the (1) 90th percentile, (2) 50th percentile, and (3) 10th percentile. A 90% probability means that the technology has a 90% chance of being available at the time considered. For each vehicle considered, the cost assumptions also follow the triangular uncertainty. Each set of assumptions is, however, used for each vehicle, and the most efficient components are not automatically the least-expensive ones. As a result, for each vehicle considered, we simulated three options for fuel efficiency. Each of these three options also has three values representing the cost uncertainties.

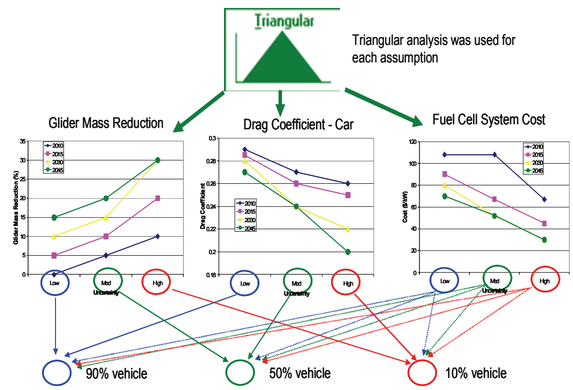

Figure 3. Uncertainty Process

Vehicle Technology Projections

The assumptions described below have been defined on the basis of inputs from experts and the FreedomCAR targets (when available).

Engines

Several state-of-the-art engines were selected for the fuels considered: gasoline, diesel, E85 FlexFuel, and hydrogen. The gasoline, diesel, and E85 FlexFuel engines used for current conventional vehicles were provided by automotive car manufacturers, while the port-injected hydrogen engine data were generated at Argonne. The engines used for HEVs and PHEVs are based on Atkinson cycles.

Different options were considered to estimate the evolution of each engine technology. Although linear scaling was used for gasoline, E85 (HEV applications only), and diesel engines, direct injection with linear scaling was considered for the hydrogen-fueled engine, and nonlinear scaling based on AVL's work was used for gasoline and E85 (conventional applications). For the nonlinear scaling, different operating areas were improved by different amounts, which resulted in changing the constant efficiency contours. The peak efficiencies of the different fuels and technologies are shown in Figure 4.

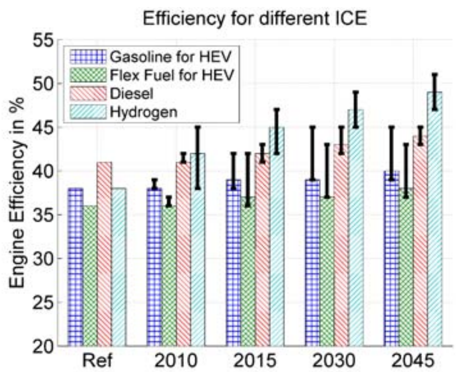

Figure 4. Engine Efficiency Evolution

Fuel Cell Systems

The fuel cell system model is based on the steady-state efficiency map. The values shown in Figure 5 include the balance of plant. The system is assumed to be gaseous hydrogen

The peak fuel cell efficiency is currently assumed to be 55%, and it will rapidly increase to 60% by 2015. The efficiency value of 60% has already been demonstrated in laboratories and therefore is expected to be achieved soon in vehicles. The peak efficiencies remain constant in the future because most research is expected to focus on reducing cost.

Hydrogen Storage Systems

The evolution of hydrogen storage systems is vital to the introduction of hydrogen-powered vehicles. Figure 5 shows the evolution of the hydrogen storage capacity.

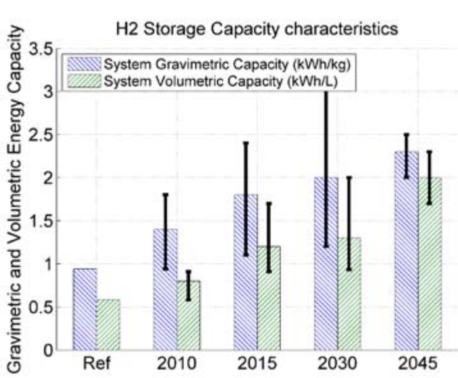

Figure 5. Hydrogen Storage Capacity in Terms of Quantity

Electric Machines

Figure 6 shows the electric machine peak efficiencies considered. The values for the current technologies are based on the current state-of-the-art electric machines. The electric machine data from the Toyota Prius and Camry were used for the power-split configurations, while the Ballard IPT was selected for series configurations.

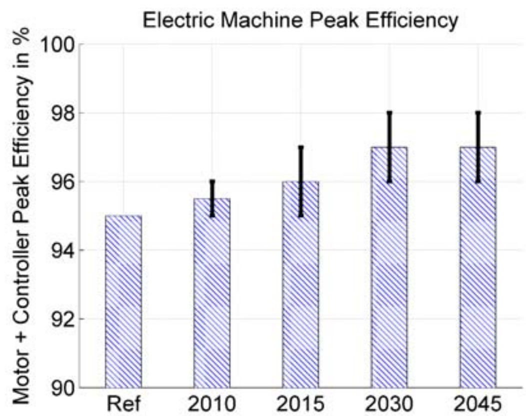

Figure 6. Electric Machine Peak Efficiency

Energy Storage System

Energy storage systems are a key component in advanced vehicles. Although numerous studies are being undertaken with ultracapacitors, only batteries were taken into account in the study. All current vehicles are defined by using nickel metal hydride (NiMH) technology. The lithium ion (Li-ion) technology is introduced for the high case in 2010 and for the medium and high cases in 2015, before becoming the only one considered for later timeframes.

To ensure that the battery has similar performance at the beginning and end of life, the packs were oversized in terms of both power and energy, as shown in Figure 7.

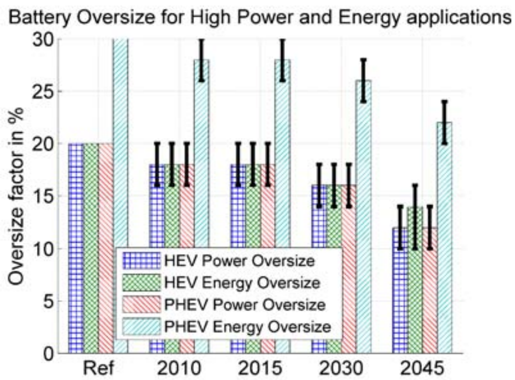

Figure 7. Battery Oversizing

Vehicle

As previously discussed, four vehicles classes were considered, as listed in Table 1.

Table 1. Vehicle Characteristics for Different Light Duty Vehicle Classes

Vehicle Class	Glider Mass (Ref) (kg)	Frontal Area (Ref) in (m^2)	Tire	Wheel Radius (m)
Compact Car	800	2.15	P195/65/R 15	0.317
Midsize car	990	2.2	P195/65/R 15	0.317
Small SUV	1000	2.52	P225/75/R 15	0.35925
Midsize SUV	1260	2.88	P235/70/R 16	0.367
Pickup	1500	3.21	P255/65/R 17	0.38165

Because of the improvements in material, the glider mass is expected to significantly decrease over time. Although frontal area is expected to differ from one vehicle configuration to another (i.e., the electrical components will require more cooling capabilities), the reduction values were considered constant across the technologies. Figure 8 shows the reduction in glider mass.

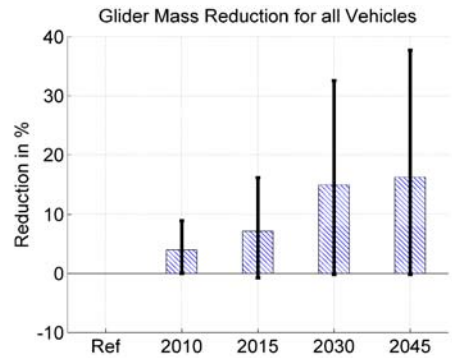

Figure 8. Glider Mass Reductions

Vehicle Powertrain Assumptions

All the vehicles have been sized to meet the same requirements:

0–100 km/h in 9 s +/-0.1

Maximum grade of 6% at 105 km/h at gross vehicle weight

Maximum vehicle speed of >160 km/h

For all cases, the engine or fuel cell powers are sized to complete the grade without any assistance from the battery. For HEVs, the battery was sized to recuperate the entire braking energy during the UDDS drive cycle. For the PHEV case, the battery power is defined as its ability to follow the UDDS in electric mode for the 10 and 20 miles cases and the US06 for the 30 and 40 miles cases, while its energy is calculated to follow the UDDS for a specific distance regardless of distance.

Input mode power-split configurations, similar to those used in the Toyota Camry, were selected for all HEV applications and PHEVs with low battery energies. Series configurations were used for PHEVs with high battery energies (e.g., 30 miles and up in EVs on the UDDS). The series fuel cell configurations use a two-gear transmission to allow them to achieve the maximum vehicle speed requirement.

Vehicle Simulation Results

The vehicles were simulated on both the UDDS and HWFET drive cycles. The fuel consumption values and ratios presented below are based on unadjusted values. The cold-start penalties were defined for each powertrain technology option on the basis of available data collected at Argonne's dynamometer facility and available in the literature. The following cold-start penalties (on the 505 cycle at 20°C) were kept constant throughout the timeframes:

Conventional: 15%

Split HEV: 18%

Split PHEV: 14%

Fuel Cell HEV: 25%

Fuel Cell PHEV: 15%

Electric Vehicle: 10%

Impact of Different Fuels on Conventional Vehicles

Figure 10 shows the evolution of the fuel consumption for different fuels on a conventional midsize vehicle. All of the results are presented in gasoline fuel equivalent. As expected, the diesel engine achieves better fuel efficiency than the gasoline engine, but the difference between both technologies narrows with time because greater improvements are expected for gasoline engines.

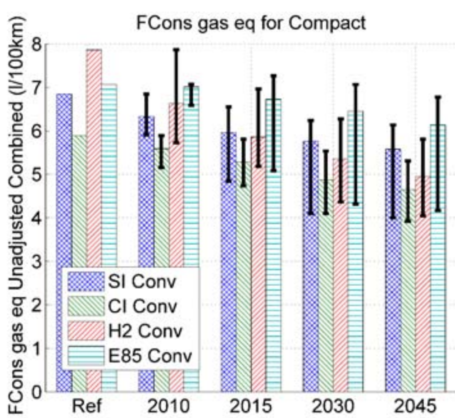

Figure 9. Gasoline-Equivalent Fuel Consumption (unadjusted for conventional midsize cars)

Hydrogen engines are penalized by the additional weight of the hydrogen storage system. With the introduction of direct-injection hydrogen engine technology combined with improved storage, hydrogen engines can compete with other fuels. It is also important to notice the large uncertainty related to hydrogen vehicles.

Ethanol engines are currently being designed to run on several fuels. When specifically designed to run on ethanol, these vehicles have the potential to achieve a better fuel efficiency.

Evolution of HEVs vs. Conventional Vehicles

The comparisons between power-split HEVs and conventional gasoline vehicles (same year, same case) in Figure 10 show that the ratios stay roughly constant for diesel, gasoline, and ethanol. In summary, the advances in component technology will equally benefit conventional vehicles and HEVs, except for the hydrogen engine, because of the additional benefits of hydrogen storage.

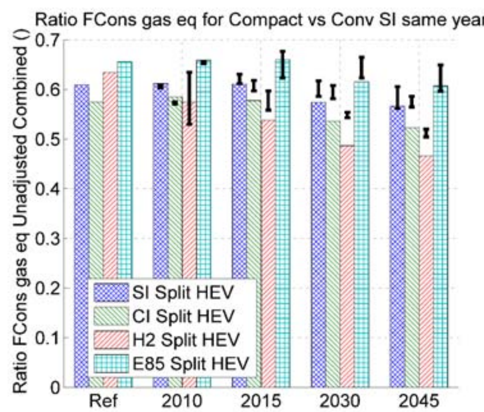

Figure 10. Ratio of Fuel Consumption Gasoline-Equivalent in Comparison to the Conventional Gasoline

Evolution of HEVs vs. FC HEVs

Figure 11 shows the fuel consumption comparison between HEVs and fuel cell HEVs for the compact-car case. First, note that technology for fuel cell vehicles will continue to provide better fuel efficiency than the technology for the HEVs. However, the ratios vary over time, depending upon the fuel considered. The ratio for the gasoline HEV increases over time because most improvements considered for the engine occur at low power and consequently do not significantly impact the fuel efficiency in hybrid operating mode. Both diesel and ethanol HEVs follow the same trend as gasoline HEVs.

Because of the larger improvements considered for the hydrogen engine, the hydrogen power split shows the best improvement in fuel consumption compared with the fuel cell technology.

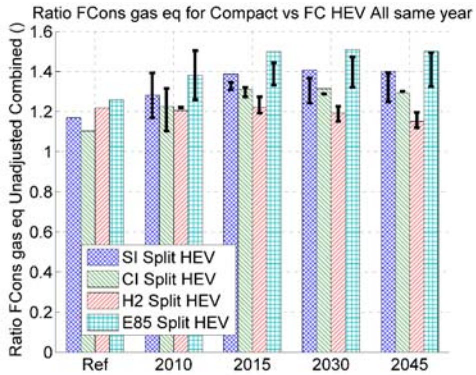

Figure 11. Ratio of Fuel Consumption Compared to the Fuel Cell HEV

Conclusions

More than 2,000 vehicles were simulated for different timeframes (to year 2045), powertrain configurations, and component technologies. Both their fuel economy and cost were assessed to estimate the potential of each technology. Each vehicle was associated with a triangular uncertainty. The simulations highlighted several points:

- The discrepancy between gasoline and diesel engines for conventional vehicles is narrowing with the introduction of new technologies, such as variable valve timing and low-temperature combustion.
- From a fuel-efficiency perspective, HEVs maintain a relatively constant ratio compared with their conventional vehicle counterparts. However, the cost of electrification is expected to be reduced in the future, favoring the technology's market penetration.
- Diesel vehicles will offer the lowest fuel consumption among the conventional powertrains in the near future.
- PHEVs offer the greatest potential to reduce fuel consumption, especially when using high-energy batteries.

D. U.S. DOE Vehicle Technologies Program Support

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Objectives

- Support any specific request from Vehicle Technologies Program occurring throughout the year.

Approach

- Gather component data for technologies to be evaluated
- Run simulations to address specific questions

Accomplishments

- Evaluated the benefit of HCCI engine for several powertrain configurations
- Assessed line haul fuel consumption for several steady-state vehicle speeds for different payloads
- Evaluated impact of displacement on engine idle fuel rate

Future Directions

- Continue to support any unplanned Vehicle Technologies requests.

Introduction

The objective of the project is to support any request from the Vehicle Technologies program that may occur throughout the year.

In the past, studies have been performed to assess the fuel consumption impact of component technologies (i.e., SIDI, HCCI), powertrain configurations and vehicle applications (i.e., heavy duty). Requests have also been made to evaluate the technologies required to meet CAFÉ standards.

The main requests during fiscal year 2010 are described below.

Fuel Consumption Benefits of HCCI Engines

Homogeneous Charge Compression Ignition (HCCI) engines have captured car manufacturers' attention because of the significant fuel efficiency gains that they achieve compared to spark-ignited (SI) gasoline engines. Improvements in automobile component controllers have solved some of the issues related to the difficult combustion control inherent to HCCI technology. In an HCCI engine, a homogeneous mixture of fuel and air is injected into the cylinder's combustion chamber, typically at a high air-to-fuel ratio. The charge is then compressed until it auto-ignites, without the use of a spark, unlike SI engines. Due to the very lean combustion process, fuel consumption as well as emissions are greatly reduced. HCCI technology is being developed at a time when numerous electric drive powertrains have been developed and produced, such as those found in Hybrid Electric Vehicles (HEVs), thus providing the opportunity to combine HCCI with multiple vehicle architectures.

In this study, two engine maps (with and without HCCI) were created by University of Michigan. These maps were then used to assess the fuel consumption benefits off the technology on several powertrain configurations.

Results for Standards Drive Cycles

All the vehicles were sized to meet the same Vehicle Technical Specifications (VTS) for performance and gradeability. The vehicles were then simulated on the standard drive cycles to evaluate their fuel consumption. Figure 1 shows the benefits of HCCI technology for the configurations considered.

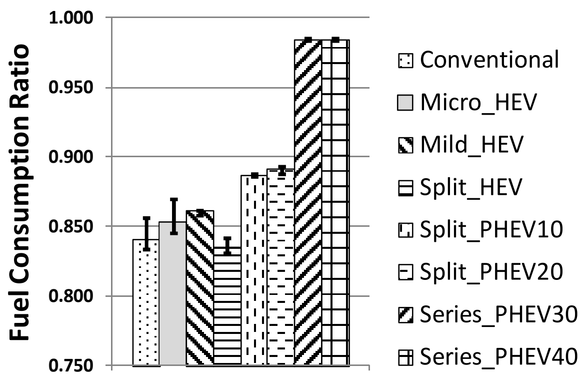

Figure 1. Fuel Consumption Ratios for HCCI vs. Regular Engine with Standard Control Strategy.

The fuel savings of HCCI technology seem to decrease as the vehicles hybridization degree increases. Indeed, while conventional vehicles with an HCCI engine consume 15% less fuel than with a regular engine, series PHEVs achieve only a 2% fuel consumption reduction. One of the reasons for this trend is that the more hybridization, the less the engine runs, and thus, there are fewer opportunities for the HCCI engine to operate at its high efficiency. Among the electric drivetrains, the power-split HEV seems to benefit the most from the HCCI technology, because of longer engine operation time (compared to the PHEV) and the possibility of operating it mainly in the HCCI region.

Table1 shows the percentage of the time the engine operates in HCCI mode for the different configurations. Because the HCCI technology operates only at low engine torque and at speeds lower than 3000 rpm, it is possible to operate outside this area if the drive cycle requires high engine torque (aggressiveness) or high engine speeds (high-speed highway). For PHEVs, this is particularly true, as low-AER vehicles spend 80% of their time in the HCCI mode and high-AER vehicles spend about 50% of their time in HCCI mode. This is due to the vehicle control strategy, which forces the engine to follow the best power-based efficiency curve, leading to possible non-HCCI operating conditions.

Table 1. Percentage of the Time Spent in HCCI Mode

	UDDS	HWFET
Conv, Micro, Mild	84–87%	81–84%
Split HEV	91%	96%
PHEV 10mi	81%	84%
PHEV 20mi	80%	84%
PHEV 30mi	52%	52%
PHEV 40mi	51%	51%

Specific vehicle level control strategies were then developed to maximize HCCI usage for all the vehicle powertrain configurations considered. Figure 2 shows the results of the optimized vehicle level control strategies.

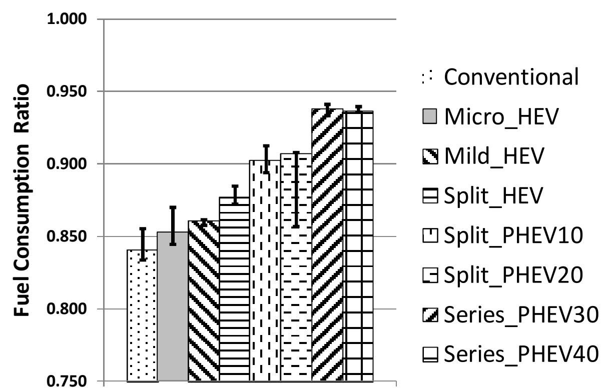

Figure 2. Fuel Consumption Ratios for HCCI vs. Regular Engine (Atkinson for hybrids) with Tuned Control Strategy

In Figure 2, it appears that HCCI technology offers lower fuel consumption reduction when compared to Atkinson-cycle engines in PHEVs and HEVs. The Series PHEVs are the vehicles showing the lowest gains, with about 6% improvement, whereas power-split PHEVs could reach 10% fuel consumption reduction, and HEVs, 12% fuel reduction. Overall, these final results reveal that the HCCI technology benefits conventional powertrains the most, and has a more limited impact as vehicles are increasingly hybridized.

Results for Real World Drive Cycles

Benefits of hybridization were then evaluated under real world drive cycles conditions. Figure 3 shows the fuel consumption values as functions of average real world drive cycles (RWDCs) vehicle speed for both the regular and the HCCI engines for a conventional powertrain.

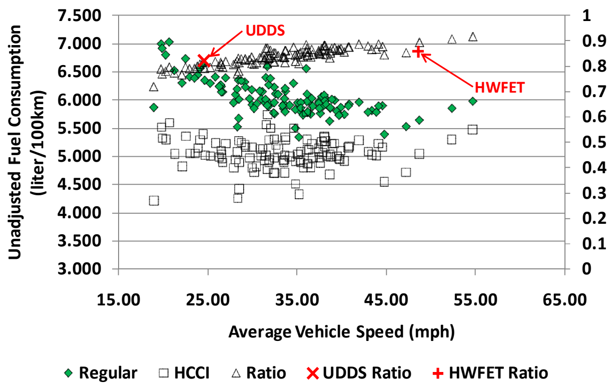

Figure 3: Fuel Consumption Impact of HCCI Technology on RWDCs for Conventional Vehicles.

The fuel consumption ratio displayed in Figure 3 varies roughly linearly with the average cycle vehicle speed. Indeed, at vehicle speeds around 25 mph, the HCCI engine fuel savings are around 20%, whereas gains of only 10% can be expected when driving at an average speed higher than 45 mph. As a comparison, the consumption reductions were around 16% for the UDDS and 14% for the HWFET. Thus, it appears that on RWDCs, HCCI offers greater fuel savings at low average vehicle speed and worse fuel savings at high average vehicle speed, than when using traditional cycles. At low average cycle speeds, the RWDCs tend to have more idling than on the UDDS, leading to more opportunities for the HCCI engine to operate more efficiently than the default engine, and thus, achieve greater fuel savings. On the other hand, at high average cycle speed, the RWDCs tend to be more aggressive than the HWFET cycle, resulting in more variation in the vehicle speed. Consequently, the engine torque requested for these cycles is usually higher than the HCCI area, hence, less fuel savings than with the HWFET cycle.

Conclusion

The results showed that conventional powertrains would benefit the most from HCCI, especially in mild urban drive cycles. For HEVs and PHEVs, more electric-only driving offers less opportunity for operating the engine in the HCCI area throughout the drive cycle. Consequently, the greater the hybridization, the lower the fuel consumption reduction in HCCI vehicles. Furthermore, when compared to Atkinson-cycle SI engines, the HCCI technology offers more limited fuel consumption reductions for HEVs and PHEVs. Maximizing the engine operating time in the HCCI region for HEVs and PHEVs could lead to potential drivability issues. More research would have to be conducted to determine if different control approaches are needed. Finally, when simulated on real world drive cycles, differences were found in the fuel-saving estimates compared to standard cycles, due mainly to more aggressive and higher vehicle-speed cycles. Nonetheless, the HCCI technology seems to promise moderate to significant fuel consumption reductions for all powertrains considered in this paper, ranging from 6% (for the most hybridized vehicles) to 15% (for conventional powertrains).

Impact of Vehicle Speed on Line Haul Fuel Consumption

Simulations were performed to evaluate the impact of vehicle speed under steady-state conditions for line haul applications. This information was used to assess the potential fuel savings under different driving conditions.

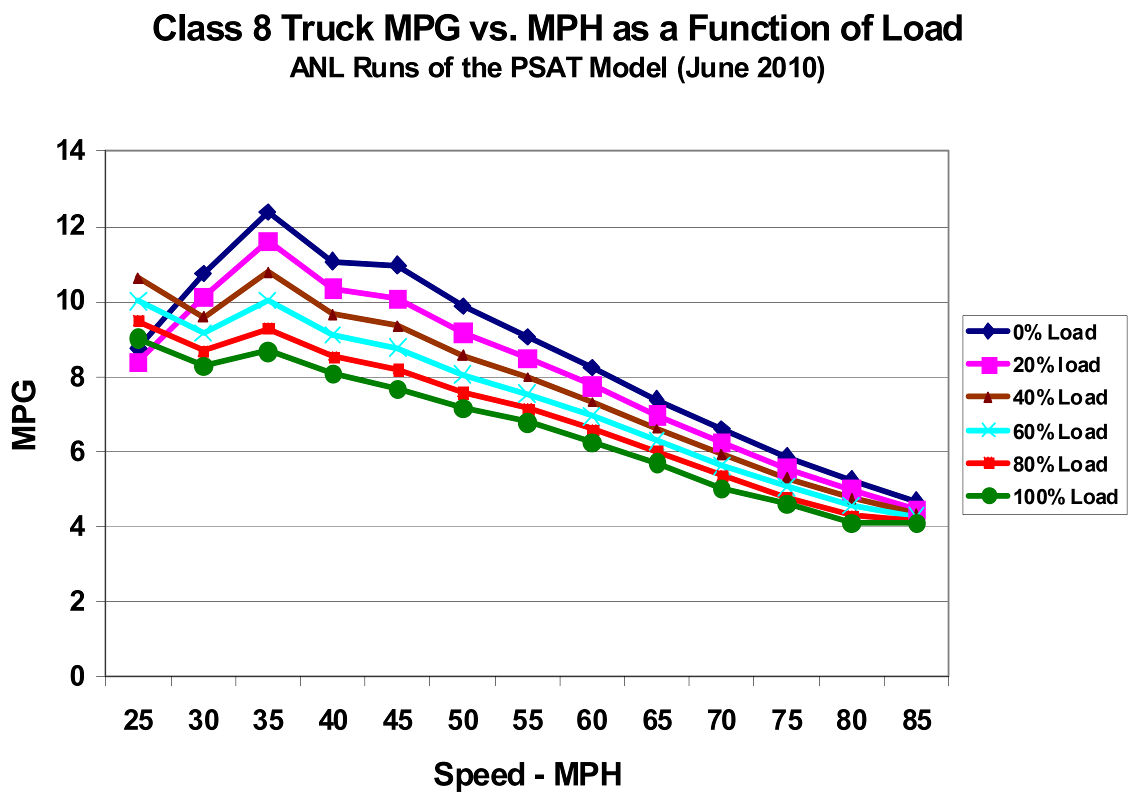

Figure 4: Impact of Vehicle Steady-state Speed on Line Haul Fuel Consumption

Impact of Engine Displacement on Fuel Rate

Using proprietary information, a relation between fuel rate and fuel displacement was developed to support engine target definitions.

Conclusion

Several studies were performed to support U.S. DOE Vehicle Technologies program, including evaluation of HCCI engine technology potential and impact of vehicle speed on line haul fuel consumption.

Publications/Presentations

1. A.Delorme & all. "Evaluation of Homogeneous Charge Compression Ignition (HCCI) Engine Fuel Savings for Various Electric Drive Powertrains", EVS 25, Shenzhen, Nov 10

E. Autonomie: A Plug&Play Software Architecture to Support Automated Model Based Design Process Efficiency

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Objectives

- Accelerate the development and introduction of advanced technologies through a Plug&Play architecture that will be adopted by the entire industry and research community

Approach

- Enable efficient, seamless math-based control system design process.
- Enable efficient reuse of models.
- Enable sharing of modeling expertise across the organization.
- Establish industry standard for architecture and model interfaces.

Accomplishments

- Release first public version of Autonomie
- Linked several experts tools to Autonomie, including GT-Power, AMESim and CarSim
- Developed, implemented and tested generic process from SIL to CIL
- Formed SAE committee to develop modeling standardization

Future Directions

- Expand the use of Autonomie within GM and other original equipment manufacturers (OEMs).
- Position Autonomie for future use in medium and heavy-duty vehicle regulations or policy options.

Introduction

Building hardware is expensive. Traditional design paradigms in the automotive industry often delay control system design until late in the process — in some cases requiring several costly hardware iterations. To reduce costs and improve time to market, it is imperative that greater emphasis be placed on modeling and simulation. This only becomes more true as time goes on because of increasing complexity of vehicles, a greater number of vehicle configurations, and larger numbers of people working on projects, which complicates design choices. To fully realize the benefits of math-based design, the models created must be as flexible and reusable as possible.

Greater reliance on modeling and simulation does come at some cost. New processes must be put in place to facilitate communication among the many model creators and consumers, and to handle the increase in files, which can be quite significant and overwhelming.

Several tools already exist to develop detailed plant models, including GT-Power, AMESim, CarSim, and SimScape. The objective of Autonomie is not to provide a language to develop detailed models; rather, Autonomie supports the assembly and use of models from design to simulation to analysis with complete plug-and-play capabilities. Autonomie provides a plug-and-play architecture to support this ideal use of modeling and simulation for math-based automotive control system design.

Plug&Play Architecture to Support Model Based Control

Definition

Model-Based Control is a math-based visual method for designing complex control systems, and is being used successfully in many motion-control, industrial, aerospace, and automotive applications. Model-Based Control integrates the development phases — modeling a plant (from first principles or system identification), synthesizing and analyzing a controller for the plant, simulating the plant and controller together, and programming/deploying the controller — providing efficiency and a common framework for communication throughout the process.

The phases of Model-Based Control are shown in Figure 1.

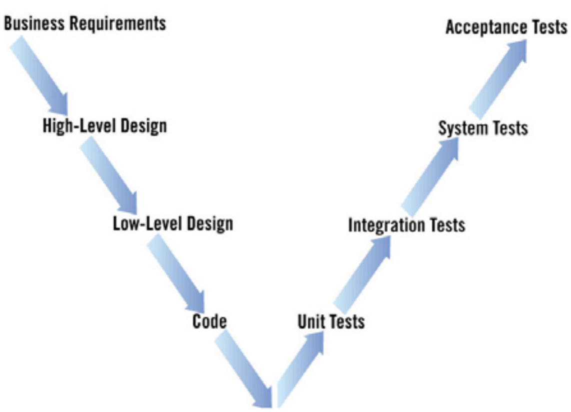

Figure 1: V Diagram for software development

Different steps in the development process are supported by a variety of approaches, from model-in-the-loop (MIL), to software-in-the-loop (SIL), hardware-in-the-loop (HIL), rapid-control prototyping (RCP), or component-in-the-loop (CIL). The software should allow users to integrate legacy code developed in different languages. In addition to reusability, flexibility is necessary for engineers to organize their models according to the Model-Based Control step considered. Autonomie was developed with these requirements in mind.

Software Architecture

Autonomie was designed for full plug-and-play support. Models in the standard format create building blocks, which are assembled at runtime into a simulation model of a vehicle, system or subsystem. All parts of the user interface are designed to be flexible to support architectures, systems, subsystems, and processes not yet envisioned. The software can be molded to individual uses, so it can grow as requirements and technical knowledge expands. This flexibility also allows for implementation of legacy models, including plant and controls.

Autonomie is based on standardized modeling architecture, on-demand model building, associated extendible markup language (XML) definition files, and user interfaces for managing models, including a file-versioning database (Figure 2).

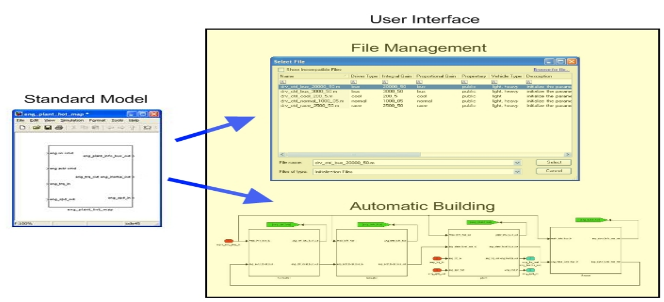

Figure 2: Simulation management concepts

All systems in the vehicle architecture can be logically categorized as either a containing system or a terminating system (Figure 3). Containing systems consist of one or more subsystems, as well as optional files to define that system. They do not contain models; they only describe the structure of interconnections of systems and subsystems. Terminating systems consist of a model that defines the behavior of the system and any files needed to provide inputs or calculate outputs. Terminating system models contain the equations that describe the mathematical functions of a system or subsystem.

Both types of systems are arranged in a hierarchical fashion to define the vehicle to be simulated. To avoid confusion, it is a best practice to mimic the structure of the hardware as much as possible. For example, low-level component controllers should be grouped with the components that they control, at different levels of the hierarchy where applicable. Only systems that actually appear in the vehicle should be represented; in other words, there is no need for unused components or empty controllers. In addition to simplifying the architecture, this philosophy will allow for easy transfer of systems among users and will fully support HIL, SIL, and RCP.

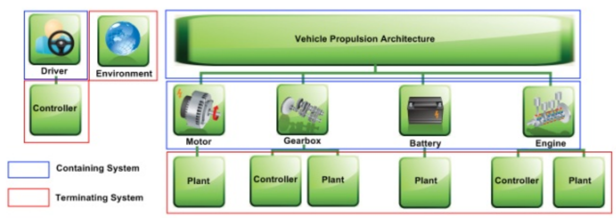

Figure 3: Class diagram of container and terminating systems

At the top level is a vehicle system containing the following systems: environment; driver; vehicle propulsion controller for advanced powertrain vehicles such as hybrids or plug-in hybrids, which require a vehicle level controller; and a vehicle propulsion architecture (VPA) (Figure 4). The VPA system will contain whichever powertrain components are required to simulate the vehicle, such as engine, battery, and wheels.

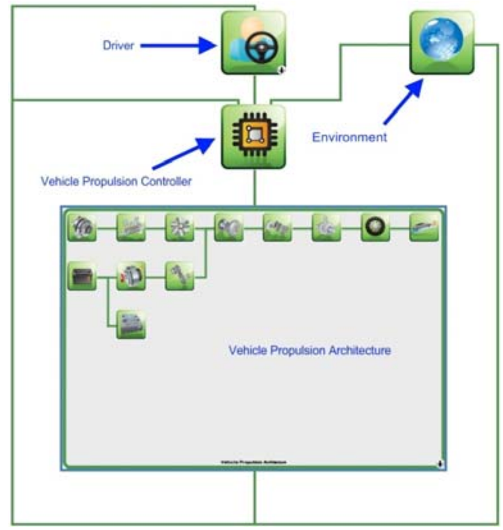

Figure 4: Top-level vehicle layout

Model Building

The model files created for the terminating systems need to be combined in a way that allows simulation in Simulink. One option is to create every possible combination of the systems and save each complete vehicle as a separate model file. This option quickly becomes infeasible when one considers the staggering number of combinations. Not only are we dealing with many different components, but we also must also consider different levels of fidelity and model versions for each component. Changing the version of a single component model would result in a new version of the entire vehicle. This method is clearly storage intensive and impractical.

A second option is to save every model in its own file and manage a library of the models. This would be an improvement over the first option; however, it still presents some difficulties. When a user wishes to create a new vehicle, he or she has to select all of the appropriate models from the library and connect them by hand into a vehicle context. Not only is this manual process time consuming, but it introduces many opportunities for error. Consider an engine control unit model for auto code generation that can have more than 2,000 inputs and outputs (I/O). Manually connecting all I/O guarantees errors. It also requires some outside solution for model library management (such as searching, versioning, and ensuring compatibility).

Autonomie uses a novel approach that combines the second option with an automated building process. This gives the user the flexibility of saving and versioning models independently without potential pitfalls of manual connections. Users select the correct files in a user interface, and the automatic building uses metadata associated with the models to create the correct connections, as shown in Figure 5.

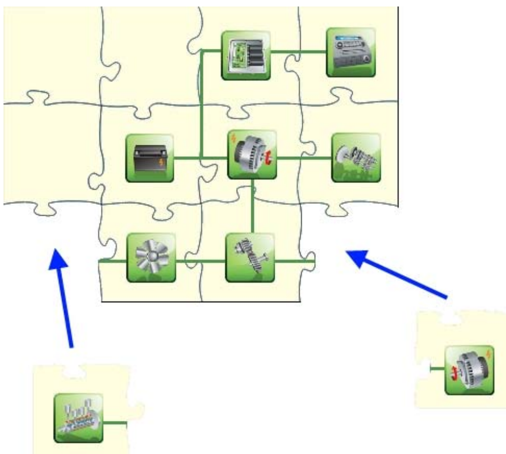

Figure 5: Models are automatically built

System Architecture Definition for Model Based Design

Autonomie allows users to select vehicle powertrain architecture configurations to automatically build the model to support specific applications. Similarly, the tool also provides the ability to select the number of systems for each component. Figure 6 shows the most generic configuration for systems. It includes specific models for controller, actuator, plant, and sensor (CAPS).

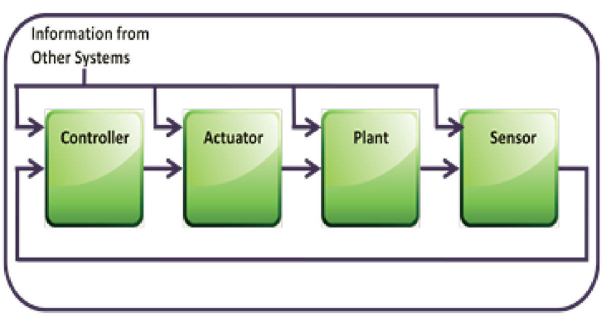

Figure 6: Generic component system configuration

To control hardware or receive feedback, specific logic needs to be introduced. This provides a convenient point at which the user can implement a testing plan or enforce checks to ensure safe operation of the hardware. Figure 7 shows the generic configuration setup used for hardware/software interactions. Note that two blocks are added to the generic component system, which is described in Figure 7.

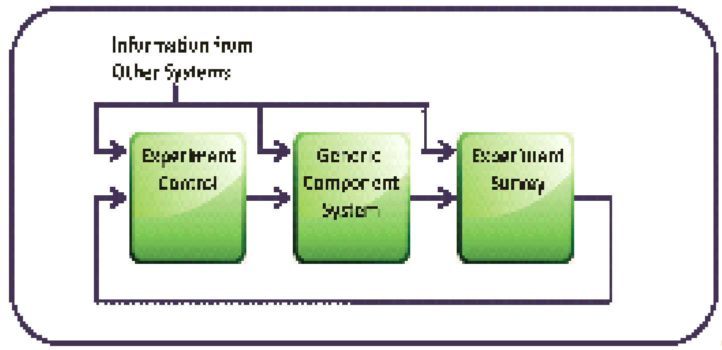

Figure 7: Hardware/Software interaction configuration

The experiment control block is concerned with the system constraints and experiment commands, as shown in Figure 8. The commands are saturated in the constraints block, and sensor signals from the hardware are available here as feedback information. If an emergency action is required on the basis of the experiment survey, the commands from the system will be overwritten to ensure safe operation. Similarly, the commands can also be changed manually in the overwrite command block, mostly for debugging purposes.

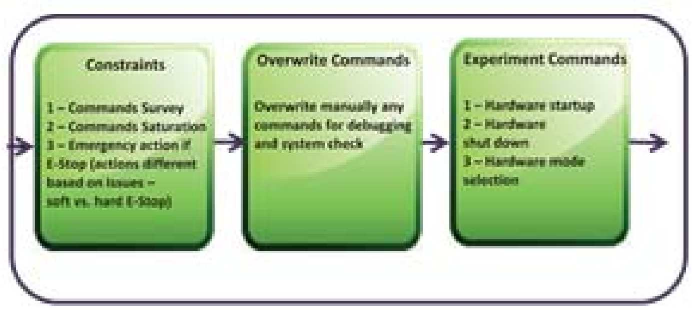

Figure 8: Experiment control block

The objective of the experiment survey block, shown in Figure 9, is to verify that each signal is within its expected operating range. This could even be extended to implement diagnostic features. If any abnormal condition is observed, a warning will be sent to the experiment control block so that action can be taken, such as limiting the operating range or even triggering an emergency shutdown.

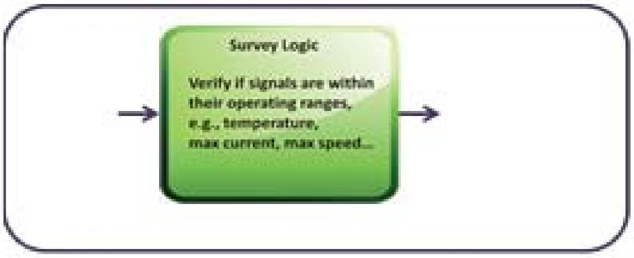

Figure 9: Experiment survey block

Different systems of the generic CAPS configuration can be adapted to support the different phases of Model-Based Design. For example, the controller algorithm will be replaced by communications with the hardware control for HIL, while the plant model would be replaced by hardware communications for RCP. For CIL, because both the controller and the plants are hardware, the entire component system is simply replaced by the hardware I/O.

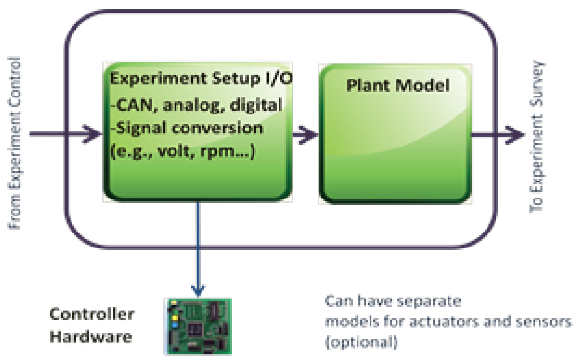

Figure 10: CIL generic system configuration

Conclusion

To reduce costs, the automotive industry must embrace math-based control system design for modeling, simulation, testing, and analysis. This paper proposes an ideal modeling process, wherein experts produce libraries of high-quality models in varying levels of fidelity for use throughout an organization and across the automotive industry. These models connect seamlessly for maximum reusability and flexibility, making collaboration quick and easy. The models developed by these experts can be used from the beginning to the end of the design process, from high-level configuration sorting studies, to code testing with production software (such as SIL, HIL, or RCP), and, finally, to solving production problems.

Each system (e.g., plant or control) can be either represented by a set of equations or by its hardware. To quickly evaluate new technologies in different environments, a generic process was presented to replace any part of the system through the user interface. This generic process allows companies to increase their productivity and take technologies to the market faster.

This process was implemented for Software-in-the-Loop (SIL) with General Motors as well as Component-in-the-loop (CIL) at Argonne with both engine and battery pack.

Publications/Presentations

1. Rousseau, A., Halbac, S., Shidore, N., Sharer, P., Vijayagopal R., Software Architecture to Support Automated Model Based Design, SAE 2010-01-1996, SAE World Congress, Detroit, April 2010

2. Michaels, L., Pagerit, S., Sharer, P., Vijayagopal, R., Halbach, S., Rousseau, A., Model-Based Systems Engineering and Control System Development via Virtual Hardware-in-the-Loop Simulation, SAE 2010-01-2325, Convergence 2010, Detroit, November 2010

F. PSAT to Autonomie Conversion

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Objectives

- Develop a process to integrate legacy models and controls from PSAT.
- Compare results for several vehicle configurations between PSAT and Autonomie.

Approach

- Develop process to migrate models and files from PSAT to Autonomie
- Integrate all PSAT code into Autonomie
- Define default vehicles in PSAT and corresponding ones in Autonomie
- Validate vehicles on a second-by-second basis

Accomplishments

- Developed Graphical User Interface and algorithms to integrate PSAT legacy models and Matlab files.
- Validated numerous vehicles for different configurations

Future Directions

- Provide guidance to migrate entire vehicles from PSAT to Autonomie.

Introduction

To facilitate the adoption of Autonomie by the current PSAT users, it is critical to facilitate the migration of the legacy code developed over the past decade into the new tool. To do so, a specific Graphical User Interface was developed for both model and files integration.

The second part of the project is focused on verifying the instantaneous behavior of different vehicles to provide confidence in the results of Autonomie. This is especially important since the vehicle model organization is radically different between PSAT and Autonomie.

Integration of Legacy Code into Autonomie

A Graphical User Interface (GUI) was developed to automate the integration of legacy code as much as possible. The specific GUI is launched from the Menu as shown in Figure 1.

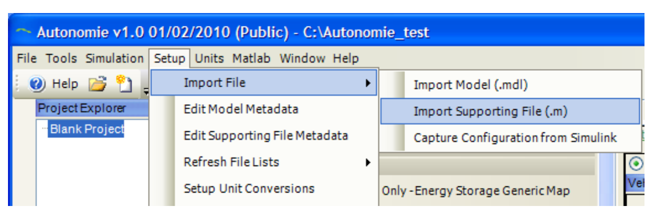

Figure 1: Launching Import File GUI

Model Integration

One of the main differences between PSAT and Autonomie resides in the radical change in the vehicle model organization both from the plant and the control point of view. For example, while the vehicle level control in PSAT included the component constraints and transients in addition to the vehicle level energy management, the entire logic related to a specific system is now located within the same Simulink block.

In addition, Autonomie now stores each system separately and uses an XML file to provide information on the model. An example of changes to be made is shown in Figure 2.

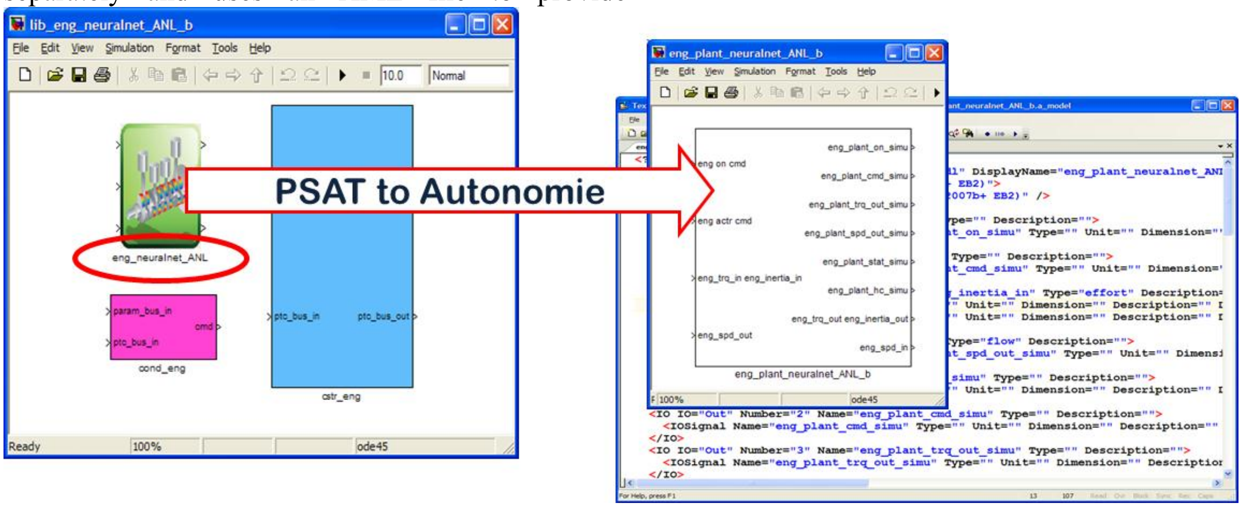

Figure 2: Model Organization Difference

The new model organization dictated a new naming nomenclature as well. One of the steps of the model integration is to rename the parameters as shown in Figure 3. A data library has been created to automatically fill the new names in the columns. Users can also add their own names to the database.

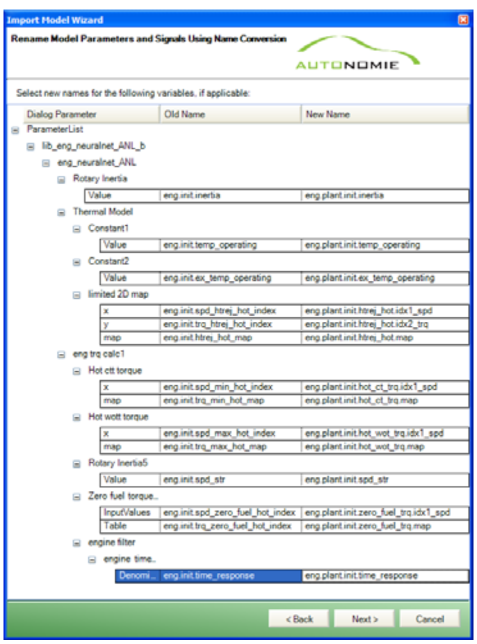

Figure 3: Naming Nomenclature Change

While the parameter names of the Simulink model are automatically changes and most of the XML file is created based on the database, users still have the ability to modify and/or add information related to the model, including description, proprietary status, etc.) as shown in Figure 4.

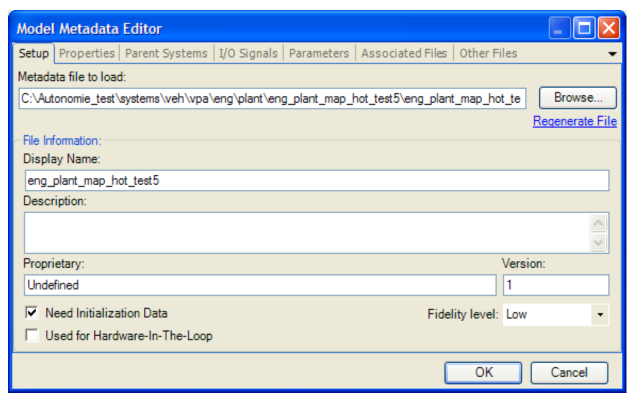

Figure 4: Editing the XML File

Matlab Files Integration

The process to integrate Matlab files is similar than for the models and controls in a sense that the new names for the parameters are modified through the GUI using the same data library.

One of the main differences is the need to associate each file with its parent system as shown in Figure 5. This information is used to only provide users the list of files (i.e., initialization, scaling, pre and post-processing) associated with the model previously selected.

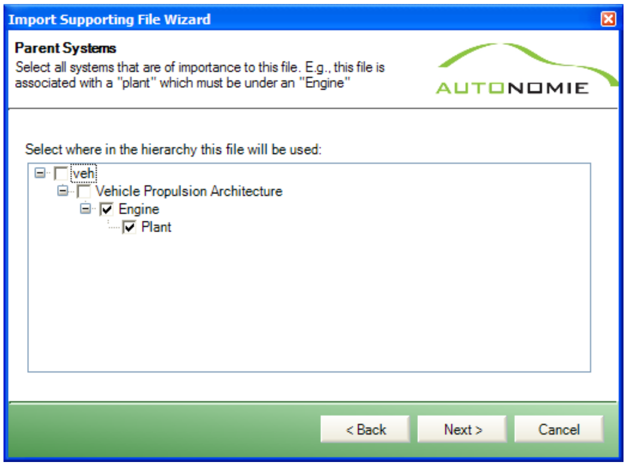

Figure 5. File association with model

One additional improvement over PSAT is the ability for Autonomie to refresh the list of models and files without restarting the tool.

Comparison between PSAT and Autonomie

Several vehicles were developed both in PSAT and Autonomie to perform a thorough comparison. These vehicles represented different powertrain configurations (i.e., conventional, HEVs, PHEVs, EVs), technologies (i.e., engine, fuel cell…) and vehicle applications (i.e., light duty, heavy duty).

Each vehicle was simulated on several drive cycles and the instantaneous and overall results were compared. Table 1 shows an example of comparison. In general all the fuel consumption results show very close correlation. The remaining difference results from the new model organization, which leads to equations being solved in a different order by the solver.

Table 1. Example of Comparison Between PSAT and Autonomie for Light Duty Application

Unit (mile/gallon)	PSAT		Autonomie	
Vehicle	UDDS	HWFET	UDDS	HWFET
Conventional Automatic (Civic)	37.11	49.47	36.69	50.11
Power Split HEV – Prius MY04	74.93	65.73	74.93	65.69
Fuel Cell only – no transmission	36.22	52.59	36.17	52.57
Series Fuel Cell HEV – no transmission	75.35	74.3	75.31	74.28

Conclusions

A process was developed to facilitate the integration of legacy code from PSAT to Autonomie both for models and data files. In addition, numerous vehicles were successfully compared in both tools to ensure consistency of the results.

Publications/Presentations

1. Rousseau, A., Presentation, "ANL - Autonomie Help Part 8A - Customization - How to Import PSAT files", October 2010

G. Trade-off between Power Split Powertrain Complexity and Fuel Efficiency

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Objectives

- Understand the impact of added powertrain complexity for power split hybrids on component sizing and fuel consumption

Approach

- Review and select power split configurations (on mode to four modes) from available patents
- Develop detailed transmission models to properly represent losses
- Develop generic vehicle-level control strategy philosophy that can be applied to all powertrains to ensure consistency
- Size the vehicles and run fuel consumption simulations

Accomplishments

- Developed detailed transmission models for each of the multi-mode selected
- Developed generic control strategies allowing fair comparison of powertrain options
- Compared component sizes and fuel consumption for a small SUV platform

Future Directions

- Evaluate the impact of vehicle classes other than small SUVs.
- Evaluate additional multi-mode powertrain options

Introduction

Various hybrid electric vehicle (HEV) architectures have been proposed, though one of the earliest and most commercially successful systems has been the power split, as used on all three generations of the Toyota Prius, other Toyota/Lexus models, as well as on the Ford Escape. The power-split configurations have both all-mechanical and electro-mechanical paths combining the planetary gear set and two electric machines, as shown in Figure 1. In one path (all-mechanical path), the power from the internal combustion engine (ICE) is directly transmitted to the wheels. In the other path (electro-mechanical path), the power from the engine is converted into the electricity by a generator to drive the electric motor or to charge the battery. A major advantage of this configuration stands in the possibility to de-couple the ICE and wheels speeds.

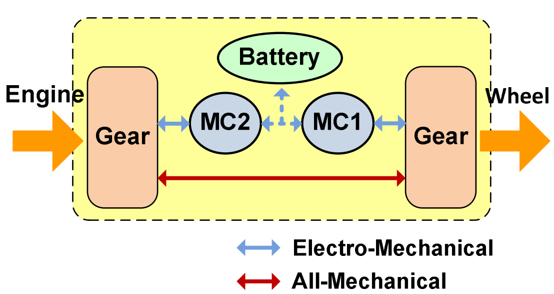


Figure 1.: Power-split transmission

However, the power-split system is characterized by internal power circulation. In the power-spilt configuration, the internal power circulation occurs along the closed loop depending on the speed ratio, and sometimes the circulated power increases enormously. Therefore, electric machines are significantly oversized in order to meet requirements. This power circulation can lead to high losses and thereby to a low efficiency of the power transmission. Such drawbacks can be addressed by combining several EVT (electro-mechanical infinitely variable transmission) modes in to one multi-mode hybrid system, thereby increasing the number of mechanical points and allowing greater operation flexibility.

The EVT efficiency of the electro-mechanical power path is proportional to the powertrain (PT) configuration complexity in the multi-mode hybrid system, since electric power can stay low with wide ratio coverage and efficiency can remain high over a wider range. However, the multi-mode hybrid system should have more planetary gears (PGs) and clutches/brakes (CLs/BKs). Therefore, EVT mechanical loss is also proportional to powertrain configuration complexity in the multi-mode hybrid system. In this study, we evaluate the benefits of several multi-mode powertrain configurations with regard to fuel consumption.

Description of the Multi-mode Hybrid System

One-mode EVT

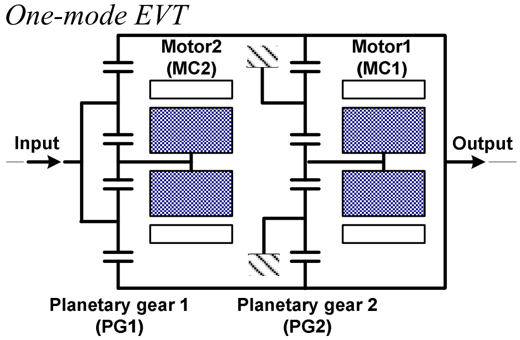


Figure 2. Schematic of the one-mode EVT

Figure 2 is a schematic diagram of the single-mode power split transmission (TM) with a reduction gear (RG). Since the input power from the ICE is split at the planetary gear which is located at the input side, and the power transmission characteristic is represented by a single relationship for the whole speed range, this power-split configuration is called the "input-split type" or "single- mode EVT." This input-split configuration consists of two planetary gears, and two electric machines (MC1 and MC2).

In Figure 3, the electro-mechanical power ratio and the EVT system efficiency (η) are plotted with respect to the speed ratio (SR). In this analysis, it is assumed that there is no power loss through the all-mechanical path and only electric machine loss is considered by using the efficiency maps of electric machines. The power ratio is defined as the ratio of the electro-mechanical power to the ICE input power and the SR is defined as the ratio of the ICE input speed to output speed. In high SR range, the system efficiency is low because the electrical machines have relatively low efficiency. The analysis results demonstrate why the Toyota hybrid system (THS), a typical example of the input-split HEV, adopts large capacity electric machines.

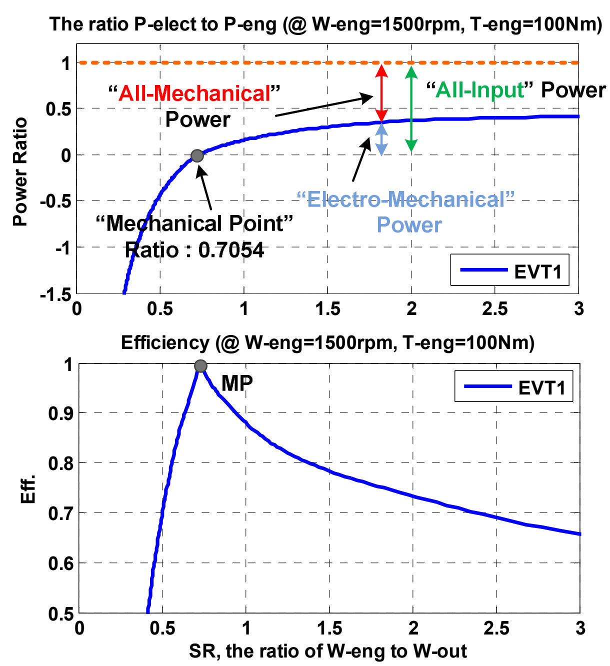


Figure 3. Power characteristics of the one-mode EVT

Two-mode EVT with Fixed Gear Ratios

Figure 4 is a schematic of the two-mode hybrid, which is called the General Motors Advanced Hybrid System2 (AHS2) for front-wheel drive (FWD). This system has an additional stationary clutch and an additional rotating clutch. Through engaging or disengaging the four clutches, it realizes six different operation modes including two EVT modes and four fixed gear (FG) modes. When operated in any of the four fixed gear modes, the vehicle is comparable to a parallel pre-transmission HEV.

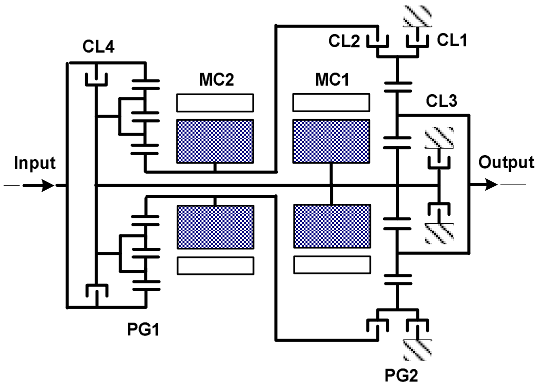


Figure 4. Schematic of the two-mode EVT with FGs

In Figure 5, the two-mode EVT already has a native fixed gear ratio, the synchronous shift ratio, where the action of two clutches at the same time provides a fixed ratio.

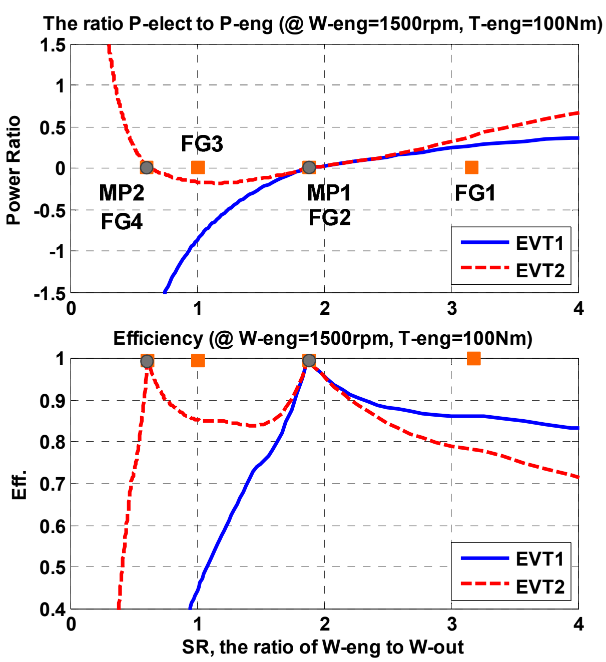


Figure 5. Power characteristics of the two-mode EVT with FGs

Three-mode EVT with Fixed Gear Ratios

Figure 6 shows a schematic diagram of the three-mode EVT, which has a double-pinion planetary gear. The three-mode EVT can operate in six different modes: three EVT modes and three FG modes. When two clutches are engaged and the other two clutches are disengaged, the powertrain has 2 degrees of freedom and operates in EVT1, EVT2, or EVT3 mode, respectively.

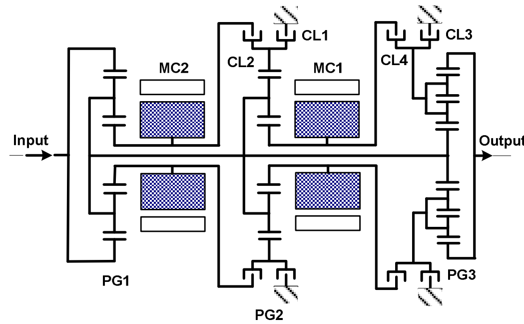


Figure 6. Schematic of the three-mode EVT with FGs

Because there are more than two power-split modes, there are several mechanical points, thus reducing the need of large electric machines, as shown in Figure 7.

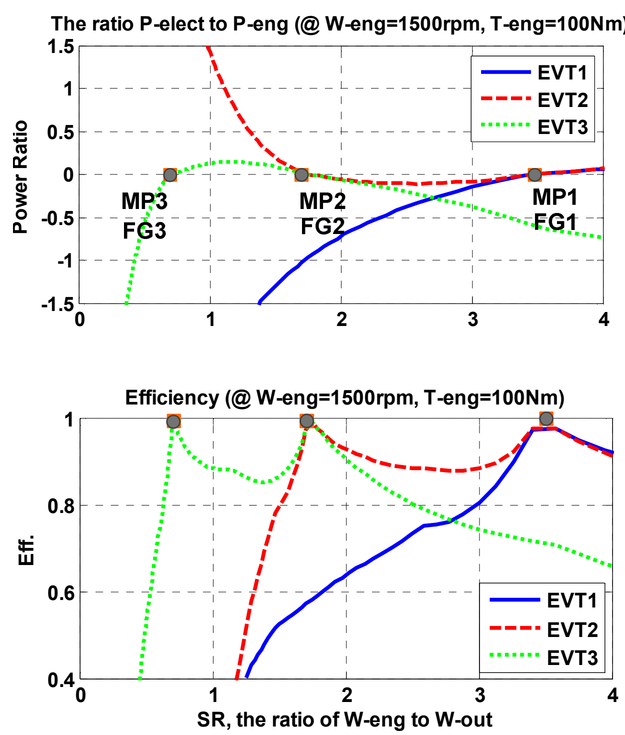


Figure 7. Power characteristics of the three-mode EVT with FGs

Component Sizing

Detailed transmission models were developed by using SimDriveline, including specific losses for gear spin and hydraulic oil, as shown in Figure 8. Such a level of detail is necessary to properly assess the trade-off between complexity and efficiency.

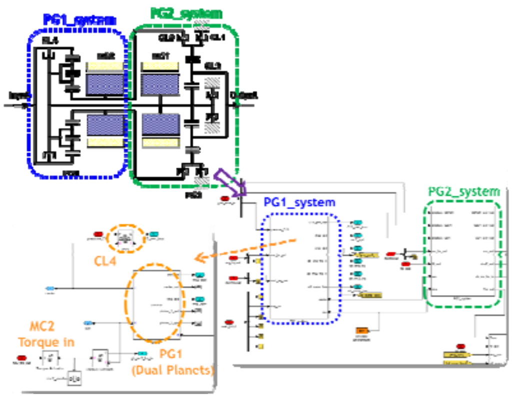


Figure 8. Transmission model for the AHS2 FWD

Sizing Process

To quickly size the component models of the powertrain, an automated sizing process was created.

The sizing results are summarized in Figure9. For comparison, two single-mode EVT hybrid systems and four multi-mode EVT hybrid systems are investigated, and the results are presented. As noted in the introduction, the multi-mode system results in significant improvements in dynamic performance at reduced capacities of the electro-mechanical power. As can be seen in Figure 9, the amount of capacities that saved by the multi-mode system ranges from 31.7% to 64.3%, relative to the single-mode. The main contributor is the addition of the EVT mode, which causes the difference between the single-mode and multi-mode systems. However, there is little difference between the three-mode and four-mode systems.

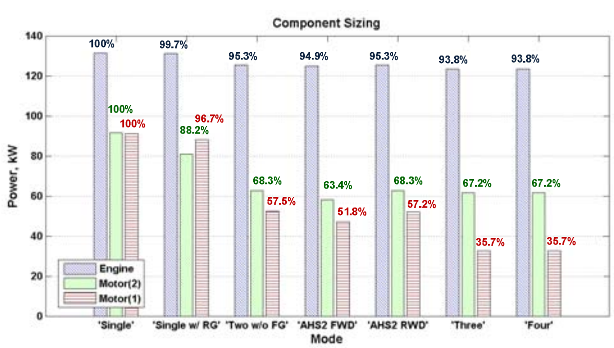
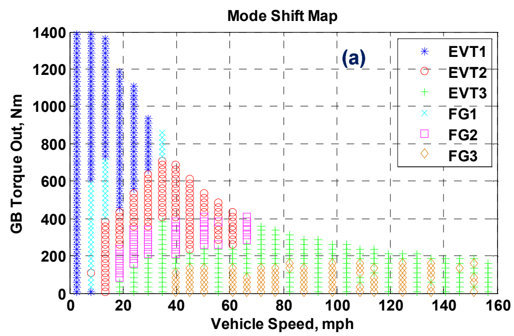


Figure 9. Component sizing results

Control Strategy

In order to evaluate the benefits of several multi-mode powertrain configurations from the standpoint of fuel consumption, an HEV control strategy is required first. One of the major challenges of the multi-mode control strategy is to properly select the operating mode. In order to develop mode shift strategy, a brute-force algorithm is used. The algorithm generates an optimal input speed and torque for each EVT mode, indexed by gearbox output speed, battery power, and gearbox output torque. The knowledge of these parameters allows us to compute the fuel power and to compare it with that in the other EVT modes. Meanwhile, obtaining a candidate input set for FGs is same as conventional way. Figure 10a depicts the optimal mode selections for various output load conditions. If we convert these results into new map by using vehicle speed and engine speed indexes, the mode selection rule is defined based on the speed ratio. The reason for this is because the selected optimal mode could be divided according to the speed ratio, which is defined as the ratio of the target engine speed to the output speed. In Figure 10b, the FG1 mode appears in the transition area between the EVT1 and EVT2 modes and the FG2 mode appears in the area between the EVT2 and EVT3 modes. The FG1 and FG2 mode are inherent modes needed for the synchronous shift between the two EVT modes. The FG3 mode supplements the EVT3 mode. The logic was validated for both single-mode and two-mode hybrid systems by using vehicle test data. Similar algorithms were implemented for the three-mode and four-mode configurations.



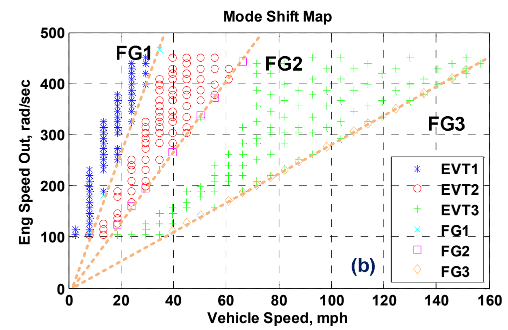


Figure 10: Mode shift Maps for three-mode EVT

Simulation Results

With the transmission models and controller described in the previous section, the vehicle was simulated on standard drive cycles: the urban dynamometer driving schedule (UDDS); the highway fuel economy test (HWFET) cycle; the new European driving cycle (NEDC); a more aggressive urban cycle with some short highway cycles (LA92); and a highly aggressive cycle, predominantly at high speed (US06). The fuel economy results are reported in Figure 11. For urban driving, the single-mode hybrid system has relatively high fuel economy compared with that of the multi-mode hybrid system. On the other hand, the trend shown by the different cycles indicates that the higher the speed of the driving pattern, the greater the advantage of the multi-mode hybrid system.

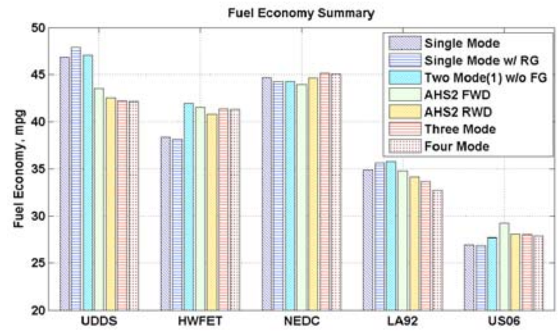


Figure 11: Fuel economy summary

Figure 12 also shows that the more aggressive/faster the driving pattern, the greater the advantage of the multi-mode with a high fixed gear ratio, FG1. However, the three-mode and four-mode systems do not result in more benefits for the aggressive drive cycle. As a consequence, the AHS2 FWD provides a greater fuel consumption advantage for the vehicle application considered on the small-size SUV specification.

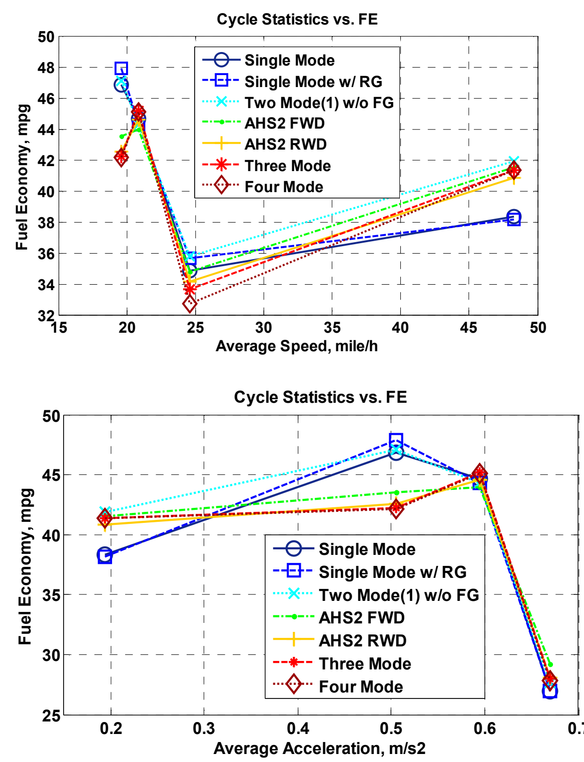


Figure 12: Fuel economy for drive cycle statistics

Conclusion

This study examines the different power-split configurations and vehicle-level controls developed in Autonomie. Detailed transmission models were implemented to allow a fair assessment of the trade-offs between complexity and fuel efficiency. The powertrains were compared theoretically from EVT system efficiency. It was found that the multi-mode EVT minimizes the power ratio, which means that we can directly transfer as much mechanical power as possible. Each powertrain was sized to represent a small-size SUV application, following the same vehicle technical specifications, such as acceleration and gradeability.

The results predicted that the multi-mode system would have better acceleration performance than a single-mode system, since the additional EVT modes significantly lower the requirement for the electric machine power. In addition, simulations were performed on a small-size SUV to characterize the impact on component operating conditions and fuel consumption for several driving cycles. It was determined that the multi-mode system has more fuel economy advantage during the high-speed cycle due to the relatively higher system efficiency. When the cycle is more aggressive, the multi-mode system with FGs has the advantage due to the relatively higher tractive capability.

To ensure a fair comparison, further work should strive to integrate additional vehicle classes (e.g., compact, midsize car, midsize SUV, etc.) and also consider additional vehicle technical specifications (e.g. passing, towing, etc.). Several drive cycles, including real-world drive cycles, should also be evaluated.

Publications/Presentations

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H. Maximizing Series PHEV Net Present Value by Simultaneously Optimizing Battery Size and Vehicle Control on Real World Driving Behaviors

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Objectives

- Size both battery power and energy to maximize the Net Present Value (NPV) of a series PHEV with optimized vehicle control on real world drive cycles

Approach

- Integrate the algorithm to optimize vehicle energy control strategy for every battery power/energy point
- Modify the algorithm to use distributed computing to minimize simulation time
- Select a representative number of Real World Drive Cycles
- Run the simulation for different battery cost assumptions

Accomplishments

- Integrated Net Present Value Calculations into the optimization algorithm
- Minimized simulation time using distributed computing
- Define optimum battery power and energy for short-term and long-term battery costs

Future Directions

- Apply the algorithm to additional powertrain configurations (i.e., power split, E-REV…)
- Analyze the impact of additional battery costs
- Integrate other component to the algorithm

Introduction

Plug-in hybrid electric vehicles (PHEVs) have demonstrated great potential with regard to petroleum displacement. Since the benefits of PHEV technology rely heavily on the battery, the development of new generations of advanced batteries with a long life and low cost is critical. The objective of the study is to determine the most effective battery power and energy, based on different cost assumptions, to optimize the net present value (NPV). To achieve that goal, Autonomie, Argonne's vehicle simulation tool, is used along with an optimization algorithm developed by The MathWorks. The PHEV used for this analysis is a midsize passenger car.

Components and their sizes differed when comparing a conventional vehicle and series PHEV. While the battery size changed, the other hybrid powertrain components were left unaltered. This allowed the focus to be placed entirely on the effect of battery size and its economic impact on the vehicle cost.

The cost of the battery along with the gasoline savings (compared with a conventional vehicle) was considered as investments. Since the investment and operating cost was specific to vehicle use during its lifetime, many assumptions were based on the Vehicle Survivability and Travel Mileage Schedules published by the National Highway Traffic Safety Administration (NHTSA).

Assumptions

Vehicle Usage Assumptions

The series PHEV was compared with a conventional midsize vehicle assumed to have an overall fuel economy of 7.9 liter/100 km (30 mpg), which is typical of a midsize sedan. The gasoline price was assumed to be \$0.86/liter (\$3.24/gallon). While we understand that fuel prices will vary in the future, such variations were not considered in this study. The studies conducted by NHTSA support the assumption that an average passenger car will travel over 240,000 km during its lifetime.

Figure 1 shows an assumption made about the decrease in vehicle daily distance over the life of the vehicle. The vehicle daily distance degradation was estimated based on average driving distances observed in NHTSA surveys and real-world driving data recorded from a group of Kansas City drivers. The NHTSA survey and real-world daily distance data were based on conventional vehicles, thus making the distance-degradation assumption in Figure 1 subject to further review as new survey and field data are obtained from vehicles with new technologies.

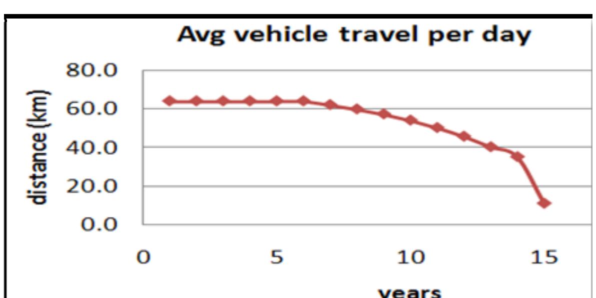

Figure 1. Vehicle daily distance

The fuel consumption of any vehicle depends on how it is driven. The studies conducted in Kansas City gave an accurate picture of real-world driving characteristics in a North American city. A representative sample from the real-world drives was used in this study to estimate the fuel consumption values for the series PHEV with varying battery sizes.

The energy & power requirements for the daily drives used in this study are shown in Figures 2 and 3. It should be noted that more than 95% of the daily drives can be completed with 11 kWh of stored electric energy. Similarly, about 50 kW of peak power are needed for about 95% of the daily drives, even though the average power requirement for the daily drives is less than 8 kW.

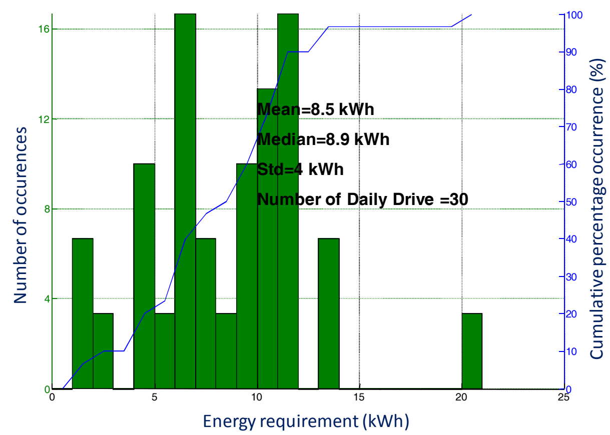

Figure 2. Energy requirement for daily drives

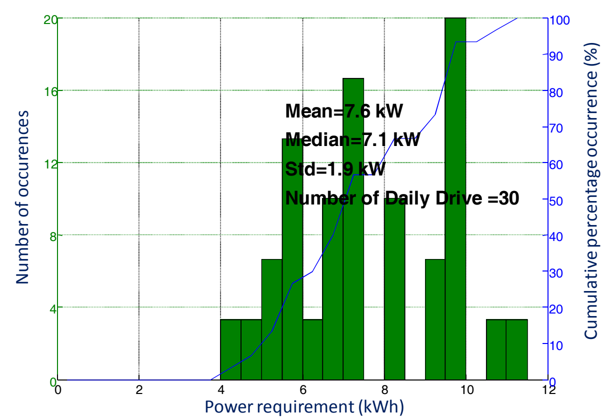

Figure 3. Average power requirement for daily drives

Battery Cost Assumptions

In simple terms, a larger battery on a PHEV requires a larger initial investment. However, it also results in lower gasoline consumption and, therefore, more savings in the future. Conversely, a smaller battery involves a lower initial cost and lower savings related to reduced gasoline consumption in the future. Hence, the quest for an optimum battery size involves minimizing gasoline consumption by varying the battery size. For this study, two battery cost scenarios were considered.

1. Short-term cost estimate: Equation 1 represents the current battery cost and is significantly higher than the long-term cost estimate.

Battery cost, \$/kWh = 32 x battery power to energy ratio + 600 Eq. (1)

2. Long-term cost estimate: Equation 2 has been developed to represent the battery cost based on the research performed by the U.S. Department of Energy (DOE).

Battery cost, \$/kWh = 20 x battery power to energy ratio + 125 Eq. (2)

If future targets are met, a battery that currently costs about \$12,000 (in the short-term estimate) will cost only about \$3,000 in the future (long-term estimate). With such a difference in battery cost, the optimization exercise will show significantly different choices in the short-term and long-term results.

Battery Capacity Assumptions

The battery capacity reduces during its life. It was assumed that the battery has a surplus capacity at the beginning of its life to ensure the rated capacity until its 'end of life' (e.g., a 10-kWh battery would be able to provide 10-kWh of storage until its 'end of life'). Beyond this 'end of life,' the degradation in battery capacity would be noticeable and characterized by a linear reduction in battery capacity, as shown in Figure 4.

It should be noted that at the end of the assumed vehicle life of 15 years (4,500 cycles), the battery is still capable of storing energy. The battery degradation was assumed to affect the vehicle fuel consumption. However, since the vehicle use was assumed to decrease with the vehicle age, the effect of the battery degradation with age was not taken into account. Under these circumstances, battery replacement at a future date was assumed to promise little return on investment.

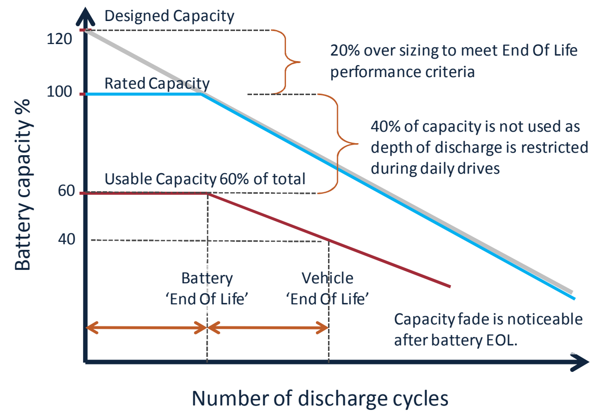

Figure 4. Battery capacity variation with battery use

Optimization

Battery Size Optimization

Battery size is determined by the energy stored in the pack and the rate at which that energy can be used. The energy and power variables for a battery pack provided a two-dimensional design space where the battery specification had to be limited. The battery size lower limits were set at 2-kWh of energy and 8-kW of discharge power capability. The lower limits approximated current HEV battery sizes and were slightly lower than the minimum size needed to earn PHEV tax credits. The upper limits were fixed at 20 kWh and 80 kW on the basis of initial simulation studies and NPV estimates.

The battery model used in Autonomie can be scaled to any desired battery energy capacity or power discharge rating. This scaling maintains the voltage at 200 V, while adjusting the capacity (Ah) value of the cells and the internal resistance to meet the desired energy and power ratings.

Vehicle Control Parameters Optimization

For this study, we assumed a controller that turns the engine ON based on the criteria mentioned below:

If the battery power alone is insufficient to drive the vehicle;

If the battery state of charge (SOC) falls below the desired charge-sustaining SOC target value; and

If the power demand at the wheel is above the engine ON threshold value, and it stays above the engine OFF threshold value.

By optimizing the engine ON/OFF thresholds, the objective was to obtain the optimum rule-based control strategy.

Net Present Value (NPV) Calculation

The NPV calculation used in this study has been used for previous applications and is illustrated in Figure 5.

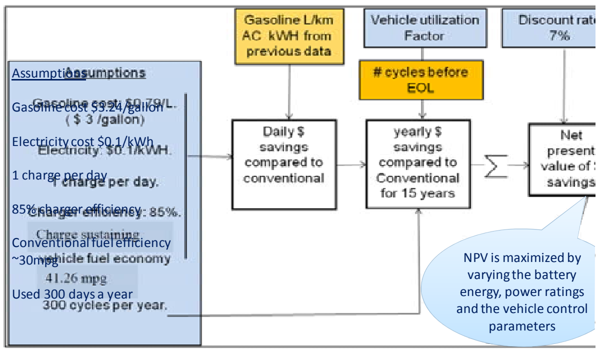

Figure 5. NPV calculation for gasoline savings over vehicle life

The fuel and electrical energy consumptions of the PHEV over the real-world drive cycles were obtained from the simulation. The PHEV gasoline savings, in comparison with a conventional vehicle, were calculated for each battery size and energy management strategy over a fixed set of real-world drive cycles. This lead to an optimum battery size and energy management strategy that considered gasoline saved per day and battery utilization over the vehicle life.

The battery cost amortization was spread evenly over the entire life of the vehicle. Therefore, the yearly savings obtained from the vehicle factored in the savings from gasoline displacement and the fraction of the battery cost. The yearly savings were repeated for the 15 years of vehicle life, which resulted in a series of numbers that represented the yearly expenses/savings from owning and using a PHEV. The NPV of each set of expenses/savings provided a dollar amount for the present worth of those expenses/savings. The optimization problem statement is shown in Figure 6.

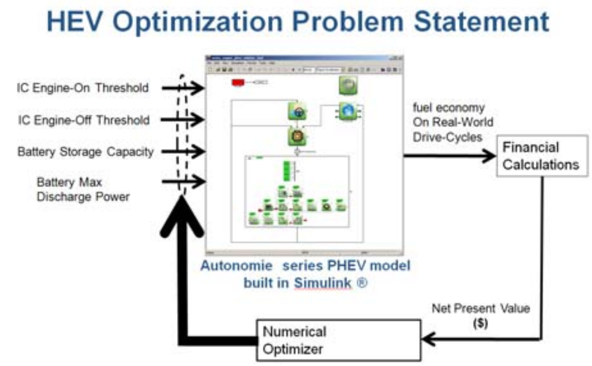

Figure 6. Optimization problem statement: Maximize the NPV by changing battery and control parameters

The left side of Figure 6 shows four independent optimization variables related to the vehicle control and battery design variables manipulated by the numerical optimizer to maximize the NPV calculation over a set of 30 real-world drive cycles. Simultaneous optimization of the vehicle control and battery design parameters was necessary to achieve a realistic result.

Optimization Approach

Figure 7 shows the top-level optimization process used to optimize the battery and control design parameters across a set of 30 real-world drive-cycles. Starting with a nominal set of four control and battery design parameters, a Direct Search optimization algorithm was used to generate an initial set of eight normalized variation coordinates in the four dimensions being searched. The initial eight-point grid was scaled to cover the entire range of the four design parameters so that local minima could be avoided. At each of the eight initial points, 30 real-world drive-cycles were simulated in parallel computing rapid-accelerator operating mode to determine the NPV for each point.

The four-dimensional coordinate with the highest NPV was then chosen as the new center-point of the optimization, and the span of subsequent variations was reduced until a 1% normalized parameter variation tolerance was met. The optimization approach shown in Figure 5 was chosen to avoid the problem of local minima, which often is encountered in systems that have discrete state changes due to variations in control and hardware parameters, and to provide a simple, robust approach to finding the global maximum NPV value.

Figure 7. Direct search optimization approach

Optimization Results

Net Operational Cost Savings

A PHEV has two operating costs: gasoline and electricity. For any specific battery size, we can compute the optimum electricity and gasoline consumption for the vehicle, as part of the control optimization. A conventional vehicle will consume approximately $16,000 worth of gasoline over its 240,000-km lifetime. With this information, we can further estimate the net savings obtained by using a PHEV, as shown in Figure 8.

This might suggest the largest possible battery as the best option. However, the battery cost will impact that choice. The NPV of the amortized battery cost and the gasoline savings accrued over the entire vehicle life will determine which battery offers the maximum value, as well as the return on investment that can be expected from a PHEV battery.

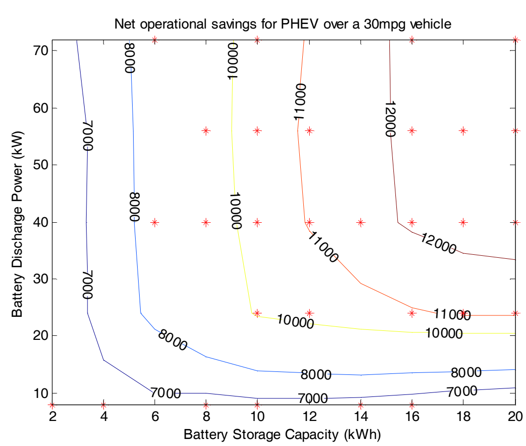

Figure 8. Variation of savings in operational cost with battery size (battery cost not included)

Two optimization tests were conducted with long-term battery costs and short-term battery costs (reflecting the present scenario). The results obtained are shown in Figure 9.

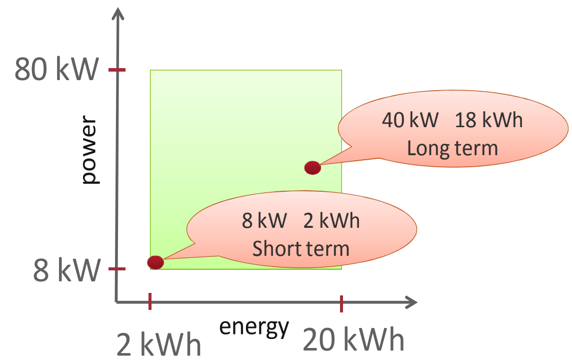

Figure 9. Battery sizes chosen for maximum NPV

Optimum Battery Choice with Current Battery Cost (short term)

The higher battery costs forced the optimizer to reduce the battery size as far as possible. The gasoline displacement obtained in this case was enough to offset the battery cost, but it was not enough to justify the investment on a larger battery. A 2-kWh battery with an 8-kW power discharge capacity would still result in higher PHEV fuel efficiency than a conventional vehicle. The gasoline savings from a small battery were not estimated to be as much as the savings associated with a large battery. Since the investment needed for a small battery was low, the series PHEV still yielded a positive NPV if the battery size was reduced. The contour plot in Figure 10 shows the gradual reduction in savings as the battery size was increased.

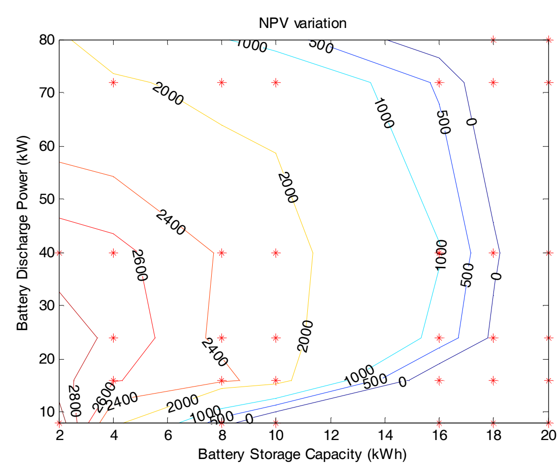

Figure 10. NPV variation with short-term battery costs

Optimum Battery Choice with Future Battery Cost (long term)

For the long-term cost estimates, the algorithm chose a large battery (18-kWh, ~11-kWh usable) with a medium-power discharge capability (40 kW) as shown in Figure 11. The optimum engine ON threshold was found to be 80 kW, and the OFF threshold was found at 10 kW. The 80-kW maximum power result suggested that the vehicle control algorithm did not find any incentive to use the engine while the battery was capable of providing the power for propulsion. The 80-kW result may have been different if emissions and penalties for frequent engine starts had been factored in.

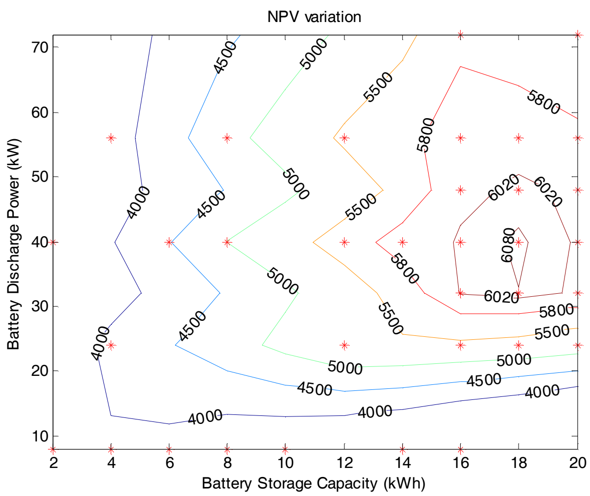

Figure 11. NPV with long-term battery costs

The actual data were recorded from the points marked in red on the contour plot. Multiple start points were used to ensure that the optimizer covered most parts of the battery design space, which minimized the chance of having a local optima issue.

Conclusions

A new development process for the planning of PHEVs has been proposed by Argonne National Laboratory, with the support of simulation and optimization tools from The MathWorks during the course of the study. Only a few years ago, a similar study involving thousands of simulated runs over 30 different drive cycles might have been very difficult due to the lack of hardware computing power and available off-shelf simulation tools compatible with parallel computing and optimization. Autonomie has provided the capability to build and run vehicle models over drive cycles, while utilizing the parallel computing and optimization capabilities in MATLAB®, thereby making such extensive studies possible within a reasonable time frame for everyday engineers. The application of the tools demonstrated the need to use such a process when sizing components to maximize NPV, which is a critical part of setting component requirements.

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2. Shidore, N., et.al., "Impact of Energy Management on the NPV Gasoline Savings of PHEVs," SAE, 2010.

I. Using GPS Driving Profiles, Including Multi-day, to Assess PHEV Fuel Efficiency

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Objectives

- Assess the expected fuel economy and performance of plug-in hybrid electric vehicles (PHEVs) under real-world driving conditions.
- Consider the influence of vehicle design, drive cycle intensity (i.e., amount of high vehicle speeds and accelerations), driving distance and day-to-day variability on PHEV fuel and electricity consumption relative to other vehicle technologies.
- Implement data processing methods for repairing and filtering travel activity data acquired using global positioning system (GPS) technology.

Approach

- Obtain GPS data sets from travel surveys/studies, and perform clean-up processing to remove/correct erroneous data points that result from data acquisition equipment limitations.
- Build driving profiles (in-use duty cycles) and generate statistics on the distribution and multi-day variability of vehicle driving distances.
- Compare the driving information from local/regional studies with that from national surveys, and evaluate the performance of different types of advanced vehicles across all of the GPS driving profiles using vehicle simulation software.

Accomplishments

- Leveraged the Department of Transportation (DOT)-sponsored and NREL-hosted Transportation Secure Data Center (TSDC) to access key datasets for supporting the PHEV analyses.
- Implemented and documented best practices for clean-up processing on GPS driving profiles (to remove erroneous data, impute missing data, etc.).
- Investigated PHEV utility factor (UF) curves derived from a Seattle-area study that recorded 17 months of driving data from nearly 450 vehicles.
- Refined analysis of various PHEV designs as compared with conventional and hybrid vehicles based on simulated operation over roughly 800 full-day real-world driving profiles from Austin and San Antonio, Texas.

Future Directions

- Apply statistical expansion/weighting factors on the Seattle-area driving profiles to improve comparability with national driving statistics, and/or obtain multi-day datasets from other U.S. cities in order to validate general multi-day UF uniformity from region-to-region.
- Further examine driving behavior differences based on different regions, consumers and/or vehicle types in order to develop more targeted PHEV benefits analyses.

- Incorporate the effects of road grade into the vehicle simulations, and continue to improve the GPS data processing methods to increase the fidelity of elevation as well as location and speed parameters.

Introduction

Plug-in hybrid electric vehicles (PHEVs) offer the potential for significant petroleum reduction relative to conventional vehicles, which in turn could lead to aggregate benefits such as reduced U.S. oil dependence, increased national security, and diminished CO_2 emissions. However, specifically estimating the likely in-use performance for this particular advanced vehicle technology is quite challenging. This is because PHEVs consume energy from two different sources (electricity from a charging plug and liquid fuel from a pump) and function in two distinct operating modes (initially depleting the net charge in the vehicle's battery and eventually sustaining it for longer distance driving). On road driving profiles collected from surveys employing GPS devices have proven very useful for revealing expected in-use PHEV performance characteristics. Such GPS profiles provide an opportunity to observe how PHEV fuel and electricity consumption vary in response to real-world driving aggressiveness as compared to operation over standard historic test cycles. The GPS data also provide valuable information on the distribution of distances vehicles drive and how much of that driving could reasonably occur in a given PHEV's depleting mode of operation (when it delivers the greatest fuel savings).

Over the past five or more years NREL has developed core competencies related to GPS data analysis and real-world PHEV performance estimation. Through collaboration with outside agencies NREL has acquired GPS data sets from multiple cities in Texas, California, Ohio, Kansas, Missouri and Washington. The resulting PHEV analysis research outcomes have been summarized in DOE deliverables as well as numerous publications and presentations over this time period [1-9]. In the past year, the U.S. Department of Transportation (DOT), Federal Highway Administration (FHWA) has added its support for NREL's GPS analysis activities. FHWA selected NREL to develop and maintain a Transportation Secure Data Center (TSDC) for securely archiving, processing and providing controlled access to valuable GPS data sets [10]. One of the first data sets FHWA helped NREL acquire for incorporation into the TSDC is a large multi-day GPS data set from the Seattle area. The Seattle data set provided the basis for the multi-day utility factor analysis described in this report, demonstrating an example for how the TSDC effort can be leveraged to support DOE PHEV analysis. This report also summarizes the results of a simulation study that evaluated the fuel economy and performance of multiple vehicle designs over real-world driving profiles collected in Austin and San Antonio, Texas.

Approach

The large multi-day GPS data set from the Seattle area was collected by the Puget Sound Regional Council (PSRC) [11]. The analysis for this report performed with the PSRC data set focused on the distribution of vehicle driving distances across multiple days. Such distribution information is needed to calculate the charge-depleting (CD) utility of different PHEV designs for prospective PHEV owners. The resulting utility factor (UF) quantifies the limited utility of a PHEV's CD range. An operating mode with a very long range, for example, will have a very high utility and, thus, a UF that approaches one. A distinct UF result is calculated for different PHEV depletion distances, which results in a curve that starts at zero and eventually reaches one for very large distances. Three different types of UFs were calculated for the PSRC data set: the fleet utility factor (FUF), the single day individual utility factor (SDIUF), and the multi-day individual utility factor (MDIUF). The values of each type of UF were calculated over a range of distances to generate a curve for each one.

The FUF is the utility factor based on the total miles traveled for a specific fleet of vehicles, and is particularly useful for calculating the expected fuel and electric energy consumption of the entire fleet. In the PSRC data set, the distance used was the distance traveled by each vehicle each day. Because the PSRC data set contained multiple days of driving, each individual vehicle is represented by multiple daily distance values—one for each day of travel.

The SDIUF is based on giving each vehicle equal weighting. Again, because the PSRC data set contained multi-day data, the SDIUF was calculated based on giving the CD utility of each vehicle-day equal weighting (excluding days when a vehicle did not drive). On the other hand, the MDIUF incorporates each driver's day-to-day variation into the utility calculation. It is the recommended utility factor to use when calculating a UF for estimating an individual vehicle's expected fuel economy over time. Calculating the MDIUF from the multi-day data set for a given CD range first involves summing the daily CD miles for a given vehicle (i.e., the lesser of the CD range or the vehicle's daily miles driven) and dividing that by the total sum of all the vehicle's driving miles. This produces a CD utility for each vehicle over all of its days of driving. The final step to calculate the expected value of this utility for any given individual is to calculate the average of the CD utility for all vehicles in the data set.

Similar utility factor (UF) calculations were performed as part of the SAE J1711/J2841 subcommittee's work related to PHEV fuel economy estimation. The FUF and SDIUF curves for those documents were derived from the (single-day) 2001 National Household Travel Survey (NHTS) [12], but the multi-day data forming the basis of the MDIUF calculations came from a single metropolitan area (Atlanta, GA) [8, 13]. It is therefore prudent to check/validate the UF calculations using a multi-day data set from another part of the country that is now available.

The second set of analysis included in this report summarizes a simulation study of different PHEV and baseline powertrains over nearly 800 full-day, in-use GPS profiles from Austin and San Antonio, TX [14]. Six different midsize platform vehicles were simulated on these cycles: a conventional vehicle (CV), an HEV, and four PHEVs. Of the four PHEVs, three had a parallel configuration with a blended control strategy, meaning that the internal combustion engine assisted the electric motor during times of high power demand. The three blended-strategy PHEVs are referred to as PHEV10, PHEV20, and PHEV40 because they were designed to travel approximately 10, 20, and 40 miles respectively on the Urban Dynamometer Driving Schedule (UDDS) before using any fuel. The fourth PHEV was a series configuration with a high-power battery energy storage system (ESS) and an electric motor capable of providing for all of the vehicle's power demands. The internal combustion engine in the series PHEV was only used to sustain the charge of the batteries for longer distance driving. This vehicle is referred to as PHEV40s and was designed to travel approximately 40 miles on the UDDS cycle before using any fuel. Table I lists some of the attributes of the vehicle models in the simulation and their performance over the standard UDDS and Highway Fuel Economy Test (HWFET).

Table 1. Simulated vehicle attributes

				PHEV			
	Units	***CV***	***HEV***	***10***	***20***	***40***	***40s***
Engine Power	kW	123	77	77	78	80	85
Motor Power	kW	n/a	36	40	41	43	130
ESS Energy (total, DC)	kWh	n/a	1.7	4.5	8.2	16.4	16.4
Curb Mass	kg	1473	1552	1578	1614	1694	1789
CS Consumption*	L/100km	6.8	4.7	4.9	5.1	5.2	5.3
CD Consumption (AC)*	kWh/100km	n/a	n/a	18.2	18.2	18.4	18.9
Urban Electric-only Range	km	n/a	n/a	16.9	33.8	67.6	64.4
	mi	n/a	n/a	10.5	21	42	40

****Values reflect unweighted composite urban/highway consumption. The CD values represent pure CD performance (when no fuel use occurs on the standard UDDS/HWFET cycles).***

Results

UF Analysis Using Multi-Day GPS Data

Figure 1 provides the UF curves calculated from the PSRC data set, along with several comparison curves. The three curves with thick dashed lines in Figure 1 show the SDIUF, MDIUF and FUF curves, respectively, that are consistent with those included in the SAE J2841 document. The FUF is the lowest of the three curves since it employs weighting based on miles driven. The longest distance drivers in the data set therefore pull the curve down. The SDIUF is the highest of the three curves since it weights based on vehicle-day observations. This is because the shorter-distance driving days with high CD utility values are treated equally to longer-distance driving days with lower utility values (but which actually make up a larger fraction of the total vehicle miles traveled and fuel consumed). The MDIUF falls between the other two curves, but significantly closer to the FUF than the SDIUF curve. This suggests that individual drivers do not drive the same distance every day, but rather have a distribution of daily driving distances over time (as is the case across the overall fleet where sampling each vehicle on a particular day also produces a distance distribution). The MDIUF curve is a little higher than the FUF curve due to the fact that averaging across all individuals diminishes the lowering effect of those vehicles in the overall fleet that regularly drive very long distances.

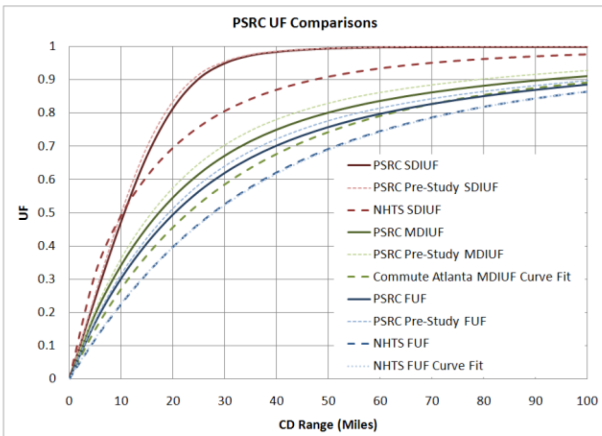

Figure 1. Utility factor curve comparisons

The three thick solid lines in Figure 1 show the SDIUF, MDIUF and FUF curves calculated from the full PSRC data set. The relationship of these three curves to each other follows the same pattern as for the baseline set of curves from SAE J2841, however all of the curves from the PSRC data set are shifted higher than their corresponding J2841 curve. The fact that this occurs for all three curves suggests that long daily driving distances make up a smaller fraction of the PSRC data set as compared to the other data sources.

Further investigation into the sample design for the PSRC Traffic Choices Study revealed the occurrence of sample enrichment to ensure that their budget-constrained study included significant numbers of individuals who might change their behavior in response to the pricing influence (e.g., over-sampling in the city near transit access points, under-sampling households with workers traveling outside of the study area, etc). This helps explain why the data set seems to have a higher proportion of shorter driving distances. In contrast, the NHTS includes rural drivers and would not have had a need for the sample enrichments specific to the PSRC study. During the course of writing SAE J2841, the same calculation approaches as applied to the PSRC data were applied to the Commute Atlanta data set to calculate the SDIUF and FUF for comparison with the NHTS-derived curves. That comparison revealed very close agreement between the curves calculated from the different data sources even without applying weighting or statistical expansion factors to the data sets [8]. Evidently such a statistical expansion exercise would be required in order to generate fair comparison curves from the PSRC data.

PHEV Analysis Using Texas GPS Data

Figure 2 shows the average fuel and electricity consumption weighted by vehicle day from the vehicle simulations for all of the vehicles in both the Austin and San Antonio data sets. Figure 3 shows the distance- weighted average of fuel and electricity consumption for all vehicles. For the PHEVs, the graphs show the fuel and electricity consumption for both the base case and the opportunity charging (opchg) case. The base case assumes the PHEVs are recharged once per day (overnight). The opportunity charging case is a best case scenario that assumes that the vehicle has the opportunity to be plugged in every time the vehicle is stopped for more than two minutes. The vehicles are recharged at a rate of 1.56 kW AC with a charger efficiency of 90%.

Since most public parking lots do not have outlets in every stall to plug vehicles into, the base case is more likely representative of the real world. However, some consumers may make many trips throughout the day, returning home between trips. One example would be a stay-at-home parent who shuttles their children from place to place and returns home between trips. For this type of situation, the opportunity charging case may be a better representation. If public parking lots were to have outlets available to plug vehicles into, the fuel savings would be very significant, as shown by the significant increase in fuel economy from the base case to the opportunity charging case.

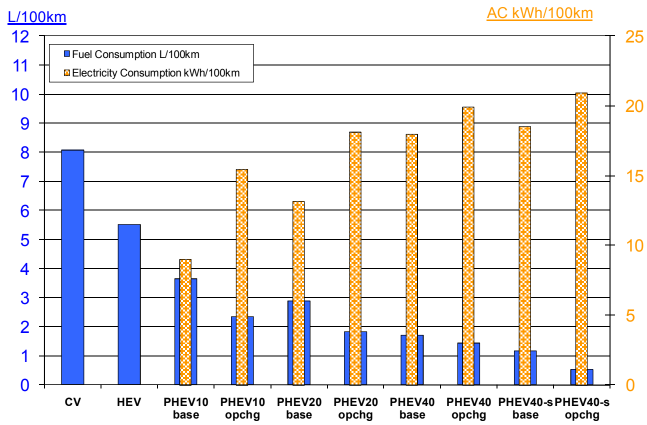

Figure 2. Average fuel and electricity consumption weighted by vehicle day for Austin and San Antonio data sets

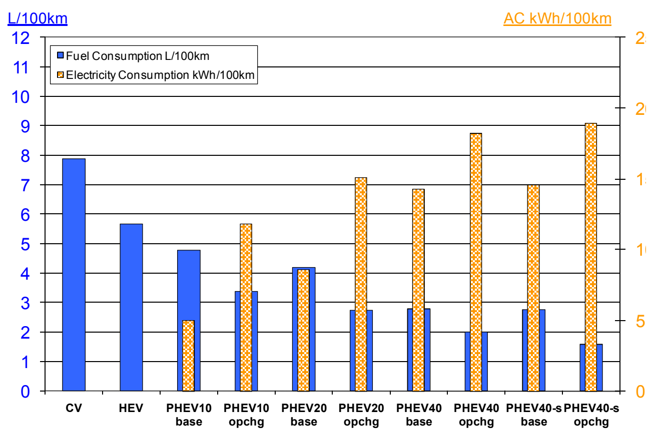

Figure 3. Average fuel and electricity consumption weighted by total miles traveled for Austin and San Antonio data sets

Note that the average fuel consumption of the PHEV40 opportunity charging case is less than the PHEV40s base case when averaging across all kilometers driven, whereas the opposite is true when averaging the results by vehicle day. This is because in the vehicle-weighted average, the vehicles that are driven short distances only in CD mode are given equal weight to those that travel far enough to enter CS mode. The distance-weighted averages, however, give more weight to the vehicles traveling long distances, and therefore include more CS operation in the averages (which also leads to higher fuel consumption results for all PHEV cases with distance vs. vehicle based averaging). Opportunity charging between trips can enable much more CD operation for the longer driving vehicles, and hence shows a larger relative fuel savings benefit when weighting by daily kilometers driven. Since the vehicle weighted average in Figure 2 is representative of the average fuel consumption per vehicle day, it is better representation of an average consumer's fuel use, while the distance weighted average in Figure 3 is a better representation of the average fuel consumption of the overall fleet (and the aggregate fuel displacement potential of each technology for this particular set of drivers). This is basically the same distinction drawn between the SDIUF and the FUF for use in combination with standard cycle testing.

Analysis over a large number of real-world drive profiles also permits examination of the fuel consumption distribution for each simulated vehicle variant. This distribution for the Austin and San Antonio data sets is shown in Figures 4 and 5. Note that the PHEV20 has a very wide distribution compared to the PHEV10 and PHEV40. Because a high percentage of daily driving is greater than 10 miles, the PHEV10 usually operates in CS mode. Likewise, because a high percentage of daily driving is less than 40 miles, the PHEV40 usually operates in CD mode. The PHEV20, however, doesn't strongly favor either mode since a high percentage of vehicles drive between 10 and 40 miles per day. Also note that the PHEV40s has a very high peak at 0 L/100km. Unlike the PHEV40, it does not use fuel for aggressive accelerations and therefore uses no fuel unless it travels more than 40 miles.

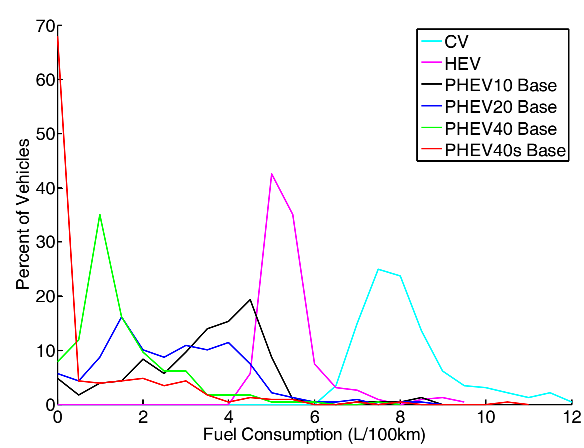

Figure 4. Fuel consumption distribution for Austin data set

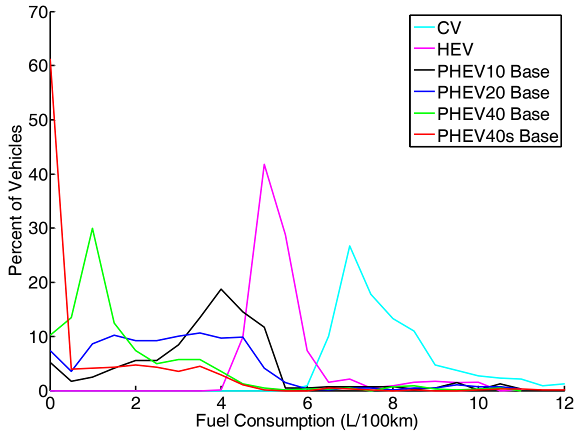

Figure 5. Fuel consumption distribution in San Antonio data set

Finally, Figures 4 and 5 also demonstrate the noticeably large percentage variation in fuel consumption of the vehicles with increased electrification as compared to the CV. The distribution differences highlight the increased sensitivity of PHEV fuel consumption (particularly for blended-strategy PHEVs) to variations in driving patterns and conditions.

Figures 6 and 7 show the electricity consumption distribution for each vehicle in the Austin and San Antonio data sets. As expected, the electricity consumption follows somewhat of an inverse trend compared to the fuel consumption. The PHEV10 uses less electricity because of lower storage capacity, causing it to run in CS mode more often, while the PHEV40 consumes more due to its high capacity, allowing it run in CD mode more often. The PHEV20 spends similar amounts of time in both modes, giving it a wide distribution similar to the fuel consumption distribution. The PHEV40s consumes the most electricity since it does not rely on the internal combustion engine to assist it with aggressive accelerations. However, the electricity consumption differences with the blended-strategy PHEV40 are small, suggesting that the PHEV40 makes just as good use of the energy stored in its batteries as the PHEV40s. (This observation is also supported by the near identical distance-weighted average consumption characteristics between the two vehicles).

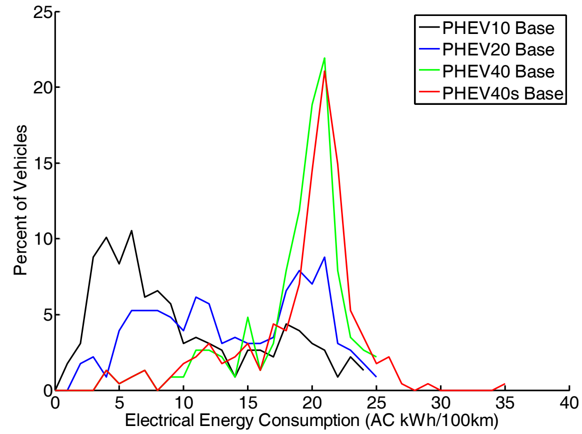

Figure 6. Electrical energy consumption (AC kWh/100km) distribution in Austin data set

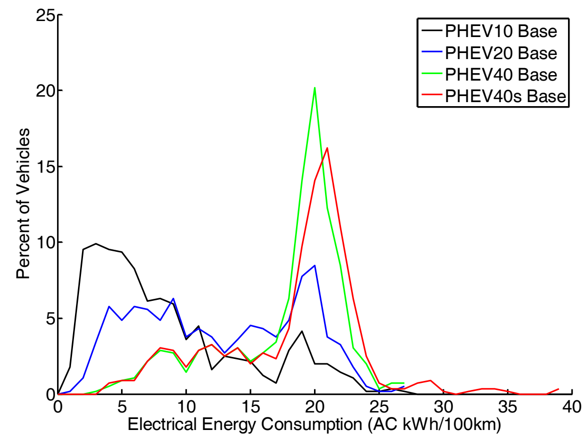

Figure 7. Electrical energy consumption (AC kWh/100km) distribution in San Antonio data set

Conclusion

The results section details the successful creation of UF curves from the Seattle-area multi-day GPS data set. Unfortunately, it was found that the vehicle driving distribution from the Seattle sample seems skewed towards shorter driving trips relative to a representative national sample due to enrichment bias introduced from the study design. Further collaboration with the original study architects will be required in order to eliminate this bias through statistical weighting so that a better comparison can be made.

The simulation results from over roughly 800 full-day driving profiles from the Austin and San Antonio data sets highlight the range of power demands present in the in-use profiles, and the resulting range of fuel and electricity consumption for the vehicle variants examined. The results also illustrate how opportunity charging can reduce PHEV fuel use even for drivers with long daily driving distances, provided that the long distances are broken up into multiple trips with opportunity to recharge the PHEV batteries in between.

Through the course of these and other GPS data analyses, NREL developed a best practice procedure for performing quality control processing on GPS data sets. While each data set is unique with respect to the data collection context and the particular logging device used, almost universally some degree of clean-up processing is needed prior to using the profiles in vehicle simulations or driving tests. Because of the data set differences, each processing routine requires some degree of customization or parameter adjustment, but the general topics included in the best practices report (removing erroneous data, imputing missing data, etc) regularly prove to be necessary. Though GPS driving profile data is certainly valuable for many PHEV analyses, it is crucial to ensure that simulation results related to peak power distribution and resulting fuel/electricity use are not being biased due to errors from the GPS recording.

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J. Medium-Duty Plug-in Hybrid Electric Vehicle Analysis

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Objective

- Assess the potential benefit of medium-duty (MD) plug-in hybrid electric vehicle (PHEV) platforms.

Approach

- Leveraging other advanced vehicle testing activity (AVTA)-funded projects, acquire and analyze vocational duty cycle data.
- Utilizing vehicle characteristics and measured fuel economy data (via ReFUEL), develop and validate a model of an existing MD HEV.
- Model cost, mass and fuel consumption impacts of adding battery capacity and more robust components.

Accomplishments

- Parcel delivery vocational duty cycle data were collected and analyzed. Evaluation of relevant real world duty cycle data resulted in a focused selection of drive cycles for chassis dynamometer testing and vehicle simulation.
- With industry partner support, a model was developed of a pre-production gasoline hybrid electric parcel delivery vehicle (gHEV), currently deployed in service by FedEx.
- Measured fuel economy data over three “vocationally relevant” drive cycles were used to validate a parcel delivery platform model.
- Operating costs and petroleum displacement were simulated across 120 design, usage and cost scenarios.

Future Directions

- Add depth and breadth to MD and HD vocation drive cycle database to ensure accuracy of modeling efforts.
- Leverage NREL MD/HD research activities – AVTA activities and ReFUEL test results – to expand validated platform models.
- Use ARRA project data streams to calibrate and validate models.
- Explore feasibility of routes (intensity and distance) for PEV parcel delivery and other vocations, including impacts of opportunity charging.
-

Introduction

Medium-duty vehicles are typically represented by classes 3 – 6, with a gross vehicle weight range of 10,000 to 26,000 pounds. There has been considerable research on PHEV technology in the light-duty vehicle segment, which, due to its large volume of fuel consumed and well-matched user driving behaviors, makes it an excellent application for PHEV technology. While heavy-duty vehicles are also large fuel consumers, they typically do not exhibit drive cycles that render them appropriate (prohibitively long and/or insufficient transients) for PHEV application. Although it has received less scrutiny for PHEV application, the medium-duty vehicle segment is well suited for the following reasons:

- Drive cycles are transient intensive, for which EDVs equipped with regenerative braking capability are well matched.
- Fleet-based vehicles return to a home base, facilitating overnight charging.
- The potential for significant fuel savings per vehicle multiplies across an entire fleet.

Plausibly attractive value proposition due to potential for reduced maintenance costs, longer period of vehicle ownership (to realize reduced fuel consumption benefits), and the increasing value of a green corporate image.

Approach

This section describes the approach to vehicle and drive cycle selection, model development and validation, battery life calculation, and economic scenarios.

Drive-Cycle Data Collection and Analysis

Leveraging concurrent U.S. Department of Energy-sponsored parcel delivery fleet evaluation activities with FedEx and UPS, 15 field vehicles were instrumented with global positioning system-enabled data loggers, and 92 days of spatial speed-time data were collected. These data were used to confirm daily route consistency and to characterize each route according to 58 drive-cycle metrics, including daily distance traveled and kinetic intensity. Kinetic intensity [1], a metric that is derived from the vehicle road load equation, is linked to the magnitude and frequency of accelerations, and, as such, offers insight into the cycle-specific benefits of adding an electric drive.

Although several drive cycle metrics (e.g., average speed, stops/km, and acceleration/decelerations) were used to compare standard drive cycles to those measured in the field, kinetic intensity was the primary comparison metric that framed chassis dynamometer test cycle selection and vehicle simulation activities. The Orange County Bus (OC Bus) cycle was selected as the standard drive cycle that best approximated the routes measured in the field, while the NYCC and HTUF4 cycles were selected as the upper and lower boundaries for vocational kinetic intensity. The kinetic intensity of cataloged stock drive cycles, the average of those measured in the field, and the test cycles selected are presented in Figure 1.

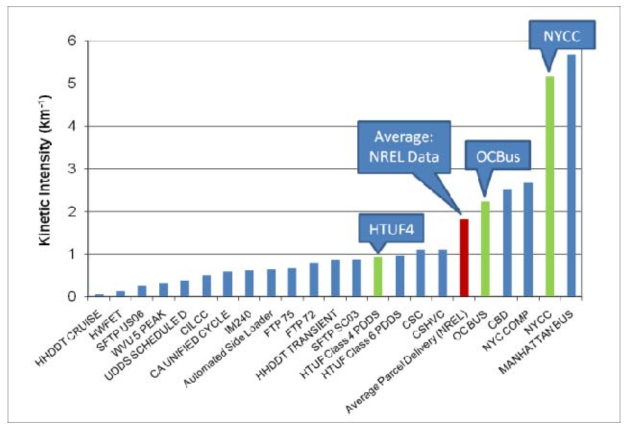

Figure 1: Drive Cycle Kinetic Intensities

Fuel Consumption Measurement

A parcel delivery charge-sustaining (CS) gasoline hybrid electric vehicle (gHEV) owned and operated by FedEx was transported from California to NREL's Renewable Fuels and Lubricants (ReFUEL) Research Laboratory chassis dynamometer for emissions and fuel consumption measurement. Fuel consumption values measured over three drive cycles are presented in Table [2].

Table 1: gHEV Measured Fuel Consumption (Photo credit: Robb Barnitt, NREL)

Drive Cycle	HEV Fuel Consumption (liter / 100km)
HTUF4	22.5
OC Bus	27.3
NYCC	34.9

Vehicle Model Development and Validation

A model of the FedEx gHEV was developed with assistance from industry partners FedEx and Azure Dynamics. The vehicle model uses vehicle and component specifications to predict fuel consumption on a given cycle. The essential parameters are shown in Table .

Table 2: Defining Vehicle-Model Parameters

Parameter	FedEx gHEV
C_d	0.7
Frontal area (m^2)	7.02
Vehicle mass (kg)	4,472
Engine power (kW)	182
Motor power (kW)	100
Battery power (kW)	60
Battery capacity (kWh)	2.5

The model was validated on three drive cycles: the HTUF4, the OC Bus, and the NYCC. The simulated results fell within 10% of the fuel consumption measured on the ReFUEL chassis dynamometer.

Table 3: Model Validation

Drive Cycle	Fuel Consumption (L/100km) Measured	Fuel Consumption (L/100km) Simulated	Error
HTUF 4	22.5	24.5	8.9%
OC Bus	27.3	27.4	0.4%
NYCC	34.9	35.2	0.9%

Battery Life Model

Battery life was estimated using data from Johnson Controls [3], as shown in Figure . The trip distance, battery discharge efficiency, and allowable state of charge (SOC) window was used to estimate the charge-depleting (CD) wear per mile. The wear per mile due to accelerating and braking was based on assumed speed versus time-drive profiles input into vehicle simulations, which was then added to calculate the total wear per mile. The usable SOC was modified until the battery life model predicted that it would last the specified 15 years.

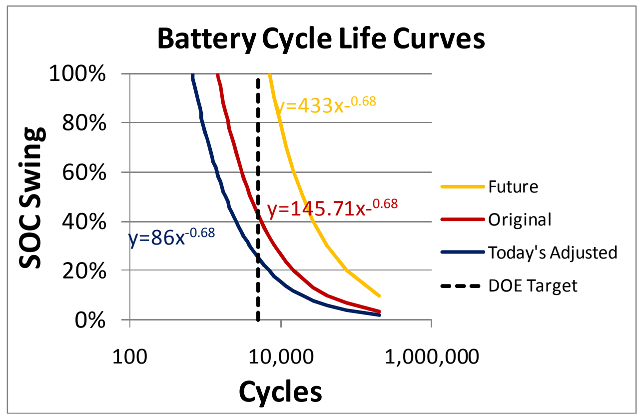

Figure 2: Battery cycle life curves

Simulation Scenarios

NREL exercised the model by sweeping a matrix of 120 component size, usage, and cost combinations (Table 4 & 5) to assess fuel consumption and vehicle cost trade-offs. The effects of increased battery and component mass on fuel consumption, as well as battery wear, are captured and accounted for in the model. Additional assumptions are listed in Table 6.

Table 4: PHEV Analysis Matrix – Drive-Cycle and Component Specifications

Drive cycles	HTUF4, OC Bus, NYCC
Control strategies	All-Electric Range (AER) CD-battery dominant
Daily distance traveled	40, 80, 120, 160 km
Additional battery capacity	20, 40, 60, 80 kWh
Battery power	30, 60 kW

Table 5: PHEV Analysis Matrix - Cost Inputs

Scenario	ESS cost	Fuel cost	Electricity cost
Current	$700/kWh	$0.79/L	0.12 $/kWh
Midterm	$300/kWh	$1.32/L	0.12 $/kWh

Table 6: Additional Assumptions

Vehicle life (years)	15
Battery cost	$22/kW + scenario $/kWh + $680
Motor and controller cost	$21.7/kW + $425
Markup Factor	1.75
Discount rate	8%
Charger Efficiency	0.9

Results

Fuel Consumption

The relationship between fuel consumption and daily distance driven is illustrated in Figure 3 (30-kW case) and Figure 4 (60-kW case).

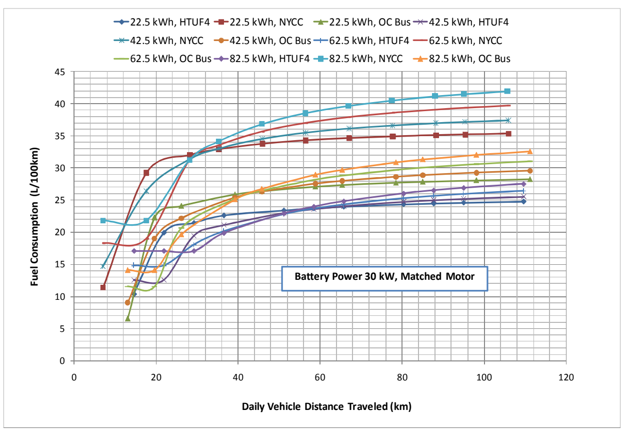

Figure 3: Fuel consumption by daily distance traveled (30 kW)

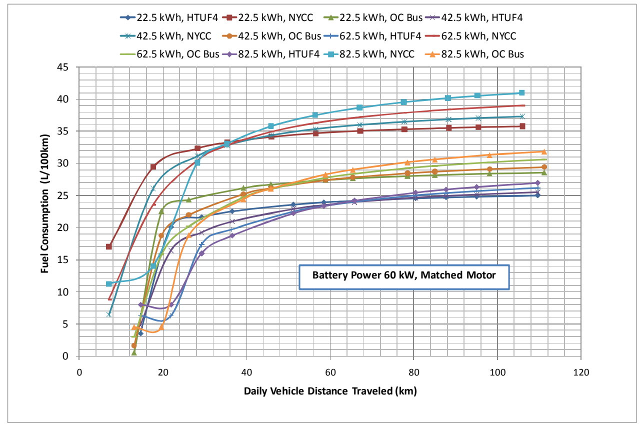

Figure 4: Fuel consumption by daily distance traveled (60 kW)

Several observations can be made for each figure. First, fuel consumption typically begins low while battery energy is available, then trends upward to a plateau, indicating battery depletion and initiation of CS mode. Second, more kinetically intense cycles with higher power demands begin at a higher fuel consumption and reach CS mode within a shorter distance traveled than do less kinetically intense cycles. Third, due to increasing mass with increasing battery capacity, fuel consumption begins higher but CD mode is possible for a longer distance than for a lower-energy capacity.

While the trends for 30-kW and 60-kW battery and motor power are similar in shape, fuel consumption is lower at the same daily distance traveled for the 60-kW case. While the 60-kW motor has a higher mass than the 30 kW motor, its higher power (and matched battery power) allows for greater utilization of battery power, increased capture of regenerative braking energy, and less reliance upon liquid fuel to meet the drive-cycle power requirements.

These results illustrate the importance of understanding both drive-cycle intensity and daily distance traveled in designing, selecting, and deploying the most appropriate technology for a given route.

Energy Storage System (ESS) Mass and Cost

The relationship between ESS mass and costs (manufacturing and with mark-up) is illustrated in Figure 5. Only the 30-kW scenario is shown as the trend shapes are identical and the mass offset (with the 60-kW scenario) is about 100 kg, and the cost offset (with the 60 kW scenario) is about $1,000.

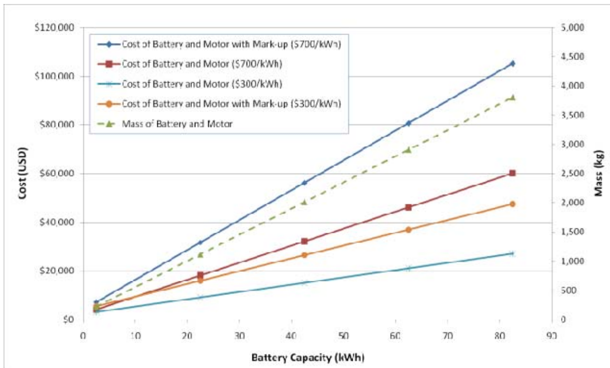

Figure 5. Battery capacity mass and costs

Battery mass and cost increase linearly with capacity. As expected, the cost of a high-capacity battery varies significantly between the two economic scenarios ($700/kWh and $300/kWh).

Lifetime Operating Costs

From the perspective of a fleet manager contemplating the purchase of parcel delivery EDVs, the lifetime cost of operation is the best comparative metric. Currently, parcel delivery vehicles are replaced every 15 years. Thus, in this analysis, the lifetime cost of operation refers to the 15-year cost of liquid fuel, electricity, additional battery capacity, and electric machine size. For each configuration, the lifetime cost of operation was calculated using current and future economic scenarios. The capital cost of the vehicle is not included, as this cost is negotiated between a seller and buyer and is subject to many more variables than can be captured in broad current and future pricing scenarios. The results presented below compare the lifetime operating cost of the vehicle configurations using the usage and economic scenarios.

Vehicle Nomenclature

For each drive cycle and daily distance traveled, the battery is sized and controlled to last 15 years. Simulation results indicate that, depending upon drive cycle and daily distance traveled, the CS gHEV with a 2.45-kWh battery capacity may not last 15 years. Thus, the additional battery capacity required for each usage scenario was added, and a new baseline CS gHEV constructed. This new baseline CS gHEV with battery sized for life (BSfL) is referenced as such in subsequent figures. Using the gHEV BSfL reference configuration, a CD control strategy was applied without adding battery capacity (PHEV+0 kWh). This vehicle configuration has the potential to decrease liquid fuel consumption without adding motor and battery costs. However, this configuration was unable to meet the 15-year life with any useful electric range in all drive cycle and daily distance traveled scenarios. Additional PHEV configurations were simulated with additional battery capacity in increments of 20 kWh (PHEV+20kWh, PHEV+40kWh, PHEV+60kWh and PHEV+80kWh).

Motor and Battery Power Levels

As shown in Table , two motor and battery power levels (30 and 60 kW) were evaluated. In every scenario, the 60-kW motor and battery have slightly higher capital cost and mass than the 30-kW motor and battery. Depending upon drive-cycle intensity and daily distance traveled, the 60-kW motor and battery is better equipped to power the vehicle using electricity rather than liquid fuel. In some cases, the avoided liquid fuel cost exceeds the higher power cost, resulting in a more cost-effective configuration. In most cases, the daily distance traveled was long enough that all the battery energy was used at both power levels, so similar amounts of liquid fuel were displaced. However, in scenarios with short daily distances and large battery capacity, the lower power levels were not capable of using all the available battery energy before the end of the cycle and thus used more high cost liquid fuel. While the additional power was cost effective for these high battery energy cases, the high cost of battery energy made both power levels less cost-effective than lower energy cases.

Control Strategies

As shown in Table , two control strategies (AER and CD battery dominant) were evaluated. The differences between the two cases are motor and battery power. The AER case uses a higher power 60-kW battery and motor compared to the 30-kW CD battery dominant case. Both use the battery as much as possible during CD mode. The high-power case, however, can provide the full load and prevent the engine from coming on more often. For the simulated drive cycles, the power difference did not have a big impact because most of the time, especially for the less intense HTUF4 and OC Bus cycles, the power level did not exceed 30 kW, and when it did, the battery was still providing a significant portion of the power. The high-power cases also captured more regenerative braking, but in most cases the added power cost more than it saved. The total end cost difference was small, so for each scenario only the most cost-effective one is included.

Lifetime Incremental Fuel and ESS Costs

Lifetime incremental fuel and ESS costs for 40 km driven per day are presented in Figure 6 (current economic scenario) and Figure7 (future economic scenario). The results for each configuration (gHEV BSfL, PHEV+0kWh, PHEV+20kWh, etc.) are clustered in groups of three. Each column represents the results for each of three drive cycles, consistently presented from left to right: HTUF4, OC Bus, and NYCC. Motor and battery power are referenced in parentheses on the x axis. The gHEV BSfL required additional battery capacities of 0, 0.1, and 0.4 kWh for 15-year life at 40 km/day of HTUF4, OC Bus, and NYCC, respectively. Using these same gHEV BSfL battery capacities, the PHEV+0kWh configuration was simulated. This configuration was only capable of lasting 15 years if driven on the least intense cycle (HTUF4); more intense cycles (OC Bus and NYCC) cycled the battery sufficiently to prevent realization of a 15 year life. While 30- and 60-kW motor and battery power levels were simulated, only the most cost effective is presented. In the 40-km/day scenario, the gHEV BSfL lifetime cost is lowest with a 60-kW power. However, in many PHEV configurations, the 30-kW power results in the lowest lifetime cost; the differences ranged from tens to thousands of dollars.

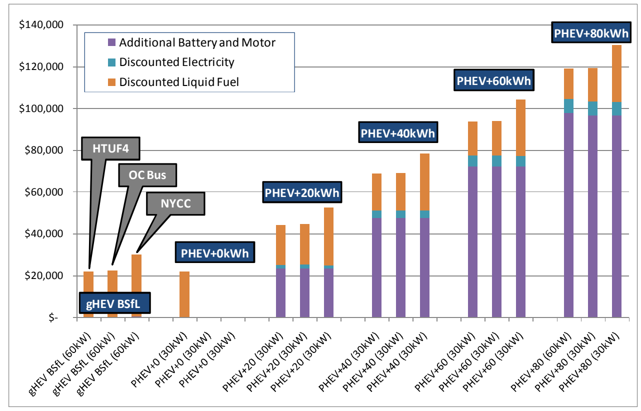

Figure 6. 40 km per day, current economic scenario

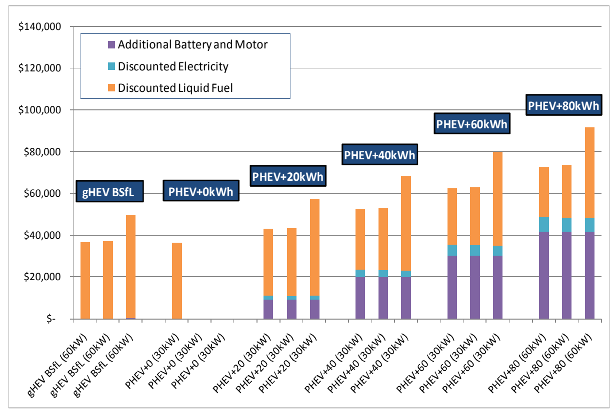

Figure 7. 40 km/day, future economic scenario

For the relatively small daily distance (40 km/day) usage scenario, the PHEV+0kWh (30-kW) configuration is feasible, and at slightly lower cost than the comparable gHEV BSfL (60 kW) configuration. This is driven primarily by the lower motor and battery costs ($1,219 less), as well as by lower fuel costs ($162 and $269 less for the current and future scenarios, respectively).

Lifetime fuel and incremental ESS costs for 80 km driven per day are presented in Figure (current economic scenario) and Figure 9 (future economic scenario). As in Figures 6 and 7, the results for each configuration (gHEV BSfL, PHEV+20kWh, PHEV+40kWh, etc.) are clustered in groups of three. Each column represents results for each of three drive cycles, consistently presented from left to right: HTUF4, OC Bus, and NYCC. Motor and battery power are referenced in parentheses on the x axis. The gHEV BSfL required additional battery capacities of 0.5, 1.6, and 2.1 kWh for a 15-year life at 80 km/day for the HTUF4, OC

Bus, and NYCC, respectively. At this longer daily distance traveled, the PHEV+0kWh configuration was not feasible in that it could not last 15 years.

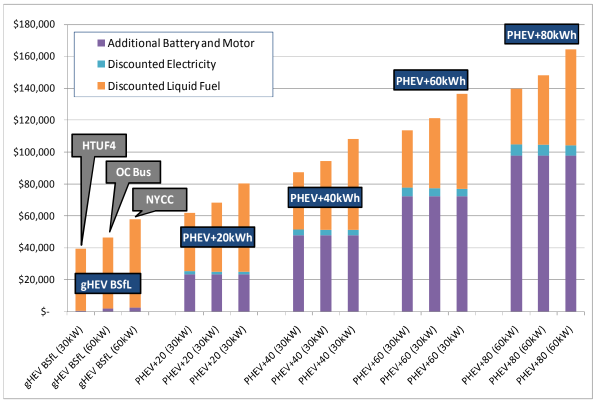

Figure 8: 80 km per day, current economic scenario

The trends for 120 km/day and 160/day usage scenarios are similar to those presented above, but are more pronounced. In general, lifetime costs increase with battery size. However, in the future economic scenario (high liquid fuel cost and lower battery cost), the lifetime cost difference between the gHEV BSfL and PHEV configurations decreases.

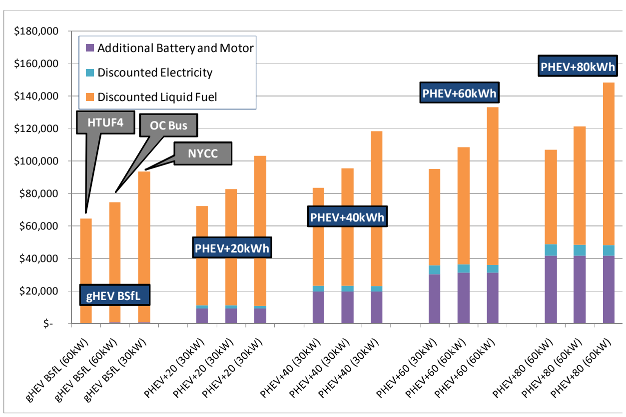

Figure 9: 80 km/day, future economic scenario

Delta Lifetime Costs

The most intuitive way to compare PHEV configurations to the gHEV BSfL baseline configuration is by delta lifetime cost. The lifetime cost for the gHEV BSfL configuration simulated for each drive cycle, motor and battery power level, and daily distance traveled was subtracted from the lifetime cost for each comparative PHEV configuration. This metric of comparison can aid fleet managers in understanding the lifetime cost implications of purchasing a particular PHEV configuration and balance that value against available purchase incentives, tax rebates, or other "green" strategic value propositions. The delta lifetime cost values are presented in Figure 10 (current economic scenario) and Figure 11 (future economic scenario). Individual columns represent daily distance traveled for a given configuration. The four configurations (PHEV+20kWh, PHEV+40kWh, PHEV+60kWh, and PHEV+80kWh) are clustered and separated by spaces. As indicated by the callouts over the PHEV+20kWh group, every two sequential columns represent results for each of three drive cycles, consistently presented from left to right: HTUF4, OC Bus, and NYCC. Motor and battery power are referenced in parentheses on the x axis.

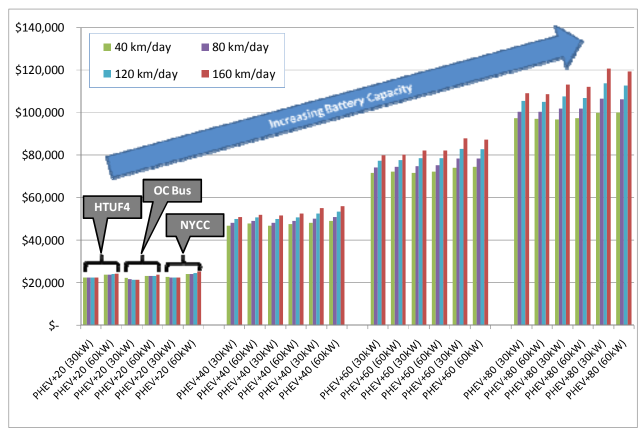

Figure 10: Delta lifetime costs, current economic scenario

Under the current economic scenario, the most cost-effective vehicle configuration is the PHEV+20kWh, with an incremental lifetime cost of over $20,000. Incremental costs vary according to drive cycle and daily distance traveled.

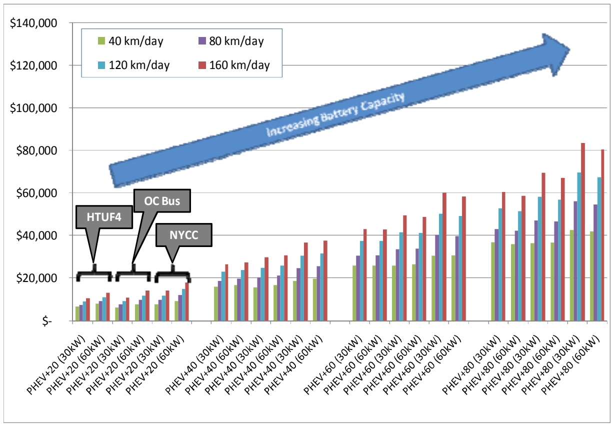

Figure 11: Delta lifetime costs, future economic scenario

Under the future economic scenario, the incremental lifetime cost of the PHEV+20kWh configuration ranges from $6,154 to $17,927, depending upon drive cycle and daily distance traveled (Table 7).

Table 7: PHEV+20kWh Incremental Lifetime Costs, future economic scenario

Vehicle	Drive Cycle	40 km/day	80 km/day	120 km/day	160 km/day
PHEV+20 (30kW)	HTUF 4	$6,568	$7,525	$9,018	$10,473
PHEV+20 (60kW)	HTUF 4	$7,944	$9,247	$11,150	$13,029
PHEV+20 (30kW)	OC Bus	$6,154	$7,600	$9,200	$10,854
PHEV+20 (60kW)	OC Bus	$7,661	$9,719	$11,880	$14,149
PHEV+20 (30kW)	NYCC	$7,620	$9,678	$11,838	$14,049
PHEV+20 (60kW)	NYCC	$9,311	$12,040	$14,924	$17,927

As evidenced in Table 7, large lifetime incremental cost differences are possible, depending upon drive cycle and daily distance traveled. With a relatively small battery capacity, longer daily distances can deplete the battery, thus requiring the vehicle to use more expensive liquid fuel.

Lifetime Liquid Fuel Displacement

For some fleets, lifetime operating cost may not be the only factor influencing the purchase of PHEVs. Lifetime liquid fuel reductions and subsequent reductions in tailpipe emissions may also figure into the purchase decision. The volume of liquid fuel saved over a 15-year vehicle lifetime was calculated. In addition, the cost per liter ($/L) was calculated for current and future economic scenarios. This $/L metric is calculated by dividing the delta lifetime cost for each vehicle configuration (gHEV BSfL is the reference) by the lifetime liquid fuel volume saved.

Figure presents these results for the 40 km/day case. Individual columns represent lifetime liquid fuel saved for a given configuration. The five configurations (PHEV+0kWh, PHEV+20kWh, PHEV+40kWh, PHEV+60kWh, and PHEV+80kWh) are clustered and separated by spaces. As indicated by the callouts over the PHEV+20kWh group, each sequential column represents results for each of three drive cycles, presented from left to right: HTUF4, OC Bus, and NYCC. The motor and battery power resulting in the largest liquid fuel savings (and lowest lifetime operating cost) are referenced in parentheses on the x axis. Lifetime liquid fuel saved is represented by blue bars, while the cost-effectiveness results are represented by red and green points.

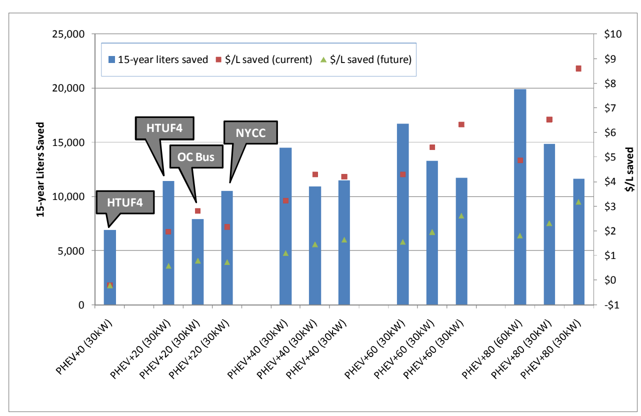

Figure 12. Lifetime liquid fuel displacement and cost effectiveness, 40 km/day

As discussed previously and as evidenced in Figure 12, the PHEV+0kWh is feasible for this low daily distance (40 km/day) and low intensity drive cycle (HTUF4) case. All PHEV configurations represent significant lifetime liquid fuel savings. This is true especially for PHEV configurations with larger battery capacity, as a shorter daily distance does not succeed in fully depleting the battery, resulting in less liquid fuel consumption and larger lifetime liquid fuel savings. The cost effectiveness of obtaining lifetime liquid fuel savings decreases with increasing battery capacity.

Figure 13 presents the results for the 80 km/day case. The chart format is the same as Figure , except that the PHEV+0kWh case is not feasible.

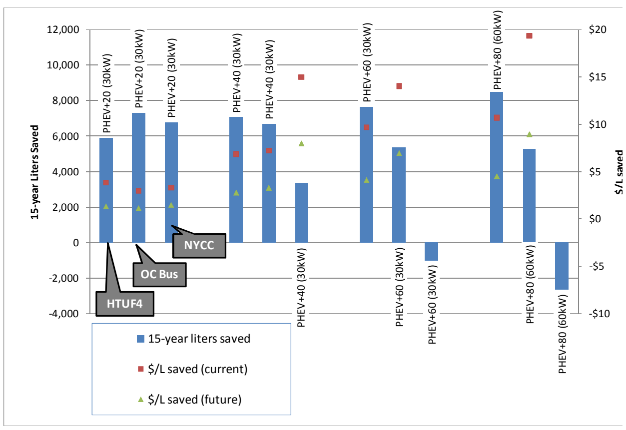

Figure 13. Lifetime liquid fuel displacement and cost effectiveness, 80 km/day

The lifetime liquid fuel savings for these PHEV configurations with longer daily distances are less than those realized in the 40-km/day case. Longer distances result in more battery depletion and eventually a transition from CD to CS operation. For the OC Bus and NYCC drive cycles, liquid fuel savings go down with increasing battery capacity. These more intense drive cycles deplete the battery more quickly, leading to an earlier transition to CS operation and a fuel consumption penalty due to the larger mass of the battery. In fact, on the NYCC drive cycle, the PHEV+60kWh and PHEV+80kWh configurations consume more lifetime fuel than the gHEV BSfL reference case. The cost effectiveness of obtaining lifetime liquid fuel savings decreases with increasing battery capacity, and the $/L saved values are higher than those in the 40-km/day case.

Figure 14 presents the results for the 120 km/day case.

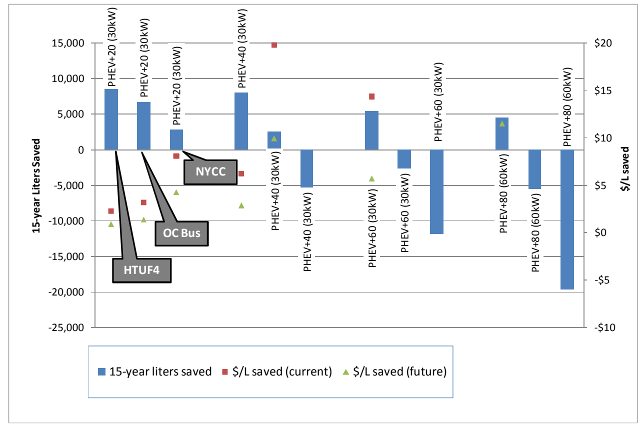

Figure 14. Lifetime liquid fuel displacement and cost effectiveness, 120 km/day

The lifetime liquid fuel savings for these PHEV configurations with longer daily distances are less than those realized in the 80 km/day case. As seen in Figure , liquid fuel savings decrease with added battery capacity due to longer daily distances, an earlier transition to CS operation, and a battery mass penalty. On the NYCC and OC Bus drive cycles, the PHEV+60kWh and PHEV+80kWh configurations consume more lifetime fuel than the gHEV BSfL reference case. The same is true for the NYCC drive cycle and PHEV+40kWh configuration. The cost effectiveness of obtaining lifetime liquid fuel savings decreases with increasing battery capacity, and the $/L saved values are higher than those in the 80 km/day case.

Conclusion

Electric drive is well suited to medium duty parcel delivery vehicles. CS gHEV vehicles have already been successfully deployed by FedEx. The results of this analysis underscore the importance of targeted design and strategic deployment of EDVs to maximize reductions in fuel consumption and lifetime operating cost.

The results of this analysis show that the 60-kW power version of the gHEV BSfL configuration has lower lifetime costs, by virtue of lower fuel consumption but despite higher capital cost, than the 30 kW power configuration. In this analysis, for one drive cycle and daily distance combination (HTUF4, 40 km/day), fuel consumption and hardware costs were below those for a gHEV BSfL baseline with a low cost control strategy adjustment (PHEV+0kWh, 30 kW). For less kinetically intense, relatively short daily routes, lower power and smaller battery capacity PHEV configurations may provide lower lifetime costs due to reduced component costs and fuel consumption. In most smaller battery capacity cases, the 30 kW power level was the most cost effective. This is due primarily to lower mass associated with a relatively smaller battery.

Even in an optimistic future economic scenario, battery costs remain the primary driver in lifetime incremental cost. With the exception of the specific case referenced above, the PHEV configurations analyzed are currently ($3/gallon fuel and $700/kWh battery) and forecasted ($5/gallon fuel and $300/kWh battery) to be more expensive than the CS gHEV reference vehicle. PHEV configurations with smaller battery capacities (PHEV+20kWh) represent the lowest lifetime incremental cost option. However, minimizing the incremental lifetime cost, even for this lowest cost PHEV option, depends upon strategic route deployment. When extended over tens to hundreds of vehicles or more, large incremental costs should motivate fleet managers to assign EDVs to routes best suited for this technology.

The largest PHEV lifetime fuel savings are realized on shorter daily distances, where they are also the most cost effective. As daily distance driven increases, CD PHEV configurations, especially those with large batteries, can consume more lifetime fuel than a CS reference vehicle.

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Publications

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K. Class 8 Line-Haul Study with PACCAR

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Objectives

- Validate a line haul vehicle model using a large number of gear ratios

Approach

- Test the vehicle on test track and on-road testing
- Implement component and vehicle data into Autonomie
- Understand and reproduce shifting algorithm

Accomplishments

- Improved the conventional line haul vehicle model in Autonomie to better represent the Cummins smart torque engine technology
- Adjusted the rolling resistance coefficients based on tire wear
- Developed a realistic "fuel-economy" oriented shifting strategy consistent for manual gearboxes with a large number of ratios

Future Directions

- Understand and model different accessory loads for line haul applications

Introduction

Line-haul class 8 trucks can be found in multiple configurations by changing the engine, the transmission, the aerodynamic profile or the tires. Although Argonne has already been involved in class 8 line-haul validations, this collaboration work with Paccar focused on a different truck configuration and included test track and on-road testing.

After giving recommendations on the most useful testing scenarios for this type of trucks, Argonne worked on building and validating the vehicle model in Autonomie that led to critical findings in specific heavy-duty truck technologies.

Component Data Integration

The line-haul truck model used in this study was a Kenworth T660 with a Cummins ISX 425 engine and an 18-speed manual transmission. The high number of gear ratios made this validation work very challenging due to the possibilities of having gear skipping.

The first step of the collaboration work was to integrate all the specific component data. In particular, specific gearbox efficiencies were implemented as well as tire and aerodynamic initialization files.

Shifting Strategy

During the first round of testing, which occurred at Paccar Research Center test track, the truck driver was instructed to use different shifting patterns. Whether the driver is driving for performance (to minimize time) or fuel economy, the shifting pattern, and in particular the engine speeds at which the shifting will occur, will change dramatically. In order to develop a realistic shifting algorithm in the vehicle model, special attention was given to the most fuel-efficient shifting strategy.

From the test data analysis, the following was found regarding the shifting behavior:

- The two first gear ratios were never used by the driver, thus the truck always started in 3rd gear or higher.
- The driver skipped one gear when he was upshifting until he reached 11th gear and he then used all the available higher gear ratios.
- Upshifting occurred at an average speed of 1500 rpm.
- The driver always skipped one gear when he was downshifting regardless of the gear ratio number.
- Downshifting occurred at an average engine speed of 1000 rpm.

The comparison between the gear number in test and in simulation using the shifting algorithm based on the above rules is shown in Figure .

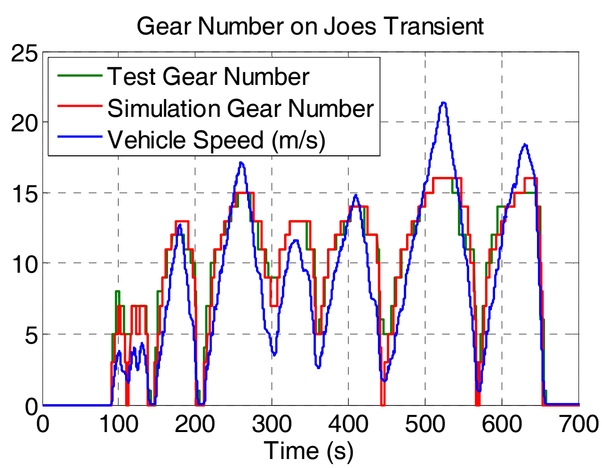

Figure 1. Gear number comparison between test and simulation

These findings were extremely useful to better understand the shifting behavior specific to gearboxes with a large number of ratios and reproduce it in simulation.

Smart Torque Engine Technology

When the validation work started, some significant discrepancies were immediately found in the engine torque signals between test and simulation. Since the discrepancies were even seen on steady states and were too large to assume differences in mechanical accessories, some research work was done on the engine technology itself. It was later found that the engine used in the Kenworth truck, which was assumed to be a regular Cummins ISX engine, actually included a Smart Torque technology. This feature of Cummins engines allows a different engine calibration to deliver additional torque when the vehicle is in the top two gear ratios (in this case 17th and 18th gears).

A new Autonomie engine model was developed to allow different maximum torque curves depending on the gear ratio.

Adjusted Tire Rolling Resistance Coefficients

In this validation work, Paccar provided Argonne with the rolling resistance coefficient, frontal area and drag coefficient to properly model the vehicle losses. The rolling resistance coefficients were,, however,, later adjusted to take into account tire wear. For the drive axles, the rolling resistance can be lowered by as much as 35% between a brand new tire and an end-of-life one. For the steering axle, the difference can reach 20% and 15%for the trailer tires. It was thus very important to know the amount of wear for each tire of the truck to properly estimate the rolling resistance coefficients.

Test Track Related Issues

The truck was tested on a 1.63 mile oval test track with banked turns (see Figure 2).

Figure 2. Paccar Test Track

The impact of the banked turns was very significant on the engine torque signal. Variations of 400 Nm were noticed when analyzing the test data (see Figure 3). Also a slight grade change (0.8% positive or negative) was also found on the test track. Finally, due to the possibility of having a head, tail or side wind on the truck, additional discrepancy was seen between the test and the simulation.

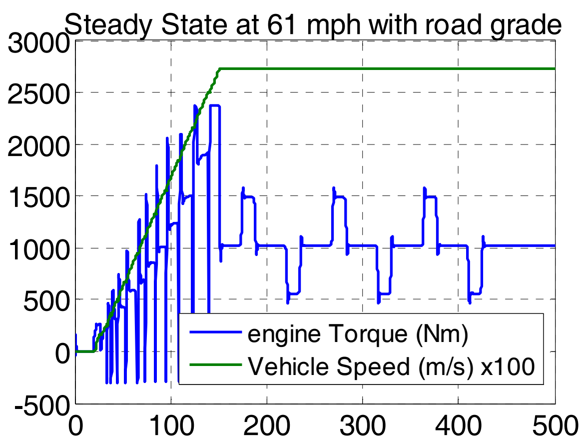

Figure 3. Engine torque during steady state testing

Argonne recommended additional testing with a better characterization of the outside parameters (wind, banked turns and grade) that were not reported after the first round of tests. A second round of tests followed this recommendation. In particular, the wind was measured by a weather station at the test track and Paccar had planned to reconstruct the wind speed seen by the truck and include this signal to the drive cycle in the vehicle model.

Conclusions

Some critical aspects of heavy duty truck technologies were found and assessed during this collaboration project. In particular, Argonne was able to improve the conventional line haul vehicle model in Autonomie to better represent the Cummins smart torque engine technology, to adjust the rolling resistance coefficients based on tire wear and develop a realistic "fuel-economy" oriented shifting strategy consistent for manual gearboxes with a large number of ratios.

L. PEV Cabin and Battery Thermal Preconditioning Analysis

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Objective

- Assess the impact of climate control system loads on plug-in electric vehicle (PEV) charge depleting (CD) range and fuel consumption. Evaluate the benefits of off-board powered thermal preconditioning on vehicle performance and battery life.

Approach

- Assemble models of three relevant PEV platforms (PHEV15, PHEV40s, and EV).
- Develop air conditioning and heater load profiles for each PEV platform.
- Simulate CD range and fuel consumption for each PEV, with and without thermal preconditioning.
- Pair battery operating temperature profiles with three ambient temperature conditions to simulate battery capacity loss and resistance growth with time.

Accomplishments

- Illustrated significant impact of climate control system loads on CD range (up to 35% reduction) and fuel consumption.
- Quantified benefit of off-board powered PEV cabin preconditioning in partial restoration of CD range (up to 19%).
- Characterized battery life reduction in climates with higher ambient temperatures; off-board powered PEV battery preconditioning has some benefit in reducing capacity loss (2-7%) and resistance growth.

Future Directions

- Instrument test vehicles, acquire data to calibrate models.
- Identify ambient temperature trends for several geographic areas, and integrate with analysis.

Introduction

Production and sales of plug-in hybrid electric and electric vehicles are forecasted to increase in the coming years. PEVs are viewed as a means to reduce liquid petroleum fuel consumption by using a greater fraction of electrical energy supplied by an on-board battery. The charge-depleting (CD) range of a PEV is limited by on-board battery capacity, which is used not only for driving but also other loads. Notably, climate control loads (heating and cooling) can reduce the PEV's CD range and/or cause the internal combustion engine to operate more frequently. Climate control loads increase PEV operating costs (liquid fuel and battery wear) and diminish the PEV's intended usability (decreased CD range). PEVs represent a unique opportunity to thermally precondition a vehicle when it is plugged into an off-board power source. During hot or cold weather, the climate control load on the on-board power source is high at startup to cool down or warm up the vehicle from a thermal-soaked condition to a comfortable condition. If the cool down or warm up can be accomplished during battery charging, the higher transient climate control load on the power source could be eliminated. The reduction of the climate control load due to preconditioning has the potential to reduce fuel consumption and partially restore CD range. Additional advantages include improved battery life, improved occupant thermal comfort, and potentially improved safety due to enhanced driver vigilance.

Approach

This section describes the approach to vehicle selection, model development and calibration, fuel economy calculation, climate control load profile development, battery life modeling, and climate control scenarios.

Vehicle Selection

PEVs that operate in CD mode at the beginning of a trip can potentially benefit from off-board powered thermal preconditioning. The most relevant PEV platforms that are scheduled for near-term market release are:

PHEV15—a blended PHEV with an approximately 15-mile (23.4-km) all-electric range (AER) under certain usage conditions.

PHEV40s—a series PHEV designed to provide up to 40 miles (64 km) of AER, then operate in charge-sustaining (CS) mode using a range-extending gasoline engine.

EV—an EV designed to provide up to 100 miles of AER.

All three PEVs use electric heating and cooling climate control systems.

Vehicle Model Development

Vehicle models were assembled using the Powertrain Systems Analysis Toolkit (PSAT). Relevant vehicle model specifications for each vehicle platform are presented in Table 1.

Table 1. Vehicle Model Inputs

	PHEV15	PHEV40s	EV
C_d	0.25	0.28	0.29
Frontal Area (m^2)	2.07	2.09	2.33
Vehicle Mass (kg)	1,490	1,588	1,271
Engine Power (kW)	73	53	NA
Motor Power (kW)	60, 42	100	80
Battery Capacity (kWh)	5.2	16	24
Battery Delta State of Charge (SOC)	66%	54%	84%
Battery Maximum SOC	80%	80%	95%
Battery Thermal Management Strategy	Air cooling	Liquid cooling	No active cooling
Battery Heat Transfer Coefficient (W/m^2K)	20	110	0
Accessory Load (W)	300	300	300

Vehicle Model Calibration

Once assembled, the models were calibrated based on fuel consumption in CS mode, CD range, and acceleration performance. Generally, the simulated results fell within 10% of the published data (.

Table .

Table 2. Vehicle Model Calibration Results

	PHEV15	PHEV40s	EV
CD Range (km)			
Published	23.4	64.4	160.9
Simulated	24.9	66.3	168.8
Error	+6.6%	+3.0%	+4.9 %
Fuel Consumption CS Mode (L/100km)			
Published	3.27	4.70	NA
Simulated	3.42	4.39	NA
Error	+4.59%	-6.60%	
0-60 mph Acceleration			
Published	10.9	8.5	NA

Simulated	9.6	8.9	NA
Error	-11.9%	+4.7%	

Fuel Economy and CD Range Calculations

A series of steps is used to estimate conventional and hybrid electric vehicle fuel economy. Before 2008, the U.S. Environmental Protection Agency (EPA) estimated vehicle fuel economy using two cycles, one representing city driving, and the other representing highway driving. Since these tests underestimated the amount of fuel use consumers would typically experience, each test result was multiplied by an adjustment factor. A weighted average was then used to combine the two adjusted test results.

In 2008, three more cycles were added to the test procedure to improve the fuel economy estimate. The five-cycle test procedure would take especially long to run for PHEVs. PHEVs have two fuel economies that characterize their performance on a drive cycle, the CD fuel economy and the charge sustaining (CS) fuel economy. Both estimates are needed to calculate a combined average based on how much driving is done in each mode. To calculate the two fuel economies, each drive cycle must be repeated until the vehicle depletes the battery and runs one complete CS mode cycle. Repeating five cycles multiple times is computationally intensive.

EPA derived a two-cycle approximation of the five-cycle test, as seen below in equations (1) and (2). This was used in this study to reduce computational time. For the PHEVs, the two-cycle approximation is used for CD mode and CS mode, as described in 1. A weighted average of the two different mode fuel economies is then calculated based on statistics that show the distance typically driven in each mode.

$$City\ MPG = 1/(.003259 + \frac{1.1805}{UDDS\ MPG}) \quad (1)$$

$$Highway\ MPG = 1/(.001376 + \frac{1.3466}{HFET\ MPG}) \quad (2)$$

The CD range estimate used for the fuel economy calculation would not work for this study. It is based on discrete cycle increments, which would not capture the shorter cycle changes caused by preconditioning. Instead, this study used SOC values to estimate the CD range. Specifically, the CD distance was defined as the distance at which the SOC first reaches the average CS SOC plus 1%. One percent SOC was added to the average CS SOC to improve the consistency of the method. Without the addition, the CD range did not consistently line up well with where the SOC leveled out.

A similar approach was used to estimate the range of the EV. This approach also used the two-cycle approximation of the five-cycle test procedure. Also, like the way each cycle was repeated multiple times for the PHEVs to estimate CD and CS mode fuel economies, the cycles were repeated twice for the EV to account for the higher heating or A/C load during the first cycle. Each depletion rate was then converted to a miles per gallon gasoline equivalent and adjusted using the two-cycle approximation equations. Unlike the PHEVs, a 30% fuel consumption adjustment ceiling was used to prevent the equations from extrapolating too far outside their intended domain. The two adjusted cycle consumption rates were then averaged based on the distance that would be driven in each mode, similar to how the CS and CD modes were averaged for PHEVs. Finally, the averaged adjusted city and highway results were average-weighted 55% and 45%, respectively, to come to a single fuel consumption rate. This rate was then multiplied by the usable capacity to estimate the total range.

Climate Control Loads

A climate control load is divided into two parts:

Transient—After a thermal soak, the transient climate control is characterized by a high initial load that decreases with time. An example is entering a hot vehicle after parking in the sun, driving, and having the air conditioning (A/C) on with maximum blower airflow to cool the interior. Vehicles have different transient times due to a variety of factors based on manufacturer design choices. We selected 10 minutes as a representative transient duration.

Steady State—During steady state, the impact of the thermal soak has been diminished. The climate control system maintains the thermal conditions in the passenger compartment. An example is driving down the interstate in the winter and having a moderate heat setting with the blower on low.

Thermal preconditioning eliminates the transient climate control load on the battery. In this situation, the on-board power supply has only to provide the steady-state climate control load. We surveyed literature and test data to develop representative A/C and heater load profiles for our simulation vehicles.

Cooling

For the A/C load, we constructed a load vs. time profile that was representative across our range of vehicles. Table shows the range of vehicle types, environments, and A/C systems from a variety of sources that we considered.

Table 3. Cooling Load Data Sources

Source	Vehicle	Environment	A/C
SAE ARCRP [2]	N/A, bench data	Hot	Mechanical
ANL [3]	Small EV	Moderate	Electrical
NREL [4]	Prius	Hot	Electrical
Ford [5]	Fusion	Hot	Electrical
ANL [3]	Mercedes S400	Moderate	Electrical
Visteon [6]	midsized SUV	Hot	Mechanical

The data from these sources were averaged to create a composite load profile. The 10-minute transient load was applied to the model as a linear decay from a peak power of 3.89 kW at the start of the drive to a 2.10-kW steady-state load. This equates to an average transient load of 2.99 kW for the 10-minute period (Table). For the thermal preconditioning case, the steady-state load of 2.1 kW is applied at the start of driving. Additionally, an electric condenser fan is assumed to draw 150 W during the 10-minute transient and 50 W during the steady-state period [7].

Heating

For the electric heating load, it was not possible to define a single load profile for all vehicles because of the different control strategies to use electric power in PHEVs and the availability of waste heat in some vehicles. We reviewed the literature and defined composite electric heating loads for a PHEV15, PHEV40s, and EV. Table 4 shows the vehicle types and environments we considered from a variety of sources.

PHEV15- The electric heaters transition from 4 kW to 0 kW in 10 minutes as waste heat becomes available in the no thermal preconditioning scenario. For the thermal preconditioning scenario, the electric heater is not used. As the vehicle begins to operate in CS mode and the engine operates intermittently, waste heat will be available for cabin heating.

PHEV40s and EV- There is no waste engine heat, and all the heating power is supplied by electric heaters. There is a peak load of 6 kW initially that decreases to 2 kW at 10 minutes (Table 5). For the thermal preconditioning scenario, the 2 kW load is applied at all time points during the simulation.

Table 4. Heating Load Data Sources

Source	Vehicle	Environment
Behr [8]	analysis	cold
ANL [3]	small EV	moderate
GM [9]	conventional	cold
Ford [10]	EV	cold
GM [11]	HEV	cold
Valeo [12-14]	EV	cold

Table 5. Climate Control Load Profiles

Mode	Vehicle	Peak Load (kW)	Average Transient Load (kW)	Steady-state Load (kW)
A/C	all	3.89	2.99	2.1
heat	PHEV15	4	2	0
heat	PHEV40 s and EV	6	4	2

In the development of the SAE mobile A/C life cycle climate performance model, it was assumed that the blower was operated any time the vehicle was operated [15]. Our analysis was consistent with this, and a 150-W blower load was applied during all runs.

Battery Life

Battery aging is caused by multiple phenomena related to both cycling and calendar age. Battery degradation is accelerated with the depth-of-discharge (DoD) of cycling, elevated temperature, and elevated voltage exposure, among other factors. Worst-case aging conditions drive the need to oversize batteries to meet warranty requirements. Systems and controls, such as thermal preconditioning, may be able to lessen the impact of some of these conditions.

At the battery terminals, the observable effects of degradation are an increase in resistance and a reduction in capacity. These two effects can be correlated with power and energy loss that cause battery end-of-life in an application. Mechanisms for resistance growth include loss of electrical conduction paths in the electrodes, fracture and isolation of electrode sites, growth of film layers at the electrode surface, and degradation of electrolyte. Mechanisms for capacity loss include fracture, isolation, and chemical degradation of electrode material, as well as loss of cyclable lithium (Li) from the system as a byproduct of side reactions.

Under storage or calendar-aging conditions, the dominant fade mechanism is typically growth of a resistive film layer at the electrode surface. As the layer grows, cyclable Li is also consumed from the system, reducing capacity. In the present model, resistance growth and Li-capacity loss are assumed to be proportional to the square-root of time, $t^{1/2}$, typical of diffusion-limited film-growth processes. Under cycling-intense conditions, degradation is mainly caused by structural degradation of the electrode matrix and active sites. Cycling-driven degradation is assumed to be proportional to the number of cycles, N.

Cell resistance growth due to calendar- and cycling-driven mechanisms are assumed to be additive,

$$R = a_0 + a_1 t^{1/2} + a_2 N \qquad (3)$$

Cell capacity is assumed to be controlled by either loss of cyclable Li or loss of electrode sites,

$$Q = \min(Q_{Li}, Q_{sites}) \qquad (4)$$

where

$$Q_{Li} = b_0 + b_1 t^{1/2}, \text{ and} \qquad (5)$$

$$Q_{sites} = c_0 + c_1 N \qquad (6)$$

Models (3), (5), and (6) are readily fit to a resistance or capacity trajectory measured over time for one specific storage or cycling condition. Using multiple storage and cycling datasets, functional dependence can be built for rate constants $a_1(T, V, \Delta DoD)$, $a_2(T, V, \Delta DoD)$, $b_1(T, V, \Delta DoD)$, $c_1(T, V, \Delta DoD)$. The present battery life model was fit to laboratory aging datasets [16-19] for the Li-ion graphite/nickel-cobalt-aluminum (NCA) chemistry as described in [19]. The NCA chemistry has generally graceful aging characteristics, and is expected to achieve 8 or more years of life when sized appropriately for a vehicle application.

Climate Control and Temperature Scenarios

Battery degradation is greatly affected by temperature, both while the vehicle is driving as well as while the vehicle is parked. Battery temperature when parked will be affected by recent driving history, outside ambient conditions, and heat dissipation path to outside ambient conditions where those ambient conditions have strong daily and annual variations. As an initial study, the present work neglects temperature variation due to variable ambient conditions.

Each climate control scenario incorporated an ambient temperature condition. For scenarios that include thermal preconditioning, the battery pack temperature was adjusted from ambient temperature. That is, for thermal preconditioning scenarios, the battery was warmed above a cold ambient temperature or was cooled below a hot ambient temperature over a 20-minute period prior to driving. These climate control, ambient, and battery pack temperature scenarios are presented in Table 6.

Table 6. Climate Control, Temperature Scenarios

Climate Control Scenario	Ambient Temp.	Thermal Preconditioning	Initial Battery Temp.
A/C on (hot)	35°C	yes	26.7°C
		no	35°C
Heat on (cold)	-6.7°C	yes	1.7°C
		no	-6.7°C
Neither A/C nor heat on	20°C	NA	20°C

Twenty-four–hour profiles for battery temperature were created using battery heat generation rates taken from previously described vehicle simulations. As shown in Figure , the profiles assume a daily travel distance of 52.8 km/day (33 miles/day), divided into two driving trips, one at 8:00 a.m. and one at 5:00 p.m. Battery charging occurs at 10:00 p.m. at a 6.6-kW rate. For cases with thermal preconditioning, the two daily driving trips are preceded by a 20-minute ramp to the preconditioned temperature.

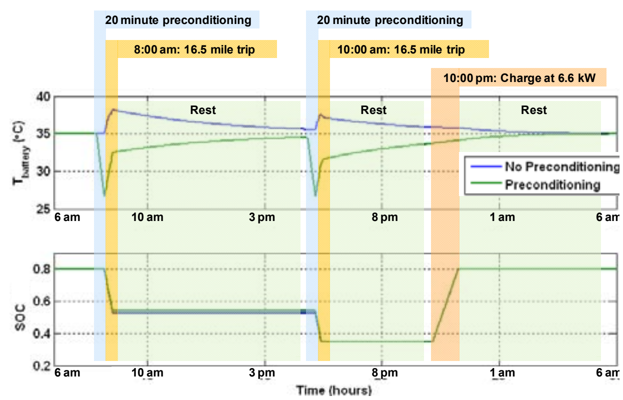


Figure 1. Battery temperature and SOC profiles for PHEV40s, 35°C ambient temperature, with and without thermal preconditioning

Results

This section presents the results of vehicle performance and battery life analyses for the range of climate control system usage, ambient and battery temperature, and thermal preconditioning scenarios.

Vehicle Performance

Fuel consumption and CD range were simulated for each vehicle platform, with and without thermal preconditioning, for each climate control scenario. Results indicate the relatively large impact of climate control on CD range reduction, as well as the benefit of thermal preconditioning in avoiding climate control system-induced battery discharge.

Figure 2 presents results for the PHEV15. This vehicle was modeled to use both engine and battery as needed in a blended fashion. Using heat increases fuel consumption by 3.3% and decreases the CD range by 19.5%. Using A/C increases fuel consumption by 49.3% and decreases the CD range by 32.3%. Thermal preconditioning provides measureable benefits by reducing the initial climate control system load. Compared to no thermal preconditioning, thermal preconditioning with heat decreases fuel consumption by 1.4% and increases CD range by 19.2%. Compared to no thermal preconditioning, thermal preconditioning with A/C decreases fuel consumption by 0.6% and increases the CD range by 5.2%.

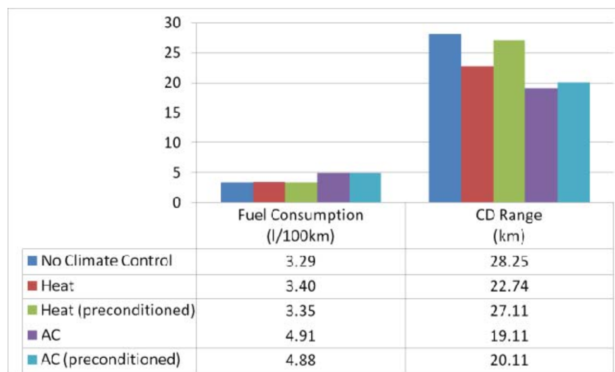
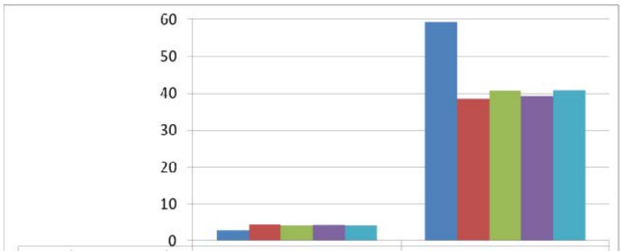


Figure 2. PHEV15 performance

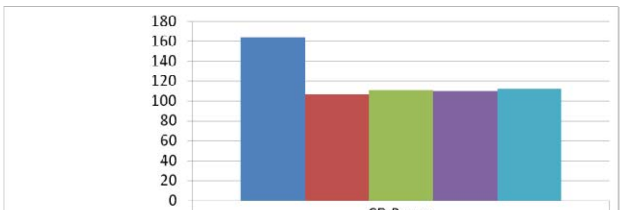
Figure presents results for the PHEV40s. Using heat increases fuel consumption by 60.7% and decreases the CD range by 35.1%. Using A/C increases fuel consumption by 56.8% and decreases the CD range by 34%. Compared to no thermal preconditioning, thermal preconditioning with heat decreases fuel consumption by 2.7% and increases the CD range by 5.7%. Compared to no thermal preconditioning, thermal preconditioning with A/C decreases fuel consumption by 1.5% and increases the CD range by 4.3%.



No Climate Control	2.73	59.34
Heat	4.39	38.50
Heat (preconditioned)	4.28	40.69
AC	4.29	39.15
AC (preconditioned)	4.22	40.84

Figure 3. PHEV40s performance

Figure 4 presents results for the EV. Using heat decreases the CD range by 34.7%. Using A/C decreases the CD range by 32.7%. Compared to no thermal preconditioning, thermal preconditioning with heat increases the CD range by 3.9%. Compared to no thermal preconditioning, thermal preconditioning with A/C increases the CD range by 1.7%.



	CD Range (km)
No Climate Control	163.79
Heat	106.98
Heat (preconditioned)	111.14
AC	110.22
AC (preconditioned)	112.06

Figure 4. EV performance

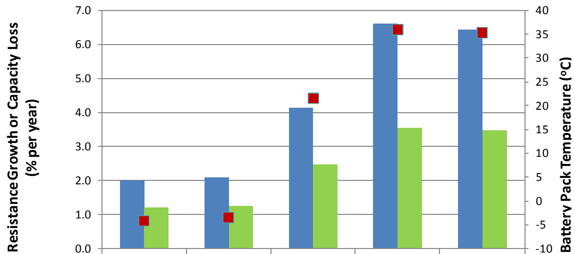
Battery Life Impacts

Battery 24-hour duty-cycle profiles were input into the life model described in Section 2.5 to simulate battery resistance growth and capacity fade over 10 years. Those results are presented here as a percent-per-year degradation rate. The primary factor causing different battery degradation rates between preconditioned and non-preconditioned cases is the battery temperature exposure. Non-thermally-preconditioned vehicles also experience slightly deeper battery discharges each day, although this is a minor factor in the present battery degradation predictions.

Figure 5 shows percent resistance growth per year (blue bar), percent capacity loss per year (green bar), and battery average temperature (red symbol) for the PHEV15 for the various constant ambient temperatures, with and without preconditioning. For reference, end-of-life is commonly defined when battery remaining capacity has reached 70% to 80% of beginning-of-life capacity. A 2.5% capacity loss per year would result in 80% remaining capacity after 8 years. For example, a 2.0% capacity loss per year in Figure would result in 80% remaining after 10 years. Ambient temperature has the strongest influence on battery degradation rates. Compared to the 20°C baseline case, the 35°C ambient case with no preconditioning increases capacity fade rates by 43%. The –6.7°C ambient case reduces fade by 52% relative to 20°C ambient.

Battery fade rates for actual geographic locations will be a composite of the constant ambient temperatures simulated here. In the United States, Phoenix, Arizona, is a typical worst-case high-temperature location, with annual and daily temperature variation expected to cause battery degradation similar to a 30°C constant temperature aging condition [20].

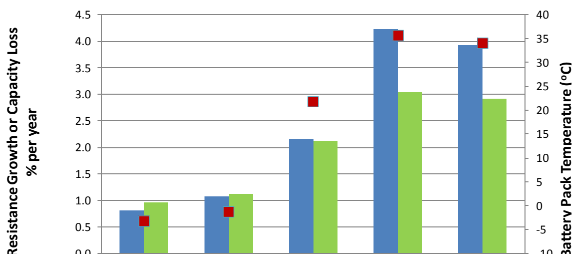
For the PHEV15 in Figure , thermal pre-heating at -6.7°C ambient has a slight negative impact on battery capacity loss, increasing fade rate by 4.5%. At such low temperatures, however, the small fade rates are relatively inconsequential. Hot ambient conditions will derive the most benefit from thermal pre-cooling. At 35°C ambient temperature, pre-cooling decreases the capacity-fade rate by 2.1% for the PHEV15 with air-cooled battery. This reduction in the hot-climate fade rate can be used in either of two ways: (1) if battery size is fixed, a preconditioned battery will last longer than a non-preconditioned battery, or (2) if battery size is not fixed, a preconditioned battery can be sized slightly smaller (with lower cost) and still achieve the same life as a non-preconditioned battery.



	-6.7°C Ambient	-6.7°C Ambient (precond-itioned)	20°C Ambient	35°C Ambient	35°C Ambient (precond-itioned)
Resistance Growth	2.0	2.1	4.1	6.6	6.4
Capacity Loss	1.2	1.3	2.5	3.6	3.5
Average Temperature	-4.2	-3.4	21.6	35.9	35.2

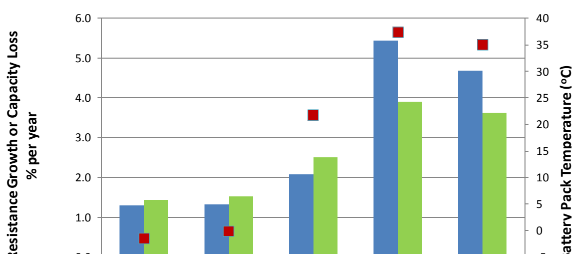
Figure 5. PHEV15 battery degradation rates (left axis) and average temperature (right axis)

Figure 6 and Figure show battery degradation rates for the PHEV40s and EV platforms, respectively. Trends are similar to the PHEV15. At 35°C ambient, thermal preconditioning reduces capacity-loss rate by 4.1% and 7.1% for the respective PHEV40s and EV platforms. Reductions in resistance-growth rate are 7.0% and 13.8% for the respective platforms.



	-6.7°C Ambient	-6.7°C Ambient (precond-itioned)	20°C Ambient	35°C Ambient	35°C Ambient (precond-itioned)
Resistance Growth	0.8	1.1	2.2	4.2	3.9
Capacity Loss	1.0	1.1	2.1	3.0	2.9
Average Temperature	-3.2	-1.3	21.7	35.7	34.0

Figure 6. PHEV40s battery degradation rates (left axis) and average temperature (right axis)



	-6.7°C Ambient	-6.7°C Ambient (precond-itioned)	20°C Ambient	35°C Ambient	35°C Ambient (precond-itioned)
Resistance Growth	1.3	1.3	2.1	5.4	4.7
Capacity Loss	1.4	1.5	2.5	3.9	3.6
Average Temperature	-1.5	-0.2	21.7	37.4	35.0

Figure 7. EV battery degradation rates (left axis) and average temperature (right axis)

In summary, pre-cooling of electric-drive vehicle batteries is predicted to reduce capacity fade by 2.1% to 7.1% and resistance growth by 3.0% to 13.8% in hot (35°C) ambient conditions. In a hot geographic location such as Phoenix, Arizona, (where degradation due to fluctuating ambient temperature is similar to constant 30°C aging), the realized reduction in battery degradation will be slightly less. The three vehicle platforms each derive slightly different benefits from pre-cooling, partly due to the assumed battery thermal management strategies (Table 1) and partly due to the size of each vehicle's battery. Battery temperature rise results from multiple factors, namely battery thermal mass, heat generation rate while driving, and rate of active cooling. Energy storage systems that benefit most from pre-cooling will be those with small battery thermal mass, those with high heat generation rates, and those with limited or no active cooling while driving. Each of these systems is likely to experience a large temperature rise while driving and will benefit from starting a driving trip with a pre-cooled battery.

Conclusions

This analysis shows that climate control system loads can significantly increase fuel consumption (up to 60.7%) and decrease CD range (up to 35.1%) in PEVs. Off-board powered thermal preconditioning of a vehicle cabin is one way to reduce the negative impact of climate control system loads. When compared to no thermal preconditioning, thermal preconditioning can provide a moderate reduction in fuel consumption (up to 2.7%). However, thermal preconditioning can partially restore CD range (up to 19.2%). The restoration of several kilometers of CD range may resonate with consumers for whom "range anxiety" is an issue and potential barrier to widespread adoption of PEVs.

Pre-cooling of electric-drive vehicle batteries is predicted to reduce capacity fade by 2% to 7% and resistance growth by 3% to 14% in hot (35°C) ambient conditions. Vehicles that benefit most from battery pre-cooling will be those with small battery thermal mass or high heat generation rates (i.e., PHEVs with a short electric range) and those with limited battery active cooling systems.

Off-board powered thermal preconditioning has benefits to the consumer via CD range extension and less expensive energy costs (electricity versus liquid fuel and/or battery capacity), as well as vehicle manufacturers via extended battery life and avoided warranty claims.

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M. Development of Models for Advanced Engines and Emission Control Components

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Objectives

- Develop component models that accurately reflect the drive performance, cost, fuel savings, and environmental benefits of advanced combustion engines and after-treatment components as they could potentially be used in leading-edge hybrid electric and plug-in hybrid electric vehicles (HEVs and PHEVs).
- Apply the above component models to help the Department of Energy (DOE) identify the highest HEV and PHEV R&D priorities for reducing U.S. dependence on imported fuels as well as regulating pollutant emissions.

Approach

- Develop, refine and validate low-order, physically consistent computational models for emissions control devices including three-way catalysts (TWCs), diesel oxidation catalysts (DOCs), lean NOx traps (LNTs), diesel particulate filters (DPFs), and selective catalytic reduction reactors (SCRs) that accurately simulate HEV and PHEV performance under realistic steady-state and transient vehicle operation;
- Develop, refine and validate low-order, physically consistent computational models capable of simulating the power out and exhaust characteristics of advanced diesel and spark-ignition engines operating in both conventional and high efficiency clean combustion (HECC) modes;
- Develop and validate appropriate strategies for combined simulation of engine, after-treatment, and exhaust heat recovery components in order to accurately account for and compare their integrated system performance in conventional, HEV, and PHEV powertrains;
- Translate the above models and strategies into a form compatible with direct utilization in available vehicle systems simulation software;
- Leverage the above activities as much as possible through inclusion of experimental engine and after-treatment data and models generated by other DOE activities.

Accomplishments

- Constructed and validated new ammonia selective catalytic reduction (SCR) and diesel oxidation catalyst (DOC) models and applied them in evaluating the emissions and fuel efficiency performance of hybrid and plug-in hybrid electric vehicles (HEVs and PHEVs) powered by diesel engines.
- Compared the relative fuel efficiency and emissions performances of various combinations of SCR, lean NOx traps (LNTs), and diesel particulate filters (DPFs) in HEVs and PHEVs.
- Evaluated the potential fuel efficiency and emissions benefits of thermal insulation on after-treatment trains in both gasoline and diesel HEVs and PHEVs.
- Published a methodology for simulating engine-out species and temperatures variations during cold and warm-start-up transients (International Journal of Engine Research, 2010, 11(2), 137-152).

- Published an LNT model for lean NOx control in vehicle systems simulations (SAE International Journal of Fuels and Lubricants, 2010, 3(1), 468-485).

Future Directions

- Demonstrate HEV and PHEV simulations with lean homogeneous charge compression ignition (HCCI) and direct-injected gasoline combustion.
- Evaluate the impact of combined three-way catalyst (TWC) and LNT after-treatment on emissions and fuel efficiency in HEVs and PHEVs powered with lean direct-injected gasoline engines.
- Continue refining models for LNTs, DPFs, and TWCs.
- Continue refinement and testing of the DOC/SCR/DPF combinations for lean exhaust and use these to assess of the impact of various operating and control strategies on HEV and PHEV fuel efficiency and emissions performance.
- Identify any potential HEV/PHEV efficiency and emissions advantages for after-treatment combinations of LNT and SCR.
- Begin development of a HC trap model that can account for HC storage at cold start and release at the following warm condition.
- Implement and validate transient engine-out and after-treatment models in Autonomie.
- Continue comparisons of diesel and gasoline HEV and PHEV fuel efficiency and emissions under the innovative combinations of emissions control devices.
- Coordinate with the Combustion MOU, ACEC, DCC Team, CLEERS to ensure access to the latest engine/emissions technology information and industry needs.

Introduction

Accurate predictions of the fuel efficiency and environmental impact of advanced vehicle propulsion and emissions control technologies are vital for making informed decisions about the optimal use of R&D resources and DOE programmatic priorities. One of the key modeling tools available for making such simulations is the Powertrain System Analysis Toolkit (PSAT) created by Argonne National Laboratory (ANL). ANL will be formally releasing a new software tool known as Autonomie to replace of PSAT soon. A distinctive feature of both PSAT and Autonomie is their ability to simulate the transient behavior of individual drive-train components as well as their combined performance effects under realistic driving conditions. However, the accuracy of PSAT/AUTONOMIE simulations ultimately depends on the accuracy of the individual component sub-models or maps. In some cases of leading-edge technology, such as with engines utilizing high efficiency clean combustion (HECC) and lean exhaust particulate and nitrogen oxide (NOx) controls, the availability of appropriate component models or the data to construct them is very limited.

Oak Ridge National Laboratory (ORNL) is specifically tasked with providing data and models that enable hybrid vehicle systems simulations with advanced engines and emissions controls. Specifically, ORNL has focused on detailed experimental measurement of emissions and fuel efficiency for advanced diesel and lean-burn gasoline engines and their associated emission control components. These data have been transformed into maps and low-order transient models that can be used to simulate vehicle performance in vehicle simulation software such as PSAT and Autonomie.

In FY2010, the ORNL team concentrated on implementing the following after-treatment models in diesel HEV and PHEV simulations:

- A urea-SCR component model for lean NOx control;
- A DOC model that accurately accounts for oxidation of hydrocarbons, CO, and NO in lean-exhaust; and

- Combinations of DOC, urea-SCR, LNT, and DPF/CDPF components that reflect the integrated behavior of complete after-treatment trains.

The above models were used to conduct several case studies of different options for diesel HEV and PHEV emissions control and comparisons between diesel and conventional gasoline HEVs and PHEVs. These studies included:

- Evaluation of the impact of thermal insulation on improving the light-off response of after-treatment devices during repeated engine start/stop events in both diesel and gasoline HEVs and PHEVs;
- Evaluation of the combined fuel efficiency and emissions performance of DOCs and DPFs coupled to SCR and LNT catalysts; and
- Comparison of the relative benefits of urea-SCR and LNT catalysts for lean NOx control in diesel HEVs and PHEVs.

In addition, journal publications were issued documenting the ORNL LNT model and also the methodology for transient engine-out exhaust simulations in the open literature.

Approach

Most current HEV and PHEV engines utilize stiochiometric engines, which are the predominant technology in most passenger cars in the U.S. today. In these engines, the fuel and air are balanced so that there is no excess oxygen present in the exhaust. With stoichiometric engines the emissions can be very effectively controlled with TWC after-treatment technology. The greatest needs for improving simulations of hybrid vehicles utilizing stoichiometric engines involve development of engine maps and models that accurately predict emissions and exhaust temperature as functions of speed and load under the highly transient conditions in normal drive cycles. Also, improved models are needed to capture the effects of start/stop transients in hybrid vehicles on the functioning of 3-way catalysts, since the latter have been developed for more continuous engine operation than what occurs in hybrids.

Advanced combustion engines offer the potential for significantly increasing the fuel efficiency of hybrid vehicles. These engines rely on lean combustion conditions (i.e., conditions where air is present in significant excess) and novel combustion states (e.g., HECC) where there is little or no flame present. While beneficial in reducing emissions, such lean combustion also involves larger and more drastic transient shifts in engine operation as driving demands change. Even though emissions are significantly reduced, they are still present in sufficient amounts to require exhaust after-treatment subsystems for removing NOx and particulate matter (PM).

Both NOx and PM removal from lean exhaust involve complex transient and hysteretic interactions with the engine. One of the most prominent lean NOx control technologies, LNTs, imposes a significant fuel penalty because of the need to periodically shift the exhaust from lean to rich to remove adsorbed nitrates from the catalyst surface. The other major lean NOx control technology, urea-SCR, requires precise control of a urea dosing system that must be closely integrated with engine controls. Current lean exhaust particulate controls consist of DPFs which trap and periodically oxidize the engine particulates. Like LNTs, DPFs require large transients in engine operation that consume additional fuel. Simulation of such complicated behavior makes it necessary to build more sophisticated component models that exploit the known physics and chemistry of these devices as well as the best available experimental data.

Considering the above, the ORNL modeling team is building stoichiometric and lean after-treatment component models for vehicle systems simulations that utilize proven approaches for simulating transient catalytic reactors. The basic elements of these models include:

- Detailed time resolved information on the flows, species, and temperatures entering the device;
- Differential, transient mass balances of key reactant species;

- Localized surface and gas-phase reaction rates;
- Differential, transient energy balances and temperatures within the device;
- Time resolved flow, species, and temperature for the gas stream exiting the device.

As much as possible, the descriptions of the internal reaction and transport processes are simplified to account for the dominant effects and physical limits while maintaining execution speeds acceptable for typical systems simulations. For example, there are no cross-flow (i.e., radial) spatial gradients accounted for in the devices and the kinetics are defined in global form instead of elementary single reaction steps. This 'in-between' level of detail still allows for faithful simulation of the coupling of the after-treatment devices to both upstream and downstream components (arranged in any desired configuration). With the above information it is also possible to determine both instantaneous and cumulative systems performance for any desired period.

Due to the greater complexity of engines, it is not practical to develop models with the same level of dynamic detail as in the after-treatment component models. Instead, the usual approach for engine modeling relies on tabulated 'maps' developed from steady-state or pseudo-steady-state experimental engine-dynamometer data. Recently, it has been possible to develop maps that extend over both conventional and HECC operating ranges. Another key feature remaining to be added is an engine control sub-model that determines how the engine should operate (e.g., make transient shifts in combustion regime) in order to accommodate the needs of after-treatment devices downstream. Typically this also involves development of sensor models that indicate the state of the after-treatment devices.

In future work, it is anticipated that experimental engine data can be supplemented with engine cycle simulations using large and complex engine simulation codes such as GT Power, which can account for many different effects and operating states that may be difficult to measure experimentally. It is expected that the results from these codes can be captured in more sophisticated formats (e.g., neural networks) than is possible with simple tabulated maps.

Results

After-treatment Model Development.

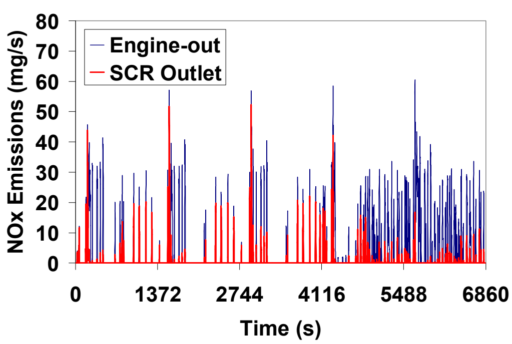
Urea SCR is the leading competitive technology to LNTs for lean NOx emissions control. The basic concept behind urea-SCR is the catalytic reduction of NOx in the exhaust using ammonia generated from the thermal decomposition of aqueous urea stored on board the vehicle. The urea solution is injected at a controlled rate into the hot exhaust to generate the ammonia, and the ammonia-exhaust mixture then passes through a monolithic SCR catalyst where the NOx reduction occurs.

We constructed a low-order urea-SCR component model based on a transient, one-dimensional representation of the key NOx reducing reactions in lean exhaust as it flows through a catalytic monolith. Three key SCR reactions considered in the current implementation include the standard reaction between NH_3 and NO, the fast reaction between NH_3 with NO and NO_2, and the NH_3-NO_2 reaction. NH_3 adsorption and desorption, as well as NH_3 oxidation and NO oxidation, are also included. Kinetic rate constants were derived from experimental data generated by the CLEERS activity for a Cu-ZSM-5 catalyst. The model was then validated with experimental data from the open literature [1].

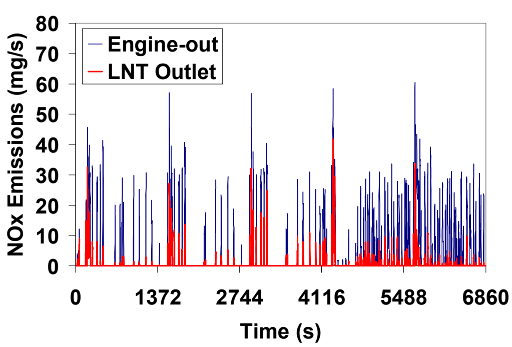
In addition to removing hydrocarbons and CO from exhaust, DOCs are critical for lean NOx and particulate control because they oxidize NO to NO_2. The NO_2 in turn enhances the rates of NOx reduction and particulate oxidation. This year we continued improving and validating our DOC model against more experimental diesel engine data from an open literature [2] over a range of loads covering 5%-100% at the engine speed of 1400rpm-2200rpm. The DOC model predictions and literature data agreed within a few percent for oxidation of CO, NO, and hydrocarbons over a temperature range of 131°C to 491°C. The DOC model is configured so that it can be located in multiple ways relative to other after-treatment components, allowing simulation of multiple engine-after-treatment system configurations for diesel and lean gasoline hybrid vehicle studies.

Hybrid Vehicle Case Studies

One area of high interest is the relative fuel economies of diesel hybrid vehicles utilizing LNT vs. urea-SCR for NOx control. To begin addressing this, we simulated a diesel-powered PHEV operating with either a 2.4-L LNT or a 2.4-L urea-SCR for NOx control. In these cases, only NOx after-treatment was considered and no DPF or DOC was included. Figure 1 illustrates the tailpipe NOx emissions from the diesel-powered PHEV with SCR and LNT catalysts over five consecutive UDDS cycles beginning with a cold start.



(a) NOx reduction in SCR



(b) NOx reduction in LNT

Figure 1. Comparison of tailpipe NO_x emissions between SCR and LNT catalysts for a diesel-powered passenger PHEV over five consecutive UDDS cycles beginning with a cold start.

The fuel economies of the SCR and LNT PHEVs are 136.4mpg and 133.8 mpg, respectively. Regeneration of the LNT causes a 1.9% fuel penalty, while the SCR generates 0.068g/mile NH_3 slip. The tailpipe NOx emissions of the SCR system are also slightly higher (0.16g/mile vs. 0.15g/mile). It appears that the SCR system performance is reduced by catalyst cool down as well as by a non-optimal urea dosing strategy. These results suggest that dosing strategy improvements could further improve urea-SCR performance relative to LNT.

Since actual vehicles require combinations of all the above mentioned devices for emissions controls, we began investigating the impact of combined DOC, LNT, SCR, and catalyzed DPF devices on fuel efficiency and emission in a 1450 kg HEV powered by a 1.5-L diesel engine. Two specific after-treatment trains were studied initially: (1) one consisting of a DOC, urea-SCR catalyst, and catalyzed DPF, and 2) another consisting of a DOC, LNT and catalyzed DPF. The sizes for the simulated DOC, LNT, SCR and catalyzed DPF were 0.59 liter, 2.4 liter, and 2.4 liter, and 1.9 liter, respectively. Simulations of the diesel-powered HEV were carried out over 80 consecutive UDDS cycles beginning with a cold start. Our simulations revealed that both the DOC-LNT-DPF and DOC-SCR-DPF combinations only required one DPF regeneration event over 80 consecutive UDDS cycles.

Another important observation here is the significant impact on fuel efficiency produced by both after-treatment options. Of the two trains, the fuel penalty for the DOC-SCR-DPF combination amounted to just 2.59%. This is considerably less than the 6.1% fuel penalty for the DOC-LNT-DPF combination, which included the penalty associated with LNT regeneration (not required by the SCR catalyst).

Figure 2 illustrates the associated tailpipe emissions for the above two diesel cases compared with conventional gasoline. CO and HC tailpipe emissions in the DOC-LNT-CDPF were higher than those for the DOC-SCR-CDPF. The higher CO and HC emissions result from reductant slip during LNT regeneration events. On the other hand, NOx tailpipe emissions for the DOC-LNT-CDPF were less than the DOC-SCR-CDPF and the DOC-SCR-CDPF combination involved potentially significant ammonia slip. All three cases had no significant particulate emissions at the tailpipe.

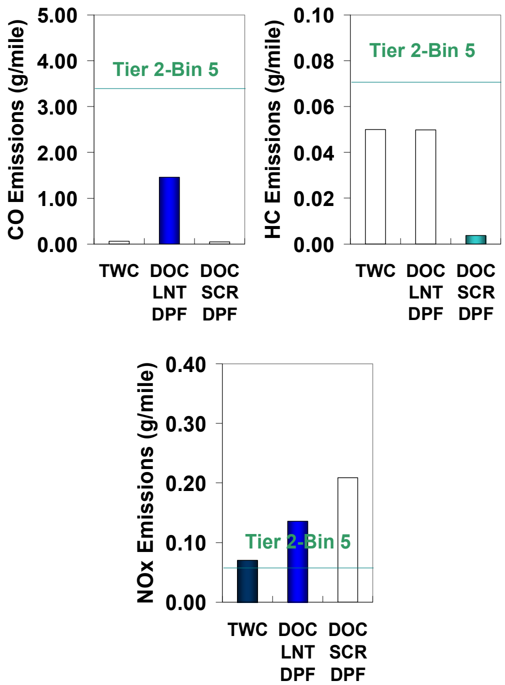


Figure 2. Comparison of cumulative tailpipe emissions from a conventional gasoline-powered passenger HEV with TWC and a diesel-powered HEV with different lean aftertreatment combinations. Simulations are for 80 consecutive UDDS cycles beginning with a cold start.

Engine operation in HEVs and PHEVs is typically very intermittent so that the after-treatment catalysts cool down and thus do not function immediately when the engine restarts. In case of passenger PHEVs, the average temperature of some catalysts could even fall below their characteristic light-off temperatures several times during FTP cycles. By reducing the rate of catalyst cool down, it should be possible to improve catalyst efficiency and thereby reduce both emissions and any associated fuel penalties for NOx and PM control.

To study the potential impact of after-treatment insulation, we initially simulated various levels of insulation on a urea-SCR catalyst installed in a diesel PHEV. In this case, the catalyst performance was tracked over five consecutive UDDS cycles beginning with a fully cold start. As would be expected, the addition of insulation significantly increased average catalyst temperature as depicted in Figure 3. The higher temperatures reduced both NOx and NH3 slip as would be expected.

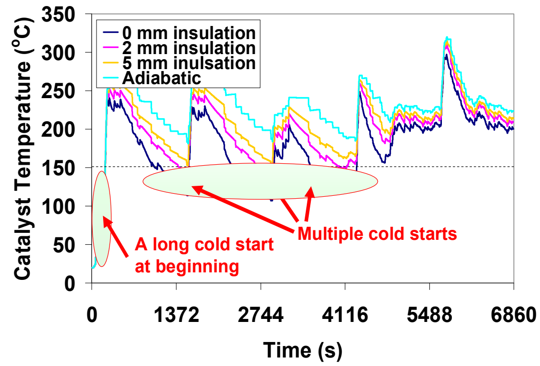


Figure 3. Impact of thermal insulation on urea-SCR catalyst temperature for a passenger PHEV under urban driving conditions.

Following the above initial study, we added realistic levels of insulation to complete diesel after-treatment trains in an HEV operating over 80 UDDS cycles after cold start. The cumulative fuel penalty associated with the DOC-SCR-DPF combination was reduced from 2.54% to 0.41% (Figure 4).

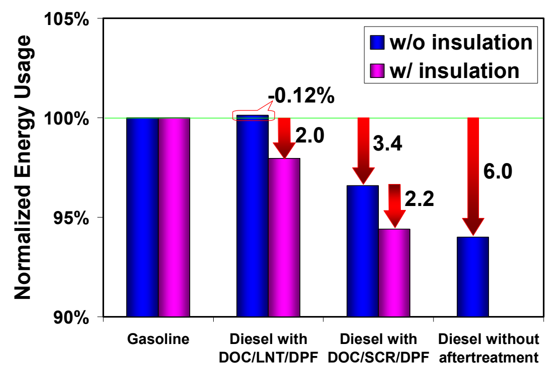


Figure 4. Impact of thermal insulation on the normalized energy usage of a gasoline passenger HEV with TWC and a diesel HEV with the different lean aftertreatment combinations. Simulations are for 80 consecutive UDDS cycles beginning with a cold start.

The corresponding NOx emissions were reduced from 0.209 g/mile to 0.144 g/mile. For the DOC-LNT-DPF combination, insulation decreased the emissions control fuel penalty from 6.1% to 3.96%, and NOx emissions were reduced from 0.136 to 0.099 g/mile. Thermal insulation also eliminated the DPF regeneration event during the 80-cycle sequence, presumably due to an increase in passive soot oxidation.

Conclusions

- A urea-SCR model based on experimental Cu-ZMS-5 catalyst kinetics has been successfully used for simulating NOx emissions control in diesel-powered HEVs and PHEVs.
- A DOC component aftertreatment model has been further refined and validated with public domain data and successfully implemented in lean-exhaust HEV and PHEV simulations.
- Combinations of DOC, LNT, urea-SCR, and DPF aftertreatment component models have been used successfully together in system simulations of HEVs and PHEVs.
- PHEV simulations indicate that the fuel penalty associated with urea-SCR NOx control is significantly less than the fuel penalty for LNTs, but there is also significant tailpipe ammonia slip associated with SCR operation for hybrid cycles. More work is needed to determine how the ammonia slip issue can be resolved.
- Diesel-powered PHEVs with DOC-urea-SCR-CDPF appear to potentially have significant fuel efficiency advantages over conventional gasoline-powered PHEVs, if the NH_3 slip and low NOx conversion issues for intermittent operation can be solved.
- The application of thermal insulation to lean exhaust aftertreatment trains can have potential benefits for emissions and fuel efficiency due to reduced catalyst cooling during engine-off periods.

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1. Z. Gao, J.C. Conklin, C.S. Daw, and V.K. Chakravarthy, “A Methodology for Simulating Transient Engine Exhaust Temperature and Emissions in Vehicle Simulations”, Int. J. of Engine Res., 2010, 11(2), 137-151.
2. Z. Gao, V.K. Chakravarthy, C.S. Daw and J.C. Conklin, “Lean NOx Trap Modeling for Vehicle Systems Simulations”, SAE Int. J. Fuels and Lubr., 2010, 3(1), 468-485.
3. Z. Gao, V.K. Chakravarthy, and C.S. Daw, “Comparisons of Simulated Emissions and Fuel Efficiency of Diesel and Gasoline Hybrid Electric Vehicles”, Submitted to Journal of Automobile Engineering.
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6. Z. Gao, V.K. Chakravarthy, and C.S. Daw, “Study of After-treatment Challenges in Hybrid Vehicles through System Simulations”, DOE Crosscut CLEERS Workshop on Lean Emissions Reduction Simulation, April 20-22, 2010 ((http://www.cleers.org).

Special Recognitions & Awards/Patents Issued

The paper "Lean NOx Trap Modeling for Vehicle Systems Simulations," by Z. Gao, K. Chakravarthy, S. Daw, and J. Conklin was selected as an outstanding SAE paper of 2010 and included in the SAE International Jounral of Fuels and Lubricants. The full citation is SAE Int. J. Fuels Lubr. 3(1): 468-485, 2010.

Acronyms

ANL Argonne National Laboratory
CLEERS Crosscut Lean Exhaust Emissions Reduction Simulation
CDPF Catalyzed diesel particulate filter
CO Carbon monoxide
DOC Diesel oxidation catalysts
DPF Diesel particulate filter
FTP Federal test procedure
HC Hydrocarbons
HECC High efficiency clean combustion
HEV Hybrid electric vehicle
LNT Lean NOx trap
NOx Nitrogen oxides
ORNL Oak Ridge National Laboratory
PHEV Plug-in hybrid electric vehicle
PM Particulate matter
PSAT Powertrain systems analysis toolkit
SCR Selective catalytic reduction of NOx
TWC Three-way catalysts
UDDS Urban Dynamic Drive Schedule
VSATT Vehicle systems analysis tech team

N. Enabling High Efficiency Ethanol Engines (Delphi PHEV CRADA)

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Objective

- To explore the potential of ethanol-based fuels for improvements in drive-cycle efficiency and emissions based on simulation and experiments.

Approach

- Make use of direct injection multi-cylinder engine with advanced powertrain components and controls for exploring the efficiency opportunities of ethanol and ethanol-blend fuels.
- Construct representative vehicle models for evaluating the efficiency of ethanol-based engines.
- Develop advanced powertrain and component models in collaboration with Delphi Automotive Systems for integration into the PSAT environment.
- Simulate conventional and advanced powertrain systems for relevant drive cycles using engine data from an advanced ethanol engine developed for use with this activity.

Major Accomplishments

- A Delphi advanced ethanol engine was tested, optmised and mapped for E85 on a dynamometer testcell over its full speed and load range
- Engine maps were developped from those experimental results and formatted into a PSAT component model
- Conventional and advanced powertrains were simulated using Delphi engine data in split and parallel HEV models for relevant drive cycles.
- Delphi and Saab Bio-Power engine vehicle level results were compared for each powertrain configuration

Introduction

Ethanol has become of increasing interest in recent years because it is a large domestic energy resource with a potential to displace a significant portion of petroleum imported into the United States. The substantial subsidies and tax breaks for ethanol production and consumption reflect the desire of the US government to increase ethanol production as a way to make the country's energy portfolio more diverse and secure. Cellulosic ethanol may provide an additional step-change in reducing petroleum consumption by greatly expanding the quantity of feedstock available for ethanol production, and would also reduce the anthropogenic CO_2 emissions per vehicle mile that contribute to global warming due to the lower energy inputs associated with this technology.

Improved utilization of ethanol will require significant technical progress toward enabling higher efficiency. ORNL has considerable experience with non-traditional fuels and improving engine system efficiency for next generation of internal combustion engines, while Delphi has extensive knowledge and experience in powertrain components and subsystems, along with real-world issues associated with the implementation of ethanol-based fuels. Partnering to combine ORNL and Delphi knowledge bases is key to improving the efficiency and implementation of ethanol-based fuels.

This CRADA makes use of a direct-injection L850 engine which has advanced Delphi components including a flexible valve train and open controller. This engine will be used in combination with modeling to improve the fundamental understanding of efficiency opportunities associated with ethanol and ethanol-gasoline blends.

This activity is co-funded by the Vehicle Technologies Fuels Utilization Subprogram. The Vehicle Systems portion of this CRADA will focus on drive-cycle estimations of efficiency and emissions based on simulation and experiments. Estimations will be performed for ethanol and ethanol blends with conventional and advanced powertrains to assess the full merit of the proposed research across a wide spectrum of powertrain technologies. To fully understand the value of the research, overall vehicle efficiency impacts will be considered. PSAT will be the vehicle level modeling environment and allows for the dynamic analysis of vehicle performance and efficiency to support detailed design, hardware development, and validation.

Approach

Engine System Experiments

Advanced engine and vehicle systems have been developed to evaluate the efficiency potential of ethanol and ethanol blends through the use of advanced technologies developed by Delphi Automotive Systems.

Vehicle System Modeling

An essential aspect of the research is to evaluate the potential of ethanol-optimized engines and their impacts on conventional and advanced powertrains. The vehicle modeling portion of the project is structured utilizing five principal tasks: model development of a reference conventional vehicle and ethanol engine model, development of an ethanol-optimised engine model representing state-of-the-art ethanol fuel economy, development of advanced powertrain models utilizing gasoline and ethanol engine maps, simulation all respective vehicle models over pertinent drive cycles, and development of a detailed final report including complete analysis and comparison of the results. These tasks are summarized below.

<u>Development of representative mid-sized conventional vehicle model</u>.

A set of vehicle performance attributes, based on a 2007 Saab 9-5 Bio-Power sedan, were used as the basis for creating the complete conventional vehicle model. The results from this task established a reference for conventional vehicle performance, using both gasoline and ethanol (E85), for subsequent advanced powertrain variations to be compared against. The vehicle specifications used for creating the vehicle model are outlined in Table 1.

An integral part of this task was to create an ethanol engine model, based on laboratory data collected at both the ORNL Fuels, Engines, and

Emissions Research Center (FEERC) and the Transportation Research Center (TRC). A Saab Bio-Power vehicle was available and has been tested at the FEERC. Data from these tests were used to develop the ethanol engine model (map), and also provided a means of model validation. The Saab ethanol engine map also provides a secondary basis for comparison, i.e., the current production "state-of-the-art" for flex fuel engines.

Table 1 Main Specifications of the Saab Bio-Power Vehicle

Component	Specifications
Engine	Gasoline and E85 based on Saab Bio-Power data
Transmission	5-speed manual Ratios: [3.38, 1.76, 1.18, 0.89, 0.66]
Frontal Area	2.204 m^2
Final Drive Ratio	4.05
Drag Coefficient	0.290
Rolling Resist.	0.009 (plus speed-related term)
Wheel radius	0.3056 m

The conventional vehicle, based on the 2007 Saab 9-5 Bio-Power sedan, was modeled and validated against actual test data collected at the ORNL and TRC in FY2008.

Table 2 shows a comparison of the gasoline and ethanol fuel economy results for each drive cycle as a point of reference for comparison to the advanced powertrain simulation results.

Table 2 Fuel economy comparison for Saab --Power conventional model validation

Facility	Fuel	Fuel Economy (MPG)		
		FTP	HWFET	US06
ORNL	Gasoline	23.2	39.8	26.5
	E85	17.2	29.8	20.0
TRC	Gasoline	22.7	39.0	25.6
	E85	17.3	28.6	19.3
PSAT Conventional	Gasoline	22.4	40.0	25.4
	E85	17.2	29.7	18.4

<u>Development of an optimised advanced ethanol engine model.</u>

Delphi tested and characterized their ethanol-optimised engine featuring a custom variable valve train on an engine dynamometer test cell. The engine calibration was optimised for both E85 and R91 fuels over its complete speed and load range. The results were formatted into PSAT to create an engine model for each fuel. Figure 1 shows the fuel flow map as an example of look-up tables used in the PSAT engine model and generated from experimental data.

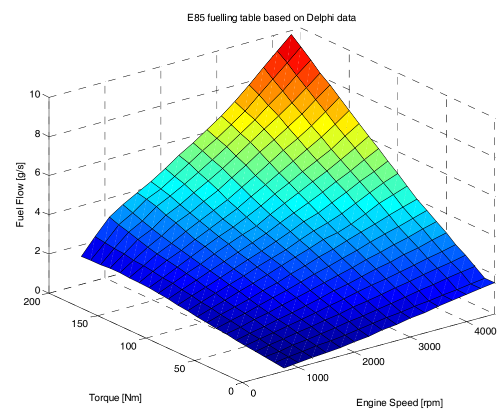


Figure 1. Ethanol-optimised engine fuel flow for PSAT engine model

<u>Development of mid-sized advanced powertrain vehicle models.</u>

In order to gain a broad understanding of the potential merits of the ethanol-optimized engine, advanced powertrain models, such as hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs), were identified and developed. Such powertrain configurations represent the most viable means of maximizing fuel economy in the near term:

- Power-split HEV
- Power-split PHEV
- Parallel HEV
- Parallel PHEV

Utilizing available component data from ORNL and industry, hybrid vehicle models that satisfy the Saab Bio-Power vehicle performance attributes were developed. For all powertrain configurations, the 2007 Saab 9-5 Bio-Power sedan remained the base vehicle platform previously validated. The Delphi ethanol-optimized engine tested on a dynamometer being less powerful (95kW on E85) than the Saab Bio-Power (132kW), its model was scaled up to even out the two engines from a vehicle performance perspective. The powertrains and energy storage systems were modified for each hybrid configuration: the power split powertrain model used a 2004 Toyota Prius powertrain and energy storage whereas the parallel powertrain model used a pre-transmission arrangement. For each hybrid powertrain application, the gasoline and ethanol engine models used for the conventional case were downsized in concert with the high voltage traction drive in order to approximate the performance characteristics of the conventional Saab Bio-Power vehicle (See Table 3 and 4 respectively for Saab Bio-Power powertrain component sizing and Delphi engine powertrain component sizing).

Table 3 Saab Bio-Power powertrain component sizing and vehicle acceleration performance

PSAT Powertrain	0-60mph [s]	Engine [kW]	E-machine [kW]
Bio-Power Engine conventional E85	**9.9**	132	N/A
Bio-Power Engine power split HEV E85	**9.8**	70	52 & 55
Bio-Power Engine parallel HEV E85	**9.7**	70	40
Bio-Power Engine conventional R901	**11.6**	110	N/A
Bio-Power Engine power split HEV R91	**10.7**	60	52 & 55
Bio-Power Engine parallel HEV R91	**10.8**	60	40

Table 4 Delphi Engine powertrain component sizing and vehicle acceleration performance

PSAT Powertrain	0-60mph [s]	Engine [kW]	E-machine [kW]
Delphi Engine conventional E85	**9.8**	132	N/A
Delphi Engine power split HEV E85	**10**	70	52 & 55
Delphi Engine parallel HEV E85	**9.9**	70	40
Delphi Engine conventional R901	**11.2**	110	N/A
Delphi Engine power split HEV R91	**11.3**	60	52 & 55
Delphi Engine parallel HEV R91	**10.9**	60	40

These powertrains reflect the current technology available (in the case of HEVs), as well as proposed (in the case of PHEVs). The control system for each powertrain configuration was “optimized” such that a good estimation of the performance of each configuration could be determined. The base control strategy approach was to maximize the efficient use of the engine, since this component is typically the weakest link in the “efficiency chain.” The energy storage systems (ESS) were sized so that they do not restrict vehicle performance. For HEV configurations, ESS state of charge was always balanced over each drive cycle.

Simulation of conventional and advanced powertrains over pertinent drive cycles.

In order to understand the operational characteristics of the engine in different configurations, the models were exercised over drive cycles of various degrees of aggressiveness and transient characteristics. The drive cycles selected were the UDDS, HWFET, and the US06

Results

Figure 2 represents a comparison of the fuel economy simulation results obtained for the engine operating on E85 for HEV powertrains fitted with the Saab Bio-Power engine. As expected, there is a substantial increase in fuel economy for both HEV powertrain configurations over the FTP cycle due to engine-off operation during idle, and the effects of reduced fuel consumption due to downsizing. The powersplit provides a substantial benefit due to increased operation at the engine's most efficient regions, while the parallel HEV powertrain still boosts fuel economy compared to a conventional powertrain but not as much as a powersplit due to its stepped transmission which limits the optimization of engine operating speed and load relative to the planetary transmission arrangement in the powersplit configuration.

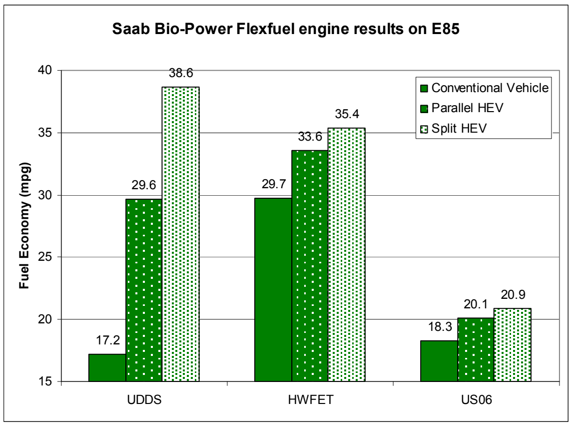


Figure 2. Comparison of Bio-Power HEV fuel economy results compared to conventional vehicle

Figure 3 shows a comparison of the fuel economy simulation results obtained for the Delphi ethanol-optimised engine operating on ethanol (E85) for HEV powertrain configuration. It shows similar trends to the ones exemplified in Figure 2. HEV powertrains demonstrate improved fuel economy over all cycles due to engine-off operation during idle, and downsizing.

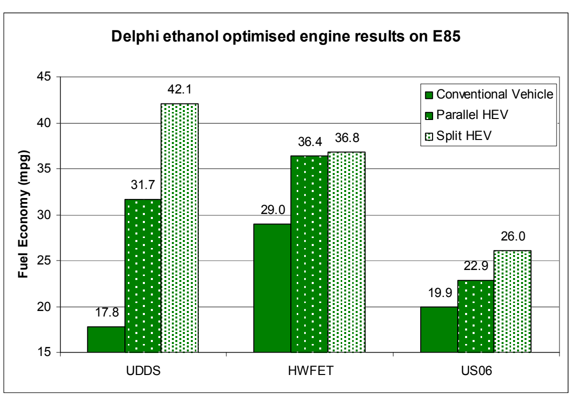


Figure 3. Comparison of Delphi ethanol-optimised HEV fuel economy results compared to Saab Bio-Power HEV

Figure 4 shows the relative improvement obtained with the Delphi ethanol-optimised engine compared to the Saab Bio-Power FFV engine for each HEV configuration, over each drive cycle . In a conventional powertrain, the ethanol-optimised engine demonstrates modest improvements (3.3% on UDDS) or even a loss (-2.6% on HFET) compared to the Saab Bio-Power engine even though its peak efficiency is 13% higher (38.9% compared to 34.4%). When used in a hybrid powertrain, improvements become more significant depending on the cycle and the hybrid powertrain configuration.

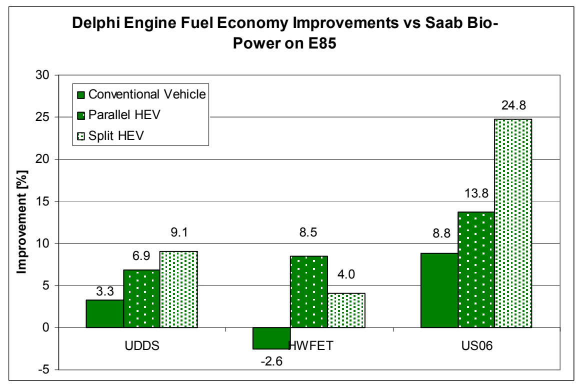


Figure 4. Relative fuel economy improvement obtained by the ethanol-optimised engine compared to the Saab Bio-Power engine

In order to explain those improvements, one has to better understand how the engine operates in each of the powertrain architectures; engine torque density plots were created to show how the engine is used during each cycle. Figure 5 shows an example of these density plots for the conventional configurations for each engine during the UDDS cycle.

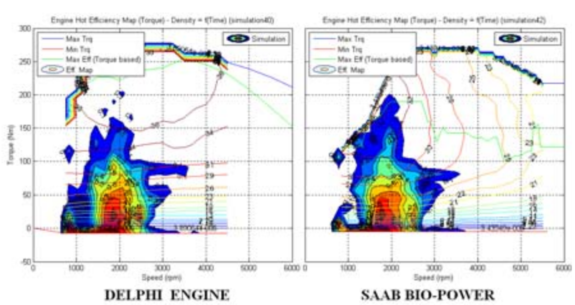
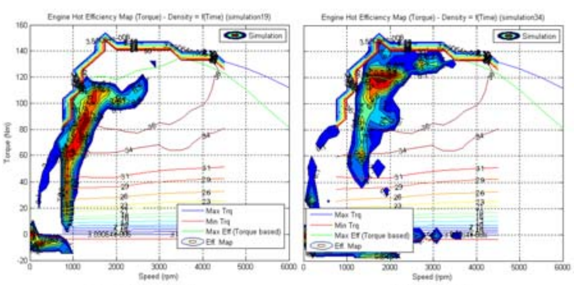


Figure 5. Conventional vehicle engine speed histograms (UDDS)

The Delphi ethanol-optimised engine has a higher peak efficiency situated in a higher speed and load region in which the vehicle barely ever run the engine on the UDDS cycle, whereas the Saab Bio-Power engine peak efficiency region is obtained for lower speeds and loads that are more frequently encountered during the UDDS cycle, allowing the vehicle to achieve a similar overall fuel economy even though that engine is less efficient.

When coupled to an electric machine in a hybrid powertrain, internal combustion engines can be downsized and run closer to their peak operating point. In those configurations, engine level efficiency improvements can be magnified at the vehicle level: see Figure 4 where HEV configurations consistently provide improved relative fuel economy compared to conventional powertrains. Figure 6 shows torque density plots for the downsized Delphi ethanol-optimised engine integrated in a parallel and powersplit configurations. In both cases the engine operates closer to its peak efficiency point resulting in improved vehicle fuel economy.



POWER SPLIT PARALLEL

Figure 6 Ethanol-Optimised engine speed histograms in HEV powertrain vehicle engine (UDDS cycle)

Fuel economy improvements were investigated for PHEV configurations assuming the same powertrains and energy storage systems but instead of balancing the state of charge over the drive cycle, the ESS state of charge started at 90% and depleted to 30% before entering charge sustaining mode thereafter. Relative improvements obtained when using the Delphi ethanol-optimised engine are shown on Figure 7. The trend is similar to the HEV applications: the Delphi engine yields better fuel economy except for the parallel PHEV on a UDDS, but improvements are not as pronounced.

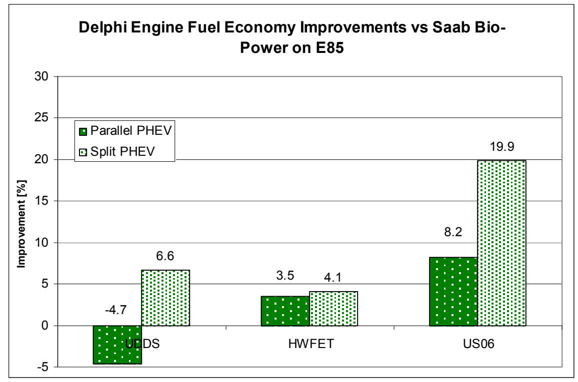


Figure 7 Comparison of Delphi ethanol-optimised PHEV fuel economy results compared to Saab Bio-Power PHEV

Conclusions

The final year of the CRADA demonstrated improved peak efficiency for an experimental engine optimised for ethanol fuel by Delphi compared with a flex fuel engine like the Saab Bio-Power. Both engines were modeled, integrated in HEV and PHEV PSAT models and run over standard federal drive cycles. The results highlight how hybrid powertrains are best suited to maximize the efficiency potential of ethanol fueled engines by offering opportunities for engine downsizing and flexibility to run engines close to their peak efficiency region.

O. Electric Vehicle Grid Integration: Vehicle Integration with Renewables and Communications Standards

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Objectives

- Identify opportunities for alternative value streams for plug-in electric vehicles through integration with renewables and support the definition of the infrastructure needed to enable these opportunities.

Approach

- Participate and contribute towards the development of plug-in electric vehicle communications standards development.
- Review renewable energy integration studies and grid support roles for energy storage.
- Analyze the coordination of vehicles supplying grid services.
- Summarize vehicle renewable energy integration opportunities.

Accomplishments

- Reviewed existing literature for renewable energy integration challenges and methods of addressing these challenges.
- Published results of vehicle communications analysis scenarios and infrastructure challenges and opportunities
- Contributed to the communications standards development process.

Future Directions

- Develop a "green" signal for vehicle charge and discharge that supports the integration of both vehicles and renewables with the grid.
- Continue to support the development of industry-led vehicle to grid communications standards.

Introduction

The Electric Vehicle Grid Integration activity performs research supporting the introduction of plug in hybrid electric and electric vehicles (inclusively (PEVs) and their interface with the utility grid. Addressing interface challenges and identifying alternative value streams via grid ancillary services and renewable expansion are intended to reduce system cost and aid with market expansion. Analysis and collaboration with industry are required to quantify the potential and identify the research to support systems integration.

Previous research in the Vehicle Technologies program identified plug-in hybrid electric vehicles as one of the best options for achieving program goals. Plug-in hybrid electric vehicles provide the opportunity to displace petroleum with electricity that is generated from a variety of sources. The high cost of PEV batteries is expected to be a major barrier to market expansion.

In parallel, the electricity system is poised to become greener by integrating more renewables. The expansion of renewables on the utility grid can result in increased costs due to operational impacts. The variability of renewable generation may increase the need for system controls providing energy balancing and grid stability resources.

The batteries in vehicles are only used for driving during a small fraction of the day. Infrastructure is needed for charging vehicles. By studying integration opportunities and developing the requirements for energy storage system management architectures the synergy between electric vehicles and renewable grid can evolve.

Approach

Both PEVs and renewable generation are poised for significant growth in the coming decades. Uncovering the synergistic opportunities between these markets is the role of the electric vehicle grid integration task in the vehicle technologies program. The focus of the task in FY10 was to review existing renewable energy integration studies and contribute to the development of communications standards.

Review of Renewable Integration Studies

To improve air quality and energy sustainability, states are aggressively targeting the integration of renewable generation into the utility grid of the future. The targets and goals have thus far been defined at a state level. The current status of these are summarized in Figure 1.

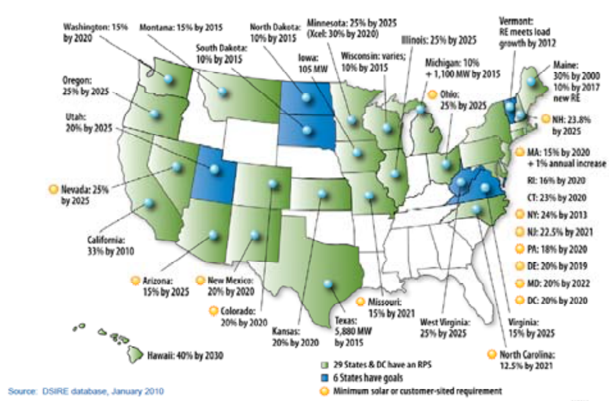

Figure 1. State Renewable Portfolio Standards Target 10-40% Generation from Renewables

The standards often correspond to the availability of renewable resources. The raw data for this chart is sourced from the DSIRE database. Regional differences in scale and timing of these standards will likely result in challenges in creating a nationally consistent method for communication between vehicles and renewables on the grid.

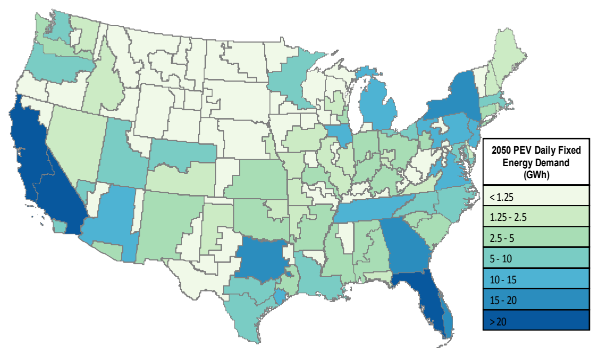

Figure 2. Transportation Analysis Portion of Renewable Electricity Futures Study Highlights Possible Regional Energy Demands of PEVs

A long term look at potential plug-in vehicle adoption and the resulting load profiles was worked on in collaboration with staff from Pacific Northwest National Laboratory in support of the Renewable Electricity Futures Study. Under a future scenario in which 40% of vehicles could be electrified by 2050 the regional mix of electric demand for these vehicles was developed and is shown in Figure 2. The demand shown is only a portion of the load as the other portion was allowed to be flexibly controlled by utilities through communication with the consumers and vehicles.

The analyses methods lead to the greatest loads correspond to population centers. In comparing with Figure 1 there is also a correspondence between PEV load and renewable standards in some instances. The PEV load in the southeast is significant while there are little to no renewable portfolio standards currently in this region.

High penetration of renewables in the utility grid can result in several operational challenges. Figures 3 and 4 provide anecdotal characteristics of solar PV and Wind generation variability.

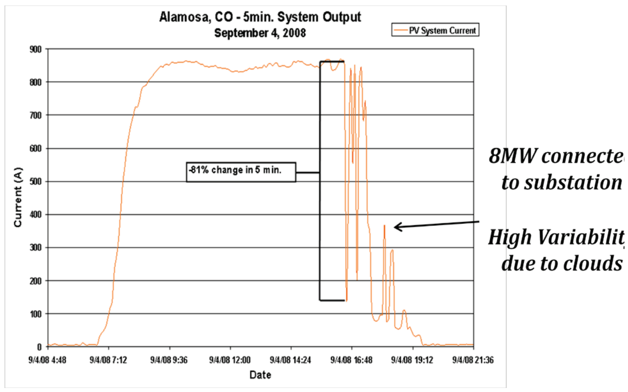

Figure 3. Cloud Patterns Create Fast Dynamics in Solar Generation

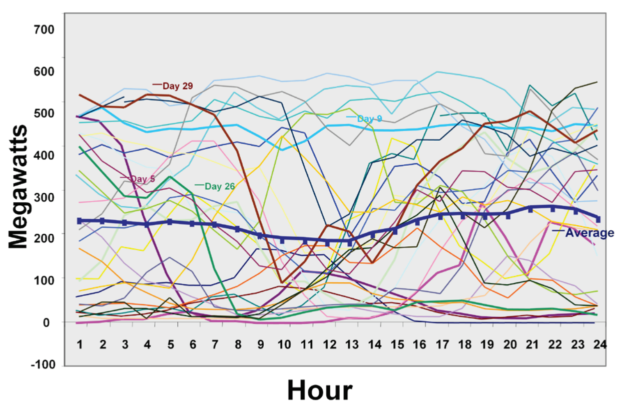

Figure 4. Wind Dynamics are gradual but dramatic while on average the generation is smooth (source: A. Brooks)

Figure 3 highlights the rapid drop in power from solar PV due to cloud cover. PV is typically integrated into the distribution grid where PEVs would also be located. PEVs can respond to charge delay or discharge commands as fast if not faster than PV dynamics. While in Figure 4, with each line representing the daily wind farm generation, wind dynamics are seen to be less dynamic but as large if not larger.

Several literature resources that consider high penetration renewables and their integration with smart grid systems were reviewed to identify synergies with PEV energy management. The following is a summary of the survey:

Smart Grid Deployment in Colorado: Challenges and Opportunities. Doran, K.; Barnes, F.; Pasrich, P.; June 2010.

- Recommend focus on dynamic dispatch and renewables forecasting
- Decentralized command and control is expected to grow as smart grid evolves

The Role of Energy Storage with Renewable Electricity Generation. Denholm, P.; Ela, E.; Kirby, B.; Milligan, M.; January 2010.

- Think of renewables as a load reduction resource, not as dispatchable generation
- With high penetration renewables, the net load is more transient and system inertia is decreased
- Growth of wholesale markets increases opportunities for energy storage

Western Wind and Solar Integration Study Law, D. GE Energy; May 2010

- Targeted 20-30% renewable energy integration in western region
- Included 5GW of nighttime electric vehicle load

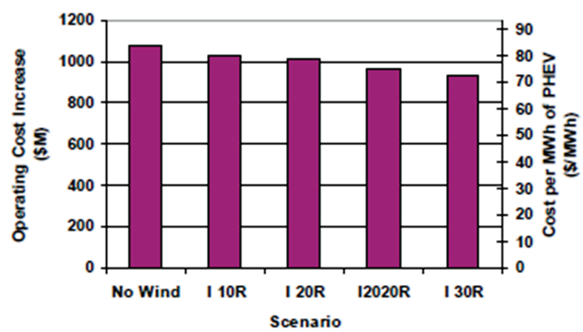

Figure 5: Increased evening loads due to PHEVs reduced the cost of RE generation by about 15%

- Figure 5 as an excerpt from the report highlights the improved cost of electricity from renewables integrated with PEV loads

Assessment of Plug-in Electric Vehicle Integration with ISO/RTO Systems. ISO/RTO Council. March 2010.

- Discusses current and future applications for vehicles managed through grid communications
- Highlights the value of standards development efforts in enabling markets
- One-way communication enables load shaping functions while two-way communication in future enables market participation of vehicles with aggregators

PEV Communications Standards Efforts

Prior to the introduction of PEVs, the utilities and automotive vendors have been collaborating through several standards development organizations to enable communication with PEVs. Communication will allow consumers to participate in utility incentive programs with vehicles. In addition communication between the vehicle and off-board devices and systems is needed for certain vehicle charge and discharge operations.

The organizations and their standards efforts supporting integration of vehicles and renewables are as follows,

Society of Automotive Engineers

J2847 /1,/2,/3 – Plug-in Vehicle communications with utility grid – Messages, /1- utility programs, /2 DC charging, /3 reverse power flow

J2931 – Power Line Communications

Institute Electronics and Electrical Engineering

1547.8 – Expanded use cases for distributed resources

P2030 –Smart Grid Interoperability and End-Use Applications and Loads

International Standards Organization

ISO/TC 22/SC 23; IEC TC69 -Vehicle to grid communication interface

National Institute of Standards and Technology

PAP11 - Common Object Models for Electric Transportation

Monitoring the development of industry standards and supporting the testing of future interoperability of systems is a key role for the national labs. The electric vehicle grid integration team participated in SAE and IEEE efforts as needed and provides an interface to the FreedomCAR Grid Integration Technical Team on these topics.

Summary

Integration challenges of renewables include,

- Increased transients in net load
- Reduced system inertia to maintain stability
- Localized distribution system stability impact
- Data collection, analysis, and forecasting methods are under development
- Differences in variability between solar and wind
- Plug-in vehicles can enable RE integration when,
- Charge and discharge events are planned and coordinated through communications
- Standards are defined that lead to consistent interfaces between vehicles and grid components
- Policies continue to support growth of renewables and PEVs in parallel

Future work

- Define a "green" signal for charge and discharge management of plug-in vehicles that addresses both local and regional renewable energy and vehicle integration challenges

- Use industry-led communications standards definitions to evaluate and demonstrate vehicle energy management integrated with electricity grid operations

Publications and Presentations

1. Markel, T., Kintner-Meyer, M., Mai, T. "Transportation Electrification Load Development for a Renewable Electricity Future Analysis." EVS-25. 2010.

2. Markel, T., Kuss, M., Denholm, P. "Communication and Control of Electric Vehicles Supporting Renewables. IEEE Vehicle Power Propulsion Systems Conference. 2009.

3. Markel, T.; Kuss, M.; Simpson, M. "Value of Plug-in Vehicle Grid Support Operation." IEEE Power and Energy 2010.

4. Kuss, M., Markel, T., Kramer, W. "Application of Distribution Transformer Thermal Life Models to Electrified Vehicle Charging Loads Using Monte-Carlo Method." EVS-25. 2010.

5. Markel, T. "Plug-in Hybrid Electric Vehicle Infrastructure - A Foundation for Electrified Transportation." MIT Energy Initiative, Electrified Transportation Symposium. 2010.

6. Markel, T. "NREL Update on IEEE 1547 and P2030." Presentation to Grid Integration Tech Team. July 2010.

P. Medium and Heavy-Duty Vehicle Simulation

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Objectives

- Integrate state-of-the-art component data and drive cycles into Autonomie.
- Develop specific control strategies for medium and heavy-duty vehicles.
- Validate conventional vehicle applications using test data

Approach

- Review literature to define specific development required.
- Work with original equipment manufacturers (OEMs) to develop and implement specific test and control strategies into Autonomie.

Accomplishments

- Integrated state-of-the-art component data through collaboration with OEMs.
- Developed specific control strategies through collaborations with OEMs.
- Validated conventional vehicles for several applications using test data provided by U.S.EPA.

Future Directions

- Validate electric drive vehicle configurations using test data
- Evaluate the impact of advanced technologies on fuel consumption.

Introduction

Medium and heavy-duty vehicles represent a significant portion of the fuel consumed in transportation activities. While their applications differ from those of light-duty vehicles, numerous technologies can be shared across classes.

Based on previous development performed on both state-of-the-art component data and control strategy for both low and high level, several conventional vehicles were validated. In addition, hybrid vehicle configuration and control was developed for a line haul vehicle.

Integration of State-of-the-Art Data

Argonne has continued to work with major OEMs and suppliers to integrate state-of-the-art component data, including engine, transmission, electric machine, vehicle, etc.

In addition, Argonne has been working with companies, NREL and ORNL to integrate Real World Cycles for several applications from bus to line haul and garbage trucks.

Distance Based Driver Development

One of the major issue when comparing automatic to manual transmission vehicle fuel consumption potential of line haul vehicles is the inability of the vehicle to closely follow the desired vehicle speed trace. As a result, both vehicles will not achieve the same distance, which introduces a bias in the comparison.

As a result, Argonne has developed a distance based drive model using drive cycle provided by an OEM. Figure 1 shows the main organization of the Simulink model of the driver. The algorithm uses both distance and time based logics to be able to handle idling time.

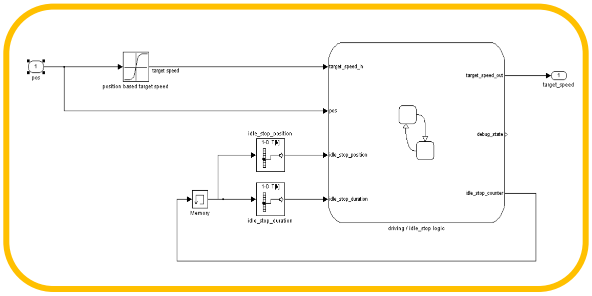

Figure 1. Distance Based Driver Model

The vehicle characteristics, especially vehicle weight, were modified to ensure that the same distance is achieved in all cases.

The Autonomie Graphical User Interface was also modified to handle both time based and distance based drive cycles.

<u>Conventional Vehicles Validation</u>

Line Haul Conventional Vehicle with EPA
A 2008 Navistar Prostar vehicle was tested by Southwest Research Institute (SwRI) under contract with U.S.EPA. Due to the lack of complete test data set, the gear ratio was estimated. A shifting algorithm was then developed and tuned in simulation. The results shown in Figure 2 demonstrate a very good correlation between test and simulated gear numbers.

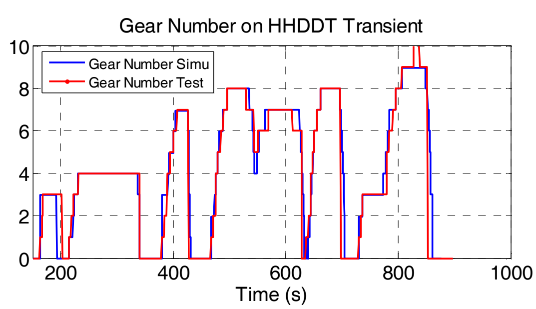

Figure 2. Gear Number Comparison

The reminder of the component data were implemented working with OEMs to validate the vehicle fuel consumption.

Since the vehicle was tested several times on each drive cycle, a single representative test for each of the drive cycle was selected to perform validation. Figure 3 shows that the simulation results are within the test to test variability.

It is worth noting that the fuel consumption of a single drive cycle can vary by as much as 17%. Further investigation should be performed to understand this significant variability.

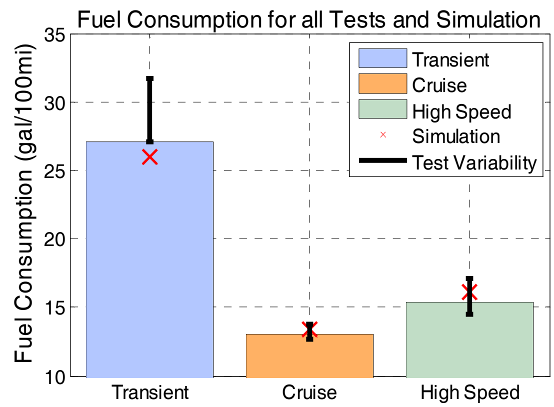

Figure 3. Simulation Results within Test-to-test Uncertainty

Parcel & Delivery Validation with EPA
A 2008 FedEx truck Freightliner MT45 Chassis with a Ford Utilimaster Body was tested by SwRI under contract with U.S. EPA. A specific vehicle model was developed using proprietary data provided by OEMs. A shifting algorithm was then developed and tuned for the specific medium duty application.

The fuel consumption results comparing simulation and test data are shown in Figure 4. Like for the line haul validation, the results are within test to test uncertainty.

Highway Cycle	Test	Simulation
Fuel Economy (mpg)	13.8	14.3
Fuel Consumption (gal/100miles)	7.2	6.9
Delta Fuel Consumption (%)		-3.5%

Figure 4. P&D Validation Results

Development of Line Haul Hybrid Electric Vehicle Model and Control Strategy

Most of the fuel consumed by heavy duty applications occurs for line haul. As such, one of the main outstanding questions is the benefit of hybridizing such application.

Argonne has been working with ArvinMeritor to develop a complete vehicle model of their dual mode configuration. To achieve that goal, several tasks were performed:

- New powertrain configuration
- Integration of proprietary component data
- New low level control strategy to handle mode change
- New high level control strategy to minimize fuel consumption while taking into account hardware limitations

The completed vehicle was simulated on several drive cycles to evaluate the fuel consumption benefits compared to a conventional vehicle.

The ArvinMeritor hybrid configuration was also compared with the series-parallel configuration previously developed to support the National Academy of Science committee for Medium and Heavy Duty fuel economy.

Conclusions

Specific component data and control strategies were implemented to represent state-of-the-art technologies for different vehicle applications. Several conventional reference vehicles were developed.

To be able to properly compare line haul applications with different transmission types, a distance based driver was modeled and validated. Conventional vehicles for both a line haul and parcel and delivery applications were validated using vehicle test data collected at SwRI under contract with U.S.EPA. A specific hybrid configuration and its control strategy were developed.

Future activities will focus on enhancing the existing control strategies and available sets of component data. Specific requirements will be developed for each application so that additional powertrain configurations, including for HEVs and PHEVs, can be developed and their benefits analyzed. Argonne will continue to work closely with truck manufacturers and suppliers to implement state-of-the-art component data.

Publications/Presentations

1. Delorme, A., Vijayagopal, R., Karbowski, D., Rousseau, A., “Impact of Advanced Technologies on Medium-Duty Trucks Fuel Efficiency “, SAE 2010-01-1929, Commercial Vehicle Conference, Chicago, October 2010

2. Karbowski, D., Delorme, A., Rousseau A., “Modeling the Hybridization of a Class 8 Line-Haul Truck “, SAE 2010-01-1931, Commercial Vehicle Conference, Chicago, October 2010

3. Delorme, A., Rousseau, A., Abiven, P., Karbowski, D., “Validation of a Line-Haul Class 8 Combination Truck “, SAE 2010-01-1998, Commercial Vehicle Conference, Chicago, October 2010

4. Delorme, A., Karbowski, D., Vijayagopal, R., Rousseau, A., “Fuel Consumption Potential of Medium- and Heavy-Duty Applications”, EVS25, Shenzhen, China, November 2010

Q. PHEV Value Proposition Study: VPS Phase I & Phase II, Market Introduction Study, and Comparative Study of Advanced Electric Vehicle Technology Analyses.

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Background

- PHEVs have been the subject of growing interest in recent years because of their potential for reduced operating costs, oil displacement, national security, and environmental benefits. Despite the potential long-term savings to consumers and value to stakeholders, the initial cost of PHEVs presents a major market barrier to their widespread commercialization.

Approach

Phase 1 (completed):

- Identification of potential propositions through a workshop with a guidance committee and other stakeholders;
- Down-selection of business cases for further study;
- Development of the analytical toolset using current technical research and industry-recognized models of vehicle design,
- Battery controls and electric utility grid operation; and
- Evaluation of the first down-selected value proposition using the toolset to identify the conditions under which the value to the owner will justify the cost or investment.

Phase 2 (completed in 2010):

- Investigate alternative geographic settings to account for the nation's diverse range of generation mixes, climates, and other variables. Conduct a sensitivity analyses on many of the study's key assumptions; and a risk/benefit assessment from the OEM, utility, and policy maker perspectives.

Market Introduction Study (completed in 2010):

- Identify and assess the effect of potential policies, regulations, and temporary incentives as key enablers for a successful market debut.
- Comparative study of advanced electric vehicle technology analyses (started in 2010):

- Addendum to the PHEV Value Proposition Study Report and the PHEV Market Introduction Study Report that will seek to demonstrate why different studies have reached different conclusions.

Major Accomplishments

- Phase I: Completed in 2009
- Phase II : Completed in 2010
- Market Introduction Study: Completed in 2010
- Comparative study of advanced electric vehicle technology analyses: Started in 2010

Future Direction

- Complete the Comparative study of advanced electric vehicle technology analyses by the end of CY 2010.

PHEV Value Proposition Study activities in 2010

ORNL and Sentech conducted the second phase of the PHEV Value Proposition Study, which included a second regional case study, sensitivity analysis, and risk assessment.

In Phase 2 of the PHEV Value Proposition study, Sentech, ORNL, Ohio State University Center for Automotive Research, and Taratec Corporation completed a second regional case study in the NERC region formerly known as ECAR; a sensitivity analyses on many of the study's key assumptions; and a risk/benefit assessment from the OEM, utility, and policy maker perspectives. As with Phase 1, the project team compared PHEV-30s to comparable ICEs and HEVs in the 2030 timeframe. Study results indicate that PHEV-30s on the road in 2030 may consume 65-75% less gasoline than a comparable HEV and ICE, reduce ownership costs by 8-10% compared to a comparable ICE and HEV, and emit 10% less CO_2 than ICEs in California but up to 13% more in Ohio.

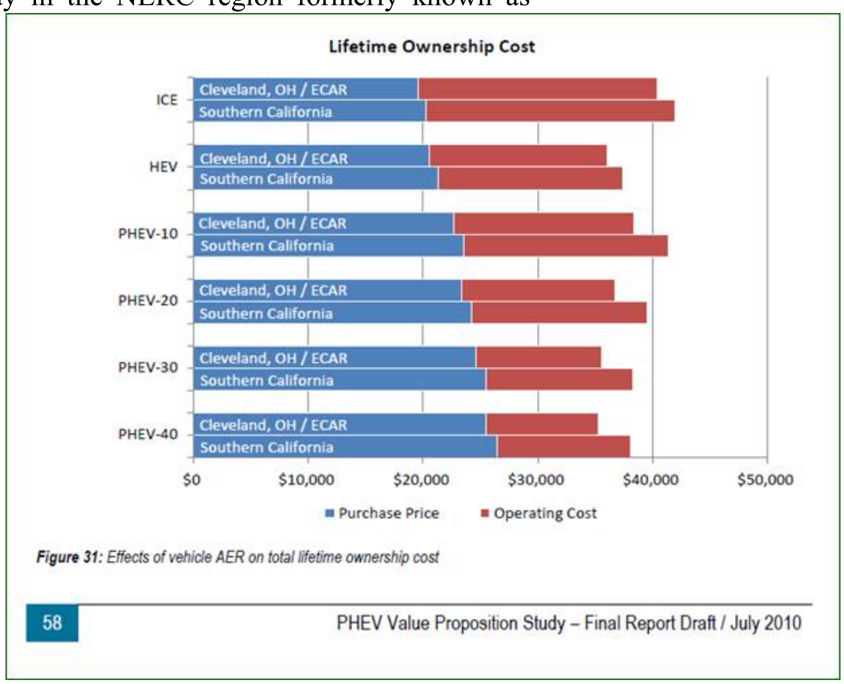

Figure 1

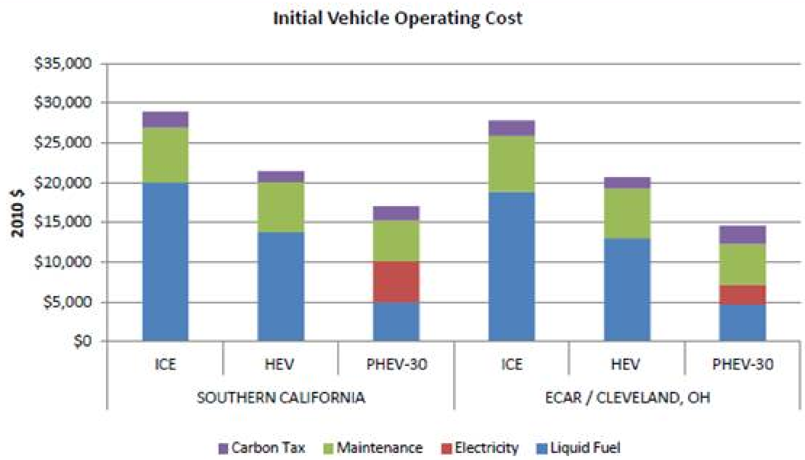

***Figure 13**: Overall vehicle operating cost comparison for ICEs, HEVs, and PHEVs in 2030 over a ten year lifetime in each case study location.*

Since paying these operating costs spanned a 10-year period, the present value of money should be factored in. Figure 14 below displays the overall vehicle operating cost differences between each vehicle type in 2030 once a 6% discount rate that covers 10 years is applied.

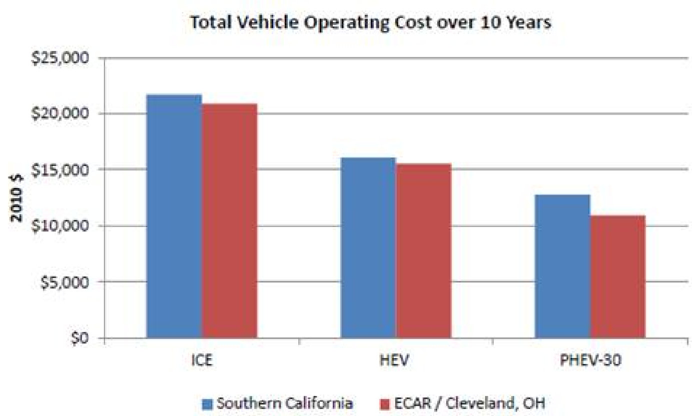

***Figure 14**: Total vehicle operating costs for each vehicle type once present value of money is incorporated.*

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Figure 2

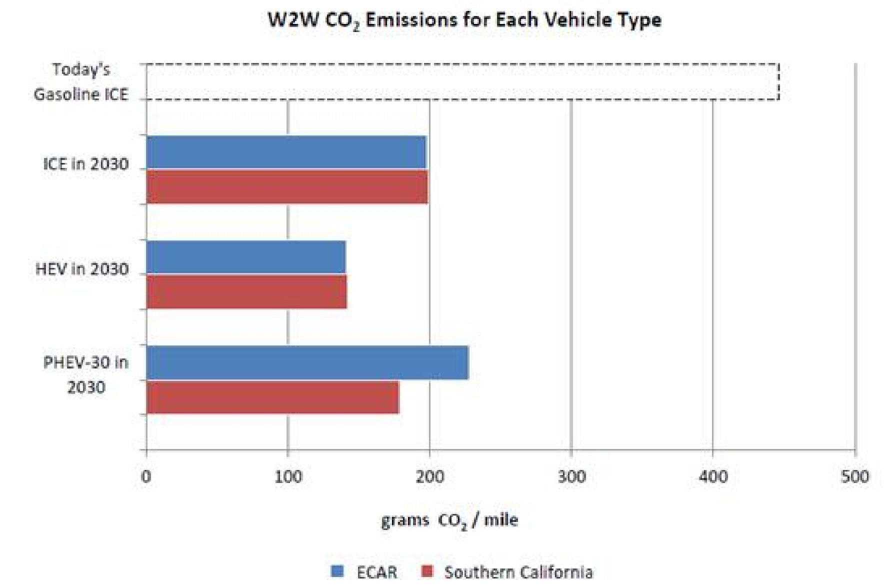

Figure 26: *Regional case study comparisons of CO_2 emissions between ICEs, HEVs, and PHEV-30s in 2030.*

Figure 3

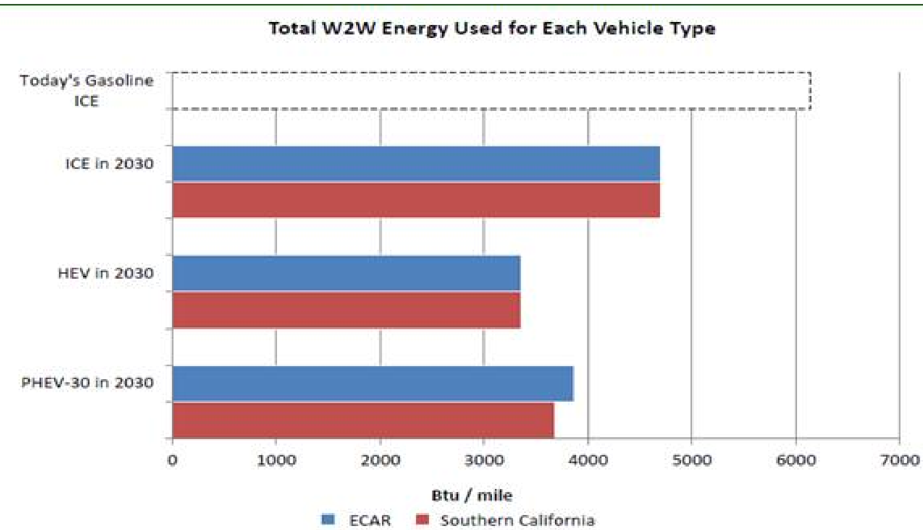

Figure 27: *Regional case study comparisons of CO_2 emissions between ICEs, HEVs, and PHEV-30s in 2030.*

4.4.3. Increased Renewable Generation

Research has shown that by implementing one-way flow smart charging technologies, PHEVs support the increased use of intermittent renewable energy sources, such as wind and solar. The majority of PHEV recharging is done overnight in off-peak hours, often with much flexibility since PHEVs charging at 220V only take two-to-three hours to fully replenish their battery pack. This leaves several hours to appropriately synchronize charging with availability of renewables. Smart chargers can stop or slow down

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Figure 4

5.6. Alternative Generation Mixes

Perhaps one of the most interesting portions of this sensitivity study is the impact power generation mixes selected by regional utilities can have on W2W CO_2 emissions. More states are adopting standards that require the increased use of low-carbon or carbon-free energy sources in their mix to help reduce the carbon footprint and improve local air quality. Such methods include more utilization of nuclear power and non-carbon renewable energy resources (e.g., hydro, geothermal, wind, solar). W2W CO_2 emissions can be further reduced when coupled with a low-carbon fuel, such as E85, used to power a region's plug-in electric vehicles. Figure 47 compares all nuclear energy, all renewable energy, and all renewable energy plus E85 to the projected base for both southern California and ECAR generation mixes in 2030.

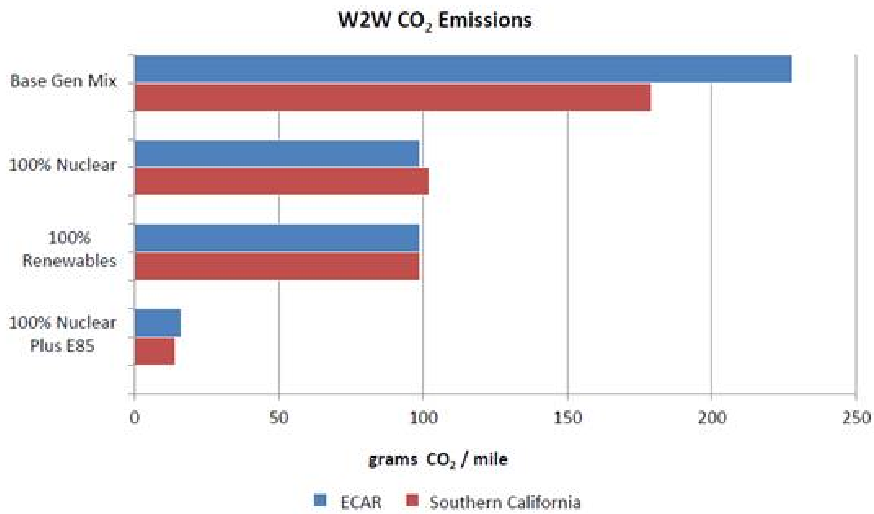
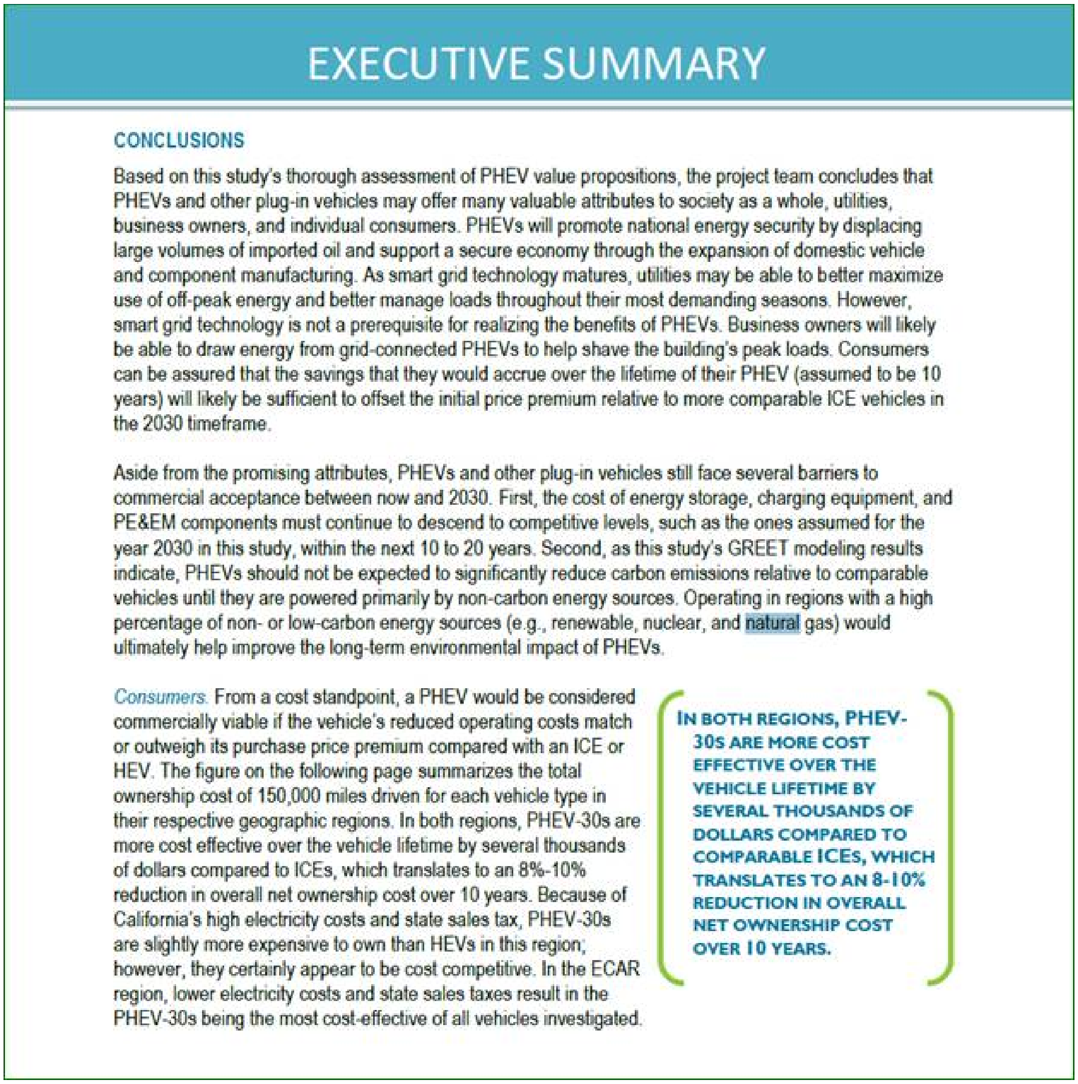


Figure 47: *Effects of alternative generation mixes on CO_2 emissions*

Figure 5



EXECUTIVE SUMMARY

CONCLUSIONS

Based on this study's thorough assessment of PHEV value propositions, the project team concludes that PHEVs and other plug-in vehicles may offer many valuable attributes to society as a whole, utilities, business owners, and individual consumers. PHEVs will promote national energy security by displacing large volumes of imported oil and support a secure economy through the expansion of domestic vehicle and component manufacturing. As smart grid technology matures, utilities may be able to better maximize use of off-peak energy and better manage loads throughout their most demanding seasons. However, smart grid technology is not a prerequisite for realizing the benefits of PHEVs. Business owners will likely be able to draw energy from grid-connected PHEVs to help shave the building's peak loads. Consumers can be assured that the savings that they would accrue over the lifetime of their PHEV (assumed to be 10 years) will likely be sufficient to offset the initial price premium relative to more comparable ICE vehicles in the 2030 timeframe.

Aside from the promising attributes, PHEVs and other plug-in vehicles still face several barriers to commercial acceptance between now and 2030. First, the cost of energy storage, charging equipment, and PE&EM components must continue to descend to competitive levels, such as the ones assumed for the year 2030 in this study, within the next 10 to 20 years. Second, as this study's GREET modeling results indicate, PHEVs should not be expected to significantly reduce carbon emissions relative to comparable vehicles until they are powered primarily by non-carbon energy sources. Operating in regions with a high percentage of non- or low-carbon energy sources (e.g., renewable, nuclear, and natural gas) would ultimately help improve the long-term environmental impact of PHEVs.

Consumers. From a cost standpoint, a PHEV would be considered commercially viable if the vehicle's reduced operating costs match or outweigh its purchase price premium compared with an ICE or HEV. The figure on the following page summarizes the total ownership cost of 150,000 miles driven for each vehicle type in their respective geographic regions. In both regions, PHEV-30s are more cost effective over the vehicle lifetime by several thousands of dollars compared to ICEs, which translates to an 8%-10% reduction in overall net ownership cost over 10 years. Because of California's high electricity costs and state sales tax, PHEV-30s are slightly more expensive to own than HEVs in this region; however, they certainly appear to be cost competitive. In the ECAR region, lower electricity costs and state sales taxes result in the PHEV-30s being the most cost-effective of all vehicles investigated.

IN BOTH REGIONS, PHEV-30S ARE MORE COST EFFECTIVE OVER THE VEHICLE LIFETIME BY SEVERAL THOUSANDS OF DOLLARS COMPARED TO COMPARABLE ICES, WHICH TRANSLATES TO AN 8-10% REDUCTION IN OVERALL NET OWNERSHIP COST OVER 10 YEARS.

Figure 6

ORNL, Sentech, and the University of Michigan Transportation Research Institute (UMTRI) evaluated the impact of various policies, incentives, and regulations on the market introduction of PHEVs.

ORNL, Sentech, Inc., Pacific Northwest National Laboratory (PNNL) / University of Michigan Transportation Research Institute (UMTRI), and the U.S. Department of Energy (DOE) conducted a PHEV Market Introduction Study to identify and assess the effect of potential policies, regulations, and temporary incentives as key enablers for a successful market debut. ORNL's Market Acceptance of Advanced Automotive Technologies (MA3T) Model and UMTRI's Virtual AutoMotive MarketPlace (VAMMP) Model were used to assess the policy options in this study. The MA3T Model simulates competition of PHEVs against several other vehicle types by placing values on specific vehicle attributes, consumer cost savings, and predefined market conditions. Using a set of vehicle assumptions for 2010 to 2020, MA3T estimated that existing policies in support of PHEVs have a strong initial impact on the PHEV market with approximately 1 million PHEVs projected to be on the road in 2015 and 425,000 PHEVs sold in 2015 alone. At this penetration rate, PHEVs would account for 2.5% of all new vehicle sales in 2015, with PHEV-12s dominating overall PHEV market sales. To further accelerate and sustain the market, additional policy options were considered that would make PHEVs cost-competitive with enough appealing features to become a significant segment of new vehicles sold in the near term. The most powerful policy drivers (as simulated by MA3T) included state sales tax exemptions, "feebate" programs, and annual operating cost allowances.

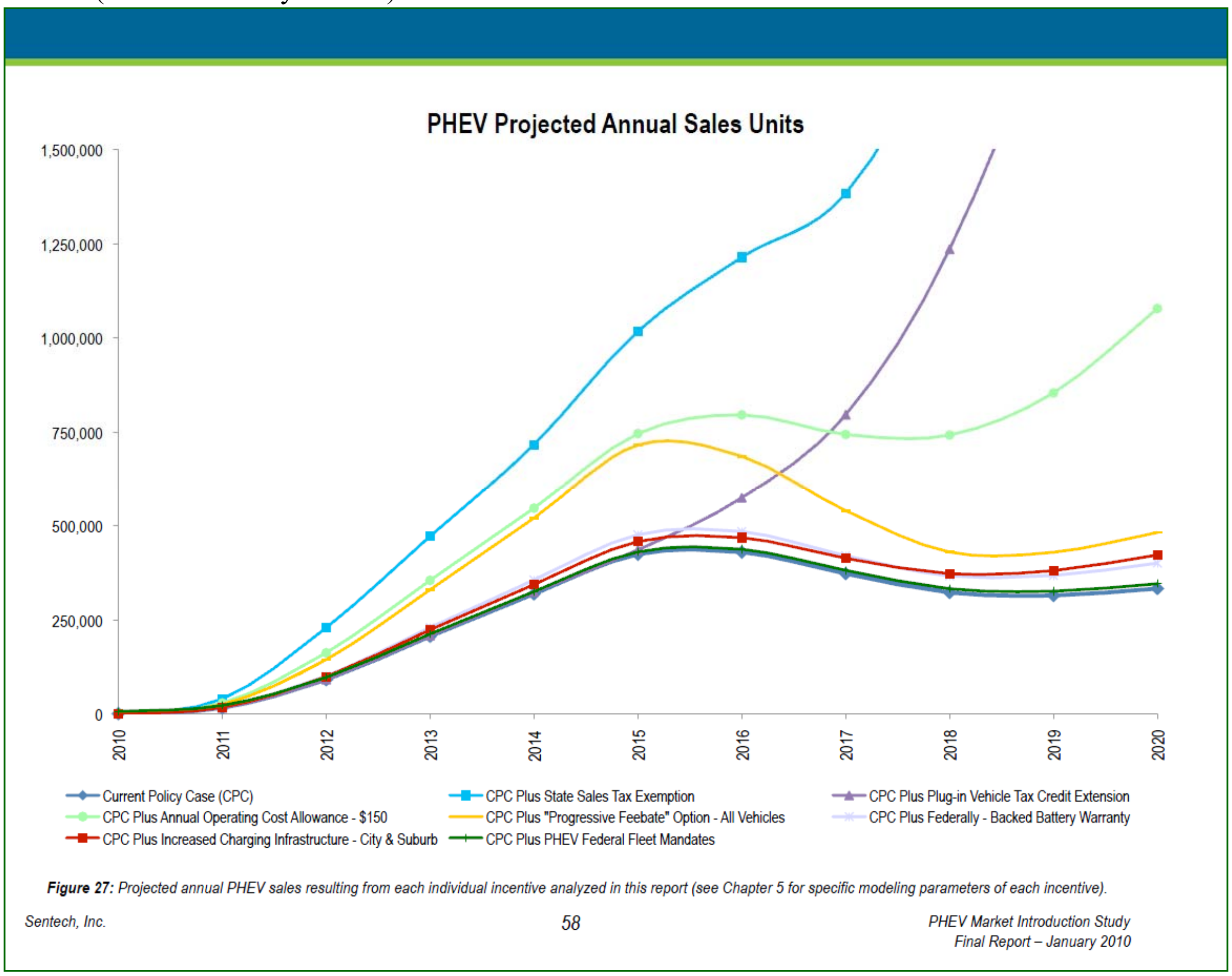


Figure 7

Sentech began work on the comparative study of advanced electric vehicle technology analyses.

Sentech is preparing an addendum to the PHEV Value Proposition Study Report and the PHEV Market Introduction Study Report that will seek to demonstrate why different studies have reached different conclusions. Many organizations have published studies that forecast 1) the environmental effects (e.g., greenhouse gas emissions) of PEVs, 2) sales penetration rates of PEVs, and 3) oil displacement achievable with PEVs. While overall approaches may be similar in nature, a great disparity appears to exist between each study's set of conclusions. The goal of this study is not to declare one analysis as correct, or to discredit others, but instead to provide an understanding to the reader by putting each into context. In fact, most organizations utilized the same models (e.g., GREET) for portions of their analyses, and results may actually align closely if organizations simply "plugged in" the same values. The general approach for this study includes a thorough literature search, consolidation of relevant studies, identification of key assumptions, extraction of pertinent information, overlay of data points, and drawing of conclusions. The report addendum summarizing the study's findings is scheduled for completion by the end of the 2010 calendar year.

VI. COMPONENT/SYSTEMS EVALUATION

A. Range Extended Electric Vehicle (REEV) Control Strategy Evaluation

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Objectives

- Evaluate the impact of supervisory control in improving the fuel efficiency of a series PHEV while maintaining emission values comparable to the baseline conventional vehicle.

Approach

- Use model-based design principle (simulation study – hardware validation) to evaluate impact of supervisory control on fuel efficiency and emissions.
- Perform study on series vehicle for Year 1 (most flexible from a supervisory control perspective) and powersplit vehicle for Year 2 (less flexibility from a supervisory control perspective).
- Use engine and after treatment model developed at Oak-Ridge National Laboratory (ORNL) and AUTONOMIE vehicle simulation model for the simulation study.
- Validate simulation results with a real engine in a virtual vehicle (Engine in the Loop).

Accomplishments

- ORNL engine and after-treatment model successfully integrated in AUTONOMIE.
- Supervisory control in AUTONOMIE reconfigured to integrate cold temperature operation (ORNL lead) and hot temperature operation (ANL lead).
- Process developed in AUTONOMIE for seamless transition from simulation to Engine in the Loop.
- Fuel consumption and tailpipe emissions for the baseline conventional vehicle quantified with Engine in the Loop.
- Validation of series vehicle simulation study using Engine in the Loop in progress.

Future Directions

- Complete validation of series vehicle simulation study.
-
- Perform the same study for a power split configuration PHEV for year 2.

Introduction

The objective of the project is to evaluate the impact of supervisory control in improving the fuel efficiency of a series PHEV while maintaining emission values comparable to the baseline conventional vehicle.

Approach- Model Based Design

The impact of supervisory control on fuel efficiency and emissions is studied in simulation. The simulation results trends are then validated using a real engine (Engine in the Loop). Figure 1 shows the different steps in the project.

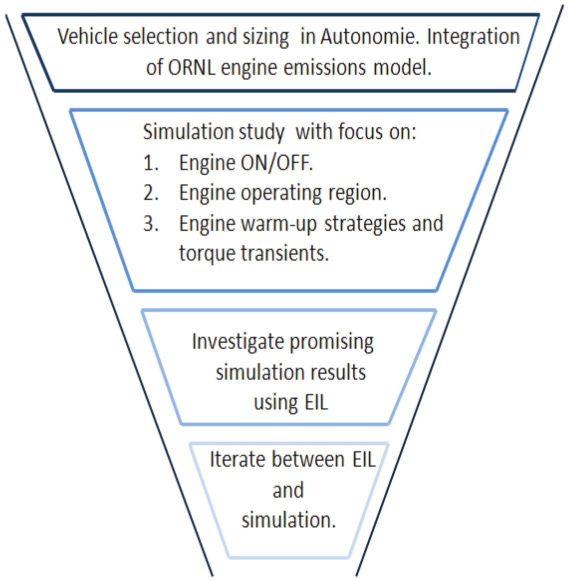

Figure 1. Model based design process

Engine in the loop (engine hardware in the loop) capability has been established at Argonne to evaluate the feasibility and potential of steady state engine R&D under transient conditions, and to study the cold start impacts and regulatory /practical considerations for advanced vehicle technologies, including plug-in hybrids.

The following sections will discuss the model based design steps in detail.

Series Vehicle Model in Autonomie and integration of ORNL emissions model

Table 1 lists the vehicle performance requirements of the series vehicle.

Table 1. Series vehicle performance targets

Acceleration	0-60 mph in ~ 9 seconds
Maximum Vehicle Speed	100 mph
Equivalent Electric Range	~ 20 miles on the UDDS cycle

The sizing was performed by the automated sizing routine in Autonomie. Table 2 lists the specifications for the final series vehicle powertrain.

Table 2. Series vehicle powertrain specifications

Parameter	Value
Curb weight	1800 kg
GVW	2440 kg
Engine	110 kW , 2.2 L SIDI engine
Electric Machine Power	130 kW / 13000 rpm
Generator Power	110 kW / 6000 rpm
Battery	41 Ah, 10 kWh Li-ion
Cd	0.37
FA	2.54 m2
Tire	P225_75_R15 (0.359)
Fixed ratio	1.6
Final drive ratio	4

The 2.2 L engine selected for the series vehicle is based on the real engine available for engine in the loop validation. A 2.2L engine also gives more freedom on engine operation for the series vehicle.

The ORNL developed engine, emissions and after-treatment model was successfully integrated into Autonomie, as a part of the vehicle model development for this project.

Reconfiguration of the Vehicle Power Train Controller For Easy Integration of Cold Start Energy Management:

The cold start engine warm up control for this study has been developed by ORNL. In order to facilitate the easy integration of the cold start control with the hot start control developed by Argonne, the series powertrain controller in Autonomie was reconfigured to seamlessly integrate the cold start control developed by ORNL (Figure 2).

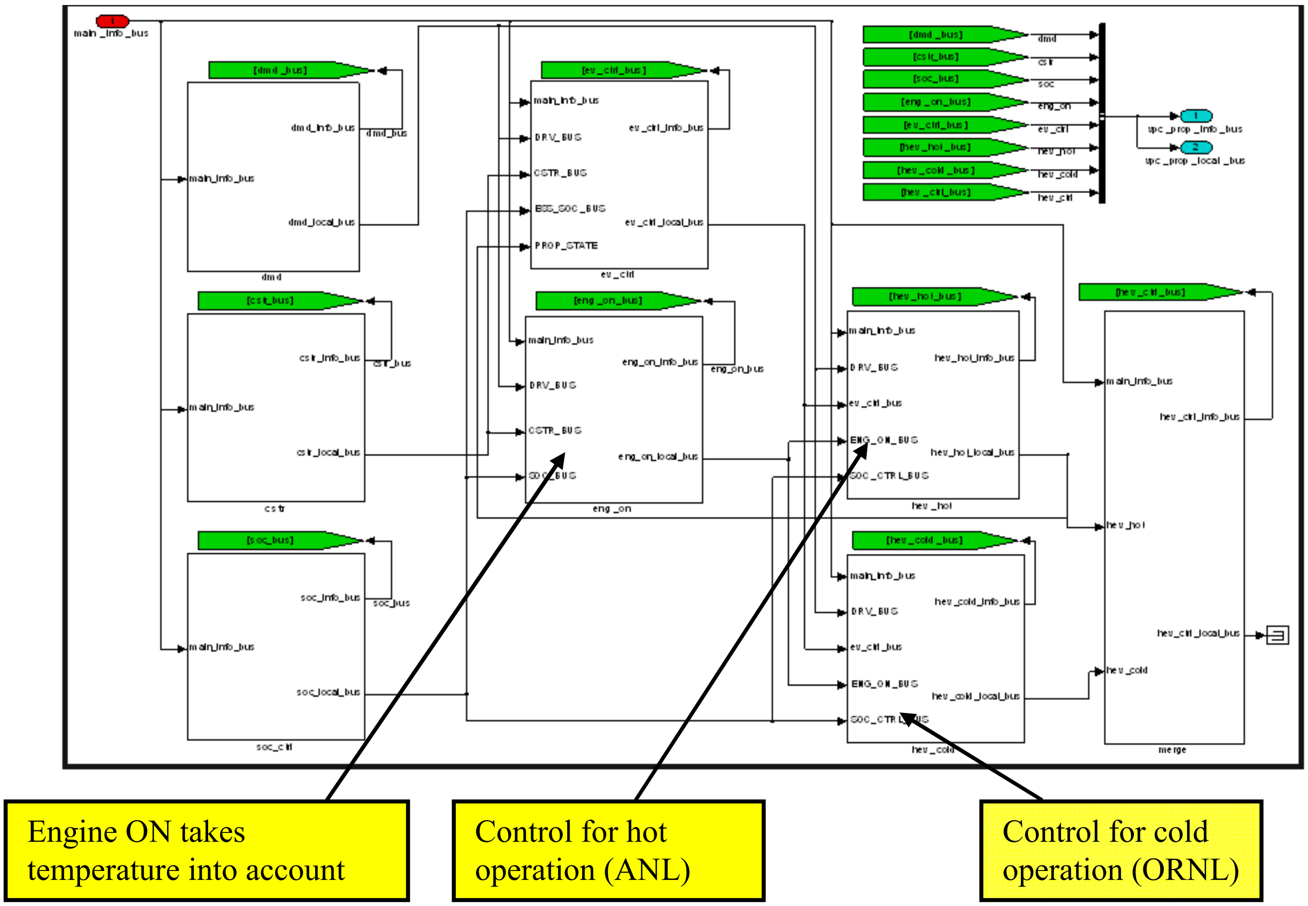

Figure 2: Reconfiguration of vehicle powertrain controller (supervisory controller) for integration of hot and cold strategy management.

<u>Process for migration from simulation to engine in the loop developed in Autonomie:</u>

A component in the loop configuration has been developed in Autonomie, which is used for engine in the loop evaluation. The engine block in Autonomie simulation can be replaced with the Engine in the Loop system, in order to control an actual engine, dynamometer, and log data from the engine, the dynamometer, air, fuel and exhaust flow sensors and all the thermocouples on the intake and exhaust lines. Figure 3 shows the different blocks in the engine –in the loop configuration, with the main tasks for each block. These blocks allow easy migration from simulation to engine in the loop testing, and vice versa. No changes are needed in any other part of the vehicle model/ control, allowing for easy validation of simulation results and easy swapping of simulation and engine in the loop modes.

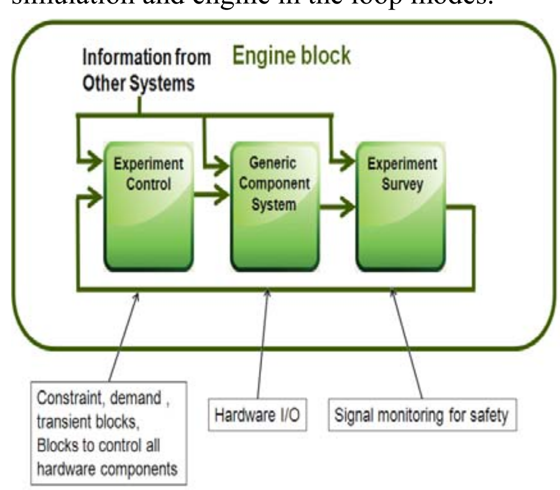

Figure 3. Engine in the loop configuration in Autonomie for easy migration from simulation to engine in the loop testing.

<u>Simulation study for series vehicle 'hot' operation in Autonomie and EIL validation</u>

For this project, the vehicle energy management in the charge-depleting mode was electric operation until 30% SOC, followed by charge sustaining operation. A simulation study was performed with the ORNL engine and after treatment models to optimize the charge sustaining operation of the vehicle over consecutive UDDS cycles. The goals of the charge sustaining simulation study (hot conditions) were to:

Evaluate of different engine – ON thresholds to maximize fuel economy.

Maximize fuel economy within emissions constraints.

Re-use system control modifications for all other PHEV studies.

For the vehicle charge sustaining operation, the engine starts at pre-determined wheel power demand thresholds, and meets the road load demand, while maintaining battery SOC. The simulations were performed over consecutive UDDS cycles, until charge sustaining operation was seen over a complete UDDS cycle. For each of the different engine ON thresholds, the battery SOC controller was tuned so as to balance the battery SOC or the different engine ON thresholds.

The simulation results were compared to actual EIL test results for the same engine ON thresholds, in order to validate the simulation engine model and measure the emissions behavior of the engine and compare the emissions trends of the hardware with the ones observed with the ORNL model. Figure 4 below shows fuel economy in the charge sustaining mode for the PHEV, for different engine ON thresholds, for three consecutive UDDS cycles. It can be seen that the simulation results are in close agreement with the actual engine results.

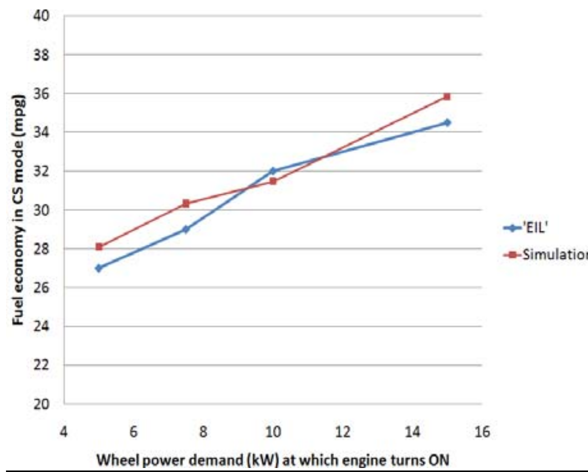

Figure 4: Comparison of the simulation and CIL fuel economy for CS mode of operation.

For the charge sustaining mode, the NOX, THC and CO emissions from the real engine were measured using an emissions analyzer. The trends observed in the emissions with the real engine were compared to the trends observed with the emissions and after-treatment model developed by ORNL. While the absolute numbers (g/mi) for the NOX,CO and THC varied from the simulations to hardware, the trends were similar. Figure 5 (a) and 5(b) compares the normalized CO and NOX emissions for the hardware and the software. In both cases, a value of '1' represents the maximum NOx or CO observed, and all other values are ratios with the maximum value.

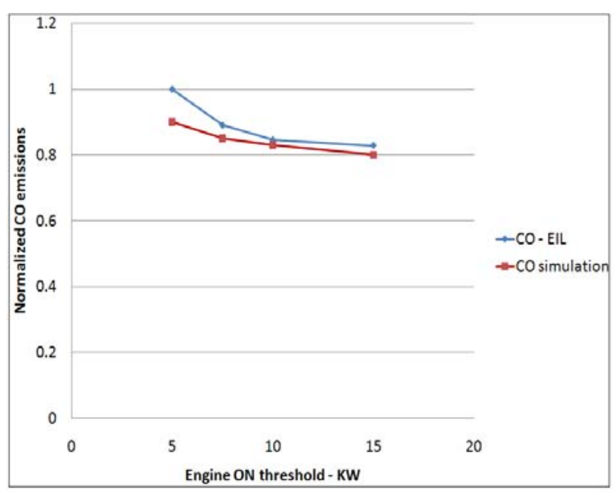

Figure 5: Comparison of CO trends for simulation and EIL.

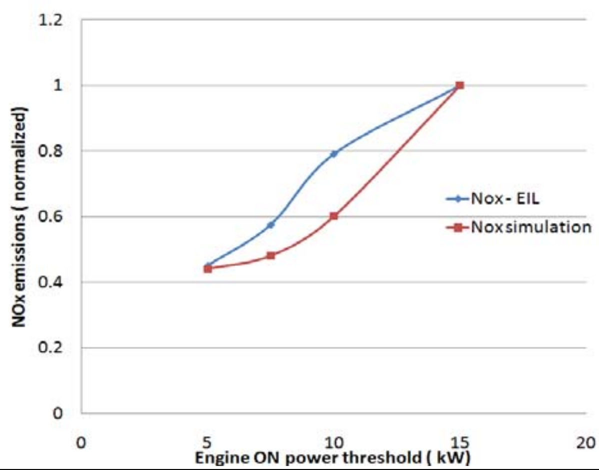

Figure 6: Comparison of NOx trends for simulation and EIL.

The following emission trends were observed during the Engine in the Loop tests:

CO emissions increase with increase in number of Engine ON events.

CO emissions are also proportional to the rate of power/torque demand from the engine. CO emissions decrease with a lower torque slew rate.

NOx is directly proportional to the engine load. NOx is generated at high combustion temperature, which is caused by high load on the engine.

Testing of cold start engine warm-up control on EIL

Vehicle energy management for cold start was developed by ORNL and integrated into the ANL vehicle model. Preliminary testing was performed using the cold start control.

Conclusion

- Model based design approach was used to evaluate the impact of supervisory control on the fuel economy and emissions of a series PHEV , this method entails a simulation study, with a subset of promising simulation results validated on hardware (Engine in the Loop).

- Argonne has developed a process for seamless migration from simulation to Engine in the Loop testing, for engines and other components.

- A series vehicle model was developed in AUTONOMIE, and the energy management was re-configured for easy implementation of charge – sustaining (hot) operation by ANL and cold start operation by ORNL. The series vehicle works in EV mode for the charge depleting region.

- A simulation study was performed for the charge sustaining operation, and the charge sustaining fuel economy results and emission trends were validated with engine the loop.

Future work

The EIL validation of the combined hot and cold start operation is currently being performed.

For the 2nd year of the study, the impact of supervisory control on fuel efficiency and emissions will be studied for a power-split PHEV. The model based design approach used for the series configuration will be used for this study. A subset of simulations will be validated using EIL.

Publications/Presentations

1. N. Shidore, et al, 'Trade-off between PHEV emissions and fuel efficiency', presentation at the 2010 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review, June 8th, 2010.

2. N. Shidore, et al, 'Impact of engine temperature and transient behavior on fuel displacement using Engine in the Loop', presentation at the Department of Energy, June 24th, 2010.

3. Rousseau, N Shidore, 'Impact of control strategy on fuel economy and emissions', presentation at DOE, September 13th, 2010.

B. Battery Energy Management at Cold Temperature

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Objectives

- Investigate energy management for fast battery temperature rise and engine efficiency improvement at very cold conditions.

Approach

- Perform a simulation study in Autonomie by integrating a response surface based thermal engine model developed at Argonne (from cold temperature dynamometer testing of a Prius) and battery temperature rise model based on battery data collected at Argonne.
- Isolate the impact of a cold battery (engine is at normal ambient conditions), a cold engine (battery is at normal ambient conditions).
- Vary battery and engine utilization by varying the parameter – wheel power demand at which the engine turns ON. Study impact of control parameter change on battery temperature rise and engine efficiency improvement.Evaluate the control strategy at cold temperature which provides the best trade-off between battery temperature rise and engine efficiency improvement (maximize powertrain efficiency) for a given driving pattern.
- Study the sensitivity of cold temperature impact on fuel and electrical energy consumption to driver aggressiveness and battery power restrictions.

Accomplishments

- Temperature dependent engine efficiency and fuel consumption model, and battery temperature model integrated into Autonomie.
- Impact of cold battery and engine on PHEV gasoline and electrical consumption identified, for varying engine ON control parameter.
- Sensitivity of the impact to variation in regen limitations, and driver aggressiveness identified.

Future Directions

- The same study can be expanded for different (colder) initial temperature scenarios.
- With flexible engine and battery thermal models, the study can be expanded to other PHEV configurations and vehicle classes.
-

Introduction

Limited battery power and poor engine efficiency at cold temperature result in low PHEV fuel economy and high emissions. Quick rise of battery temperature is not only important to mitigate lithium plating and thus preserve battery life, but also to increase the battery power limits so as to fully achieve fuel economy savings expected from a PHEV. Likewise, it is also important to raise the engine temperature so as to improve engine efficiency (therefore vehicle fuel economy) and to reduce emissions. One method of increasing the temperature of either component is to maximize their usage at cold temperatures thus increasing cumulative heat generating losses. Since both components supply energy to meet road load demand, maximizing the usage of one component would necessarily mean low usage and slow temperature rise of the other component. Thus, a natural trade-off exists between battery and engine warm-up.

In this study, the engine ON power-threshold is varied to create different battery and engine utilization scenarios and battery and engine temperature rise. The impact of the different temperature rise scenarios on fuel and battery energy consumption is studied.

Battery and engine 'thermal' models, cabin heater load modeling

For a fair comparison of the impact of battery utilization on battery temperature rise, battery temperature rise is modeled as a function of battery utilization (current) only. This model is based on actual testing of a 41 Ah, 10 kWh, 60 kW peak power Li-ion battery at cold conditions at ANL (Figure 1). It is assumed that on account of the battery cells being surrounded by a coolant jacket, there is minimal heat rejection by the battery to the ambient. The coolant is not circulated at the cold temperature, and therefore, there is no active cooling by the coolant itself.

The engine model is a response surface model developed by ANL as a part of another DOE funded study [1], using cold temperature testing of the Prius at 20 °F. The engine efficiency and fuel usage are a function of engine temperature and engine power. Engine temperature increases with engine usage, improving efficiency. Figure 2 shows the conceptual block diagram of the model.

Passenger comfort at cold temperatures can be provided by heating the cabin through engine waste heat or through a PTC heater. With infrequent engine ON in the charge depleting (CD) mode, it is anticipated that the engine temperature will not be sufficiently high to heat up the cabin. Therefore, for this study, the following assumption has been made to account for cabin heat: If the engine temperature is below 70 °C, the heater load will be provided by a PTC heater which will draw energy off the high voltage battery. The load profile (power) assumption for the PTC heater is shown in figure 3.

Design of experiment

A power split PHEV with a Prius powertrain model developed in Autonomie is used for this study. The default Prius battery model is replaced by the battery model described in the previous section. The battery power restrictions are a function of SOC and temperature.

It should be noted that through-out this study, initial temperatures for the cold battery or the cold engine are -6 °C. Also, the impact of cold temperature on the powertrain efficiency, other than the efficiency of the engine and the battery, has been neglected. In comparison to the inefficiencies of the engine and power restrictions of the battery, energy loss due to a cold powertrain will be minimal. Also, when comparing the impact of different control parameter settings at cold temperature, the powertrain efficiency is a common factor which can be therefore overlooked for a comparison study.

The virtual vehicle, with the engine thermal model and the battery temperature rise model, is subjected to consecutive LA92 cycles for a fixed driving distance.

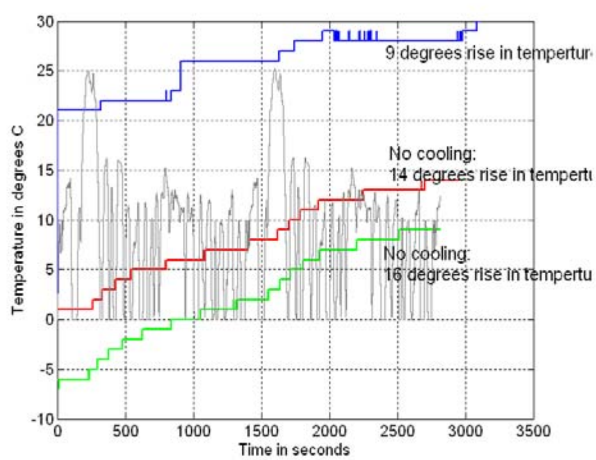

Figure 1. Actual battery temperauture rise data which was used for the battery temperature model.

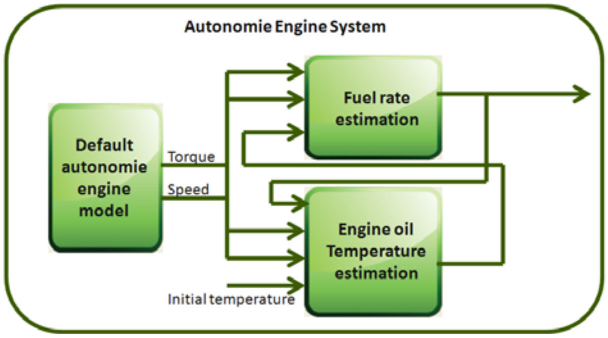

Figure 2. Engine model for efficiency as a function of engine usage, temperature.

In order to emulate different battery and engine energy utilization scenarios, the wheel power demand at which the engine turns ON, is varied.

Impact of cold battery, cold engine on battery and fuel energy usage for a given distance

Figure 4 is a plot of fuel energy consumed on the Y axis and battery energy consumed on the

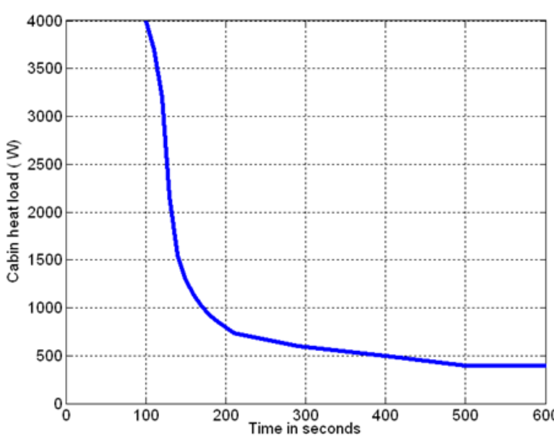

Figure 3. Cabin heating load assumption

X axis, for 20 miles of LA92 driving for engine ON at 15, 20 and 25 kW wheel power demand, at normal battery and engine temperatures (Blue line).The energy and battery consumption for 20 KW engine turn –ON due to a cold battery at an initial temperature of -6°C (engine at 20 °C), cold engine at initial temperature of -6°C (battery at 20°C) , and both cold engine and cold battery is shown by the purple, green and red dot From the plot, it can be observed that when comparing the impact of a cold engine (hot battery) and cold battery (hot engine), the impact of the cold engine and its low efficiency is significantly higher than that of the power restrictions of a cold battery. This can be attributed to two reasons:

1. PHEV batteries have a high P/E ratio, resulting in surplus power given that the battery has been sized for energy to last a certain equivalent electrical range. Therefore, in spite of power restrictions by the BMS at low temperature, the impact of battery power restrictions are low.

2. Use of PTC heater for a cold engine results in additional use of battery energy, even for the ‘engine COLD, battery at normal temperature’ scenario.

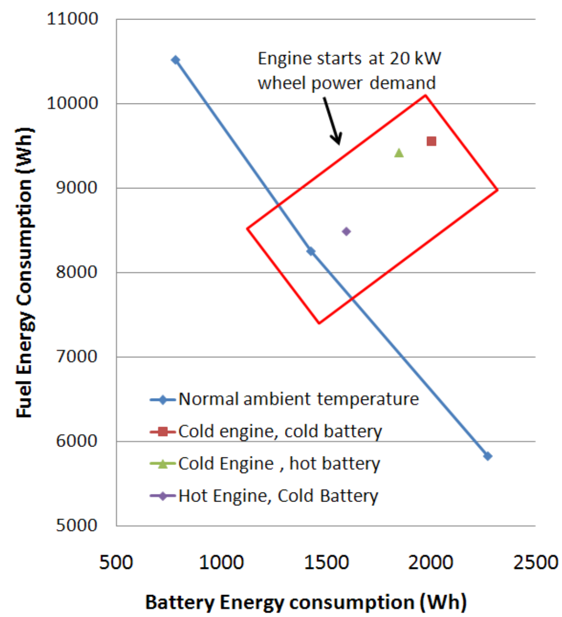

Figure 4. Impact of low temperature of battery and engine (individually and together) on fuel and battery energy consumption for a given distance, and control parameters.

Figure 5 shows the variation in fuel and battery energy consumption for the four scenarios of component temperatures outlined above due to variation in the wheel power demand for engine ON (from 5 kW to 30 kW).

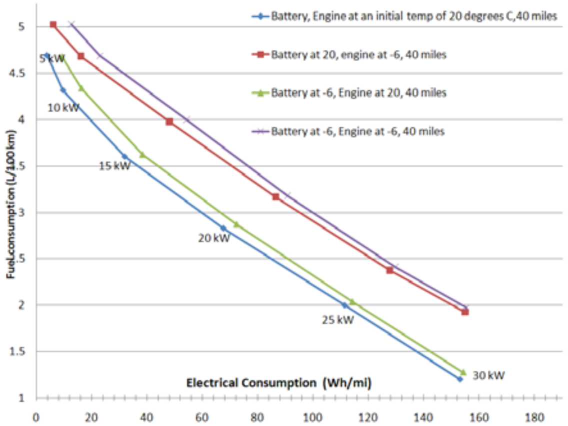

Figure 5. Impact of low temperature of battery and engine (individually and together) on fuel and battery energy consumption for a given distance, different control parameters.

One notices that when the engine turns ON at lower wheel power demands (e.g. 5 kW, 10 kW), the engine warms up faster and therefore the red curve (where the engine ONLY is cold) leans towards the blue (both engine and battery are at normal temperature) curve. In this case, the battery does not warm up fast if the engine turns on at a low power threshold, and therefore the green curve leans away from the blue curve. Similarly, if the engine turns on at a high power threshold (e.g. 25 kW, 30 kW), the engine remains at a lower temperature, and therefore inefficient, and therefore the red curve leans away from the blue curve. The battery temperature rises quickly on account of heavy utilization and the green curve leans towards the blue curve. The curve when both the engine and the battery are cold is a resultant of the green and the red curves. Based on the above curves, one can conclude the following:

1. The impact of low engine efficiency is greater than the impact of battery power restrictions at cold temperature.

2. In order to reduce the impact of a cold engine, it is expected that the engine be used often (lower engine ON threshold), while in order that maximum regen be captured, it is expected that the engine usage be reduced (higher engine ON threshold). Thus, there is a natural trade-off between engine efficiency improvement and battery power improvement.

Trade-off between battery temperature rise and engine efficiency improvement – maximizing powertrain efficiency.

For a given driving profile, the engine ON parameter which offers the best trade-off between battery temperature rise and engine efficiency improvement is the point at which powertrain efficiency is maximum, where powertrain efficiency is defined as:

$$\text{Power train efficiency} = \frac{\text{Energy at the wheel}}{\text{Fuel Energy} + \text{Battery Energy}}$$

For different engine ON parameters, the energy at the wheel will remain constant. Variation in the engine ON parameter will result in a variation in engine and battery utilization. A small power threshold for engine ON will result in large amount of engine usage (fuel energy), but result in more efficient engine operation on account of quick engine temperature rise, while a high power threshold will result in lower engine usage and low engine temperature rise.

In order to have a fair comparison between engines ON thresholds, only those engine ON parameter values which result in full battery discharge (60% SOC swing) have been compared.

Figure 6 shows the powertrain efficiency for different engine ON parameters, for a cold battery and cold engine initial condition, as well as when both the battery and engine are at normal ambient.

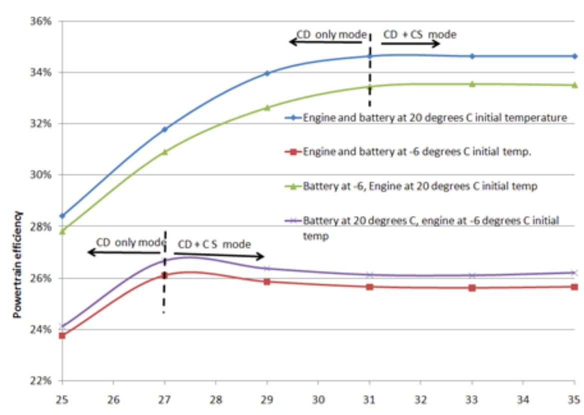

Figure 6. Powertrain efficiency over different engine turn-ON thresholds, with cold initial temperatures for the battery and or the engine.

The following observations can be made from figure 6:

1. The overall powertrain efficiency decreases significantly with an engine at an initial temperature of -6 °C, the impact of a cold battery on decrease in efficiency is minimal.

2. Maximum powertrain efficiency is achieved for lower engine ON thresholds for a cold engine scenario as compared to a scenario when the engine is at normal ambient temperature. This is expected, since a lower engine ON threshold results in more engine ONs and higher engine utilization, improving engine efficiency.

3. For the case when the battery and engine are cold, maximum powertrain efficiency is seen for 27 kW, after which powertrain efficiency decreases, unlike the case when both battery and engine are hot. This is the point of optimum usage of engine and battery power. Additional battery usage (higher engine ON threshold) results in lower engine temperature rise, lowering the efficiency.

Sensitivity to aggressive driving

All results above have been presented for the LA92 cycle, which represents typical urban driving. It is important to understand the impact of cold battery and engine temperature for more aggressive driving (US06) and a milder drive cycle (UDDS). Figure 7 below shows the electrical and fuel energy consumption, on a per mile basis for the two cycles in comparison to the LA92.

The percentage increase in fuel consumption, when the engine turns ON at 10 kW, 15 kW, 20 kW and 25 kW road load power, for the UDDS, LA92, and the US06, is given in Table 1. A table can be similarly constructed for the electrical consumption. From the table, it can be seen that the impact of cold temperature on fuel consumption decreases with aggressive driving. This is expected, since higher road load demand leads to higher utilization of the engine as well as the battery, causing quick temperature rise and lowering the impact of cold battery and cold engine.

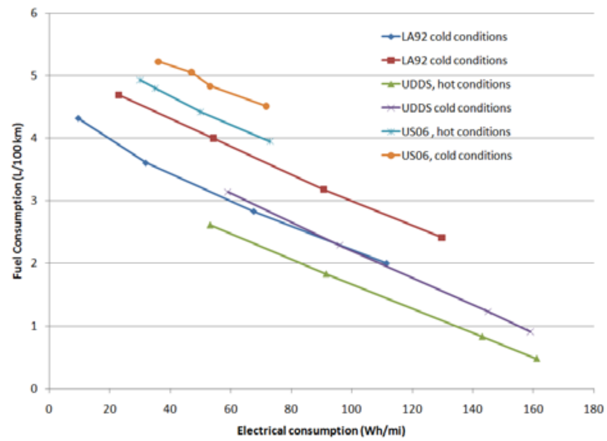

Figure 7. Impact of cold temperature on fuel and electrical consumption for mild and aggressive driving.

Table 1. Fuel consumption variation for different cycles, different engine ON thresholds.

Cycle	10 kW	15 kW	20 kW	25 kW
UDDS	25%	25%	48%	89%
LA92	8.5%	10.96%	12.35%	20.61%
US06	5.1%	9%	8.2%	14.7%

Impact of battery power limitations

The battery power restrictions, as a function of temperature, were varied, as shown in Figure 8. The battery power limits were halved and doubled, to see the impact on cold temperature behavior. Figure 9 shows the impact of battery power restrictions on fuel and gasoline energy consumption.

As seen from Figure 9, the impact of changing power restriction on the fuel or electrical consumption is minimal. It can be anticipated that the effect of changing power restrictions will be more if the driving distance is short, for example 10 miles or 20 miles.

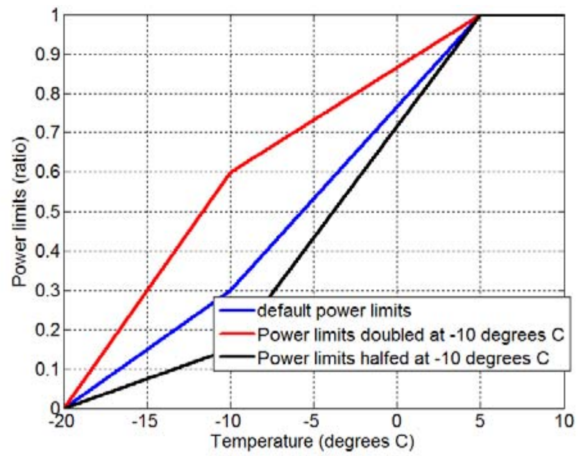

Figure 8: Battery power limit variation at cold temperature.

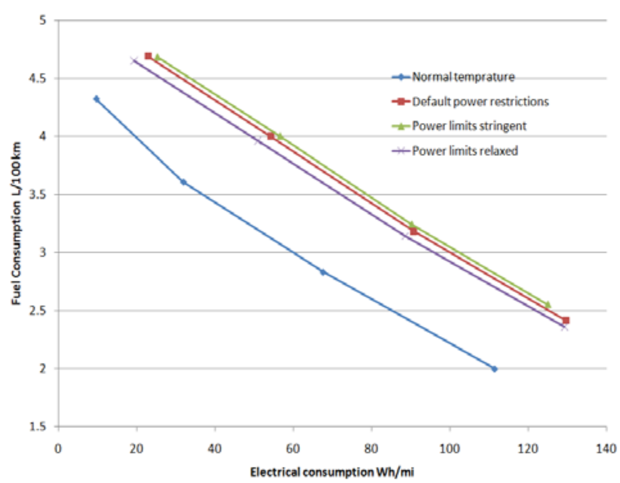

Figure 9: Impact of change in battery power restrictions at cold temperature for 40 miles, LA92.

Conclusion

The impact of battery and engine utilization, at cold temperature, was varied by changing the wheel power demand for engine ON, for a PHEV Prius configuration. The impact of a cold battery and a cold engine was assessed; the impact of a cold engine is higher than the impact of a cold battery, for the given configuration.

In order to attain maximum possible powertrain efficiency at cold temperature, it is needed to have more frequent engine starts (lower engine ON threshold).

The impact of driver aggressiveness and battery power restrictions on cold temperature fuel economy and emissions was assessed.

Future work

Drivability and cold start emissions from the other two aspects which decide powertrain control parameters. With more sophisticated models, the study can be repeated with the above factors in consideration. The study can be extended to see the impact of different engine and battery temperatures (colder temperatures).

Publications/Presentations

1. N. Shidore, et al, 'Energy management strategies for fast battery temperature rise and engine efficiency improvement at cold temperatures', presentation at the 2010 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review, June 8th, 2010.

C. International Cooperation Task

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Objective

The primary objective of this task was to help the DOE Vehicle Technologies (VT) Program meet its obligations in International Initiatives, as requested by DOE EERE management or Policy & International Affairs.

Introduction

The DOE's approach to cooperation in Europe has shifted from bi-lateral to multi-lateral agreements, emphasizing coordination through the U.S.-EU Energy Council that was formed in July 2009 by DOE Secretary Chu and the Deputy Prime Minister Olofsson of Sweden. Three working groups were formed under the auspices of the Council to address mutual interests, one of which was the Smart Grid-Electric Vehicle (SG-EV) Working Group.

The U.S.-China EV Initiative was announced by Presidents Barack Obama and Hu Jintao in November 2009 to accelerate the deployment of electric vehicles. The scope of cooperation includes joint standards development, demonstration projects, technical roadmapping, and public education projects. The DOE manager of this task is responsible for activities related to EV standards, as well as the transportation electrification demonstration programs.

In addition to the continuous activities outlined above, ad hoc support is often requested for meetings that include a variety of representatives of foreign governments/private companies. Further support is also offered at international events planned by other U.S. government agencies that are related to the mission of DOE VT (e.g., Climate Change Conferences and trade missions).

Approach

Direct support to the VT Program is provided through partial support of the M&O assignment of Keith Hardy to DOE Headquarters in Washington, D.C. In response to the changing nature of the relationship with Europe and Asia, EU-related support activities have transitioned from bi-lateral (e.g., cooperative technology development with Test Site Sweden) to EU-level interactions, and the scope of the international task has been expanded to encompass cooperation with China.

The approach to supporting international activities is to leverage the results of ongoing technology development within VT to minimize additional demands on technical activities, while credibly supporting the primary message of global harmonization of grid connectivity standards. The most obvious dependency is the Argonne Grid Connectivity task (Ted Bohn, Principal Investigator), which is the critical resource for the vehicle-grid communication methodology and standards that are reflected in the interactive vehicle-grid display.

Accomplishments

This task does not have the typical milestones of a technology development or testing program at Argonne. Therefore, the accomplishments listed below are presented in approximate chronological order.

Coordinated DOE VT participation in the Climate Change Conference (COP 15 in Copenhagen) BrightGreen Exhibition, which included design of the interactive vehicle-grid display (Figure 1) to demonstrate the interaction among energy supplies, grid operators, electric power grids, and EVs, with a focus on grid connectivity and the consumer interface. Efforts required interaction with the Swedish Energy Agency, Test Site Sweden, and the Departments of State and Commerce.

Figure 1. Ted Bohn Describing the Interactive Vehicle-to-Grid Display Exhibit at the Climate Change Conference (COP 15) in Copenhagen, Sweden

Supported the U.S.-EU Energy Council SG-EV Working Group:

Authored the original U.S.-EU Energy Council Smart Grid and Electric Vehicles Working Group Work Plan and

Served as the U.S. organizer of the Transatlantic Workshop on EVs and Grid Connectivity.

Supported U.S.-China EV Initiative:

Authored a white paper on U.S.-China cooperation on standards,

Developed a U.S.-China workshop outline and materials for the U.S.-China pre-meeting regarding challenges and opportunities for cooperation on codes and standards, and

Moderated a vehicle-grid connectivity session and delivered a presentation on standardization/harmonization of the vehicle-grid interface at the U.S.-China Electric Vehicle and Battery Technology Workshop.

Proposed joint activities with the International Energy Agency (IEA), reviewed objectives of the IEA Advanced Technology Forum, recommended a follow-up study to confirm "funding commitments" in the EV Technology Roadmap, and proposed that IEA serve as the independent analyst for the data gathered in cooperative U.S.-EU and U.S.-China vehicle demo programs. These became two of three elements of the eight-country multi-lateral "Electric Vehicles Initiative" announced in Paris in October 2010.

Participated in the U.S. Trade Mission to Paris, and provided an overview of transportation research and opportunities for cooperation/new business.

Participated in the workshop, "Government Support for Battery Manufacturing," sponsored by DOE and the French Environment and Energy Management Agency (ADEME), and discussed batteries and standards in the vehicle-grid system.

Delivered the keynote address at the Batteries 2010 Conference, and discussed implications for batteries in the vehicle-grid interface.

Organized and chaired the EVS 25 Plug-in Vehicle Workshop in Shenzhen, China, and included the design of the second-generation vehicle-grid display that highlights the activities of the Grid Interaction Technical Team in the system context.

Supported EERE management in meetings with international delegations to discuss potential bi-lateral cooperation with respect to vehicle-grid connectivity/codes and standards (e.g., Germany, Netherlands, and Spain).

Supported EERE management in technical briefings/proposals by various private companies, including Greenwave Reality, Mercedes Benz, and BMW.

Papers/Presentations

1. Hardy, K. and Bohn, T., *Proposed U.S.-China Cooperative Standards Activities*, background paper for U.S.-China interactions to DOE-EERE, Washington, D.C., January 2010.

2. U.S.-EU Energy Council Smart Grid and Electric Vehicles Working Group Work Plan, prepared for working group adoption, April 2010.

3. *Transatlantic Workshop on Electric Vehicles and Grid Connectivity*, working paper for workshop guidance, original drafted in April 2010.

4. Bohn, T. and Hardy, K., *Opportunities for Standardization/Harmonization in the Vehicle-Grid System*, presentation at the U.S.-China EV & Battery Technology Workshop, Argonne National Lab, Argonne, IL, August 2010.

5. Bohn, T. and Santini, D., *The Role of Batteries in the Vehicle-Grid System*, presentation B2B Conference at ADEME, Paris, France, September 2010.

6. Bohn, T. and Santini, D., *The Role of Batteries in the Electric Vehicle-Smart Grid Interface*, keynote address at Batteries2010, Cannes-Mandelieu, France, September 2010.

D. PHEV Engine Control and Energy Management Strategy

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Objective

- Investigate novel engine control strategies targeted at rapid engine/catalyst warming for the purpose of mitigating tailpipe emissions from plug-in hybrid electric vehicles (PHEV) exposed to multiple engine cold start events.
- Validate and optimize hybrid supervisory control techniques developed during previous and on-going research projects by integrating them into the vehicle level control system and complementing them with the modified engine control strategies in order to further reduce emissions during both cold start and engine re-starts.

Approach

- Select an engine suitable for hybrid applications and characterize its components operation as well as its overall performance, fuel consumption and emissions.
- Develop an open source prototype engine controller capable of replacing the production controller in order to implement new engine/catalyst warm up strategies
- Implement engine control algorithms into an experimental engine-in-the-loop test stand in order to validate control methodologies and verify transient thermal and emissions performance. (FY11)
- Integrate, develop and optimize hybrid supervisory control strategies in coordination with engine level strategies to minimize cold start emissions (FY12)

Major Accomplishments

- Held co-operation discussions with two American OEMs for engineering support. Unsuccessful up to Q4 of FY10 when Tier 1 supplier intervention revived hope of collaboration for FY11.
- Selected research engine: GM 2.4l Ecotec stoichiometric direct injected gasoline engine
- Characterized engine operation, performance, fuel economy and emissions over the complete operating range.
- Set-up open source controller and steady state control strategies for test engine
- Installed engine on The University of Tennessee engine dynamometer test cell

Future Direction (FY11)

- Develop and calibrate engine control strategies with focus on engine warm-up, rapid catalyst heating and reduced cold emissions (with limited regards for fuel consumption)
- Engine control strategies implementation and validation on dynamometer
- Hybrid powertrain Hardware-In-the-Loop (HIL) System Development
- Supervisory hybrid vehicle control integration onto HIL platform

Introduction

Plug-in hybrid electric vehicle (PHEV) technologies have the potential for considerable petroleum consumption reductions, at the expense of increased tailpipe emissions due to multiple "cold" start events and improper use of the engine for PHEV specific operation. PHEVs operate predominantly as electric vehicles (EVs) with intermittent assist from the engine during high power demands. As a consequence, the engine can be subjected to multiple cold start events. These cold start events have a significant impact on the tailpipe emissions due to degraded catalyst performance and starting the engine under less than ideal conditions. On current hybrid electric vehicles (HEVs), the first cold start of the engine dictates whether or not the vehicle will pass federal emissions tests. PHEV operation compounds this problem due to infrequent, multiple engine cold starts.

Previous research focused on the design of a vehicle supervisory control system for a pre-transmission parallel PHEV powertrain architecture. Energy management strategies were evaluated and implemented in a virtual environment for preliminary assessment of petroleum displacement benefits and rudimentary drivability issues. This baseline vehicle supervisory control strategy, developed as a result of this assessment, was implemented and tested on the Mobile Advanced Technology Testbed (MATT) at the ANL Advanced Powertrain Research Facility (APRF) over a baseline test cycle.

Engine cold start events were aggressively addressed in the development of this control system, which led to enhanced pre-warming and energy-based engine warming algorithms that provide substantial reductions in tailpipe emissions over the baseline supervisory control strategy. The flexibility of the PHEV powertrain allowed for decreased emissions during any engine starting event through powertrain "torque shaping" algorithms that eliminate high engine torque transients during these periods.

This project expands the work completed so far to include investigating the effects of complementing supervisory powertrain control techniques with novel engine control strategies targeted at rapid engine/catalyst warming.

Approach

Target Engine Identification

The engine used for this program has to be representative of typical engines used for PHEV applications from a size and power perspective. It has to be state-of-the-art technology to offer all the latest advanced technologies to reduce emissions and increase fuel economy. Discussions were held with domestic OEMs for them to provide engineering support while using one of their engines as the research engine, but lack of resources on their parts prevented that co-operation to materialize in FY10. On-going discussions with a Tier one supplier might results in collaboration starting in FY11.

The GM Ecotec 2.4l LAF was selected for that study because it is a gasoline direct injected engine which makes it relevant for PHEV applications, with the direct injection system providing additional degrees of freedom for cold start emissions reduction. This engine is naturally aspirated which reduces the overall controller level of complexity; bearing in mind the absence of support from the OEM, it is reasonable to limit the scope of work by reducing the number of degrees of freedom. The engine capacity of 2.4l is larger than targeted for a PHEV application but no other smaller capacity direct injected gasoline engine was readily available in the U.S. when the selection process took place. Table 1 shows the engine main specifications.

Table 1. Main Specifications of the GM Ecotec LAF Engine

Component	Specifications
Capacity	2.4l 4 cylinder
Injection system	Stoichiometric direct injection
Max power	136kW (182hp) @ 6700rpm
Max Torque	233Nm (172lb.ft) @ 4900rpm

Target Engine Characterization

The engine was characterized in order to establish a benchmark of the production engine fuel economy and emissions as well to provide the necessary information required to replace the production engine controller with an open source prototype controller.

The engine characterization could not be performed on an engine dynamometer because this type of testing requires a pre-production engine controller that is only available from the OEM. Without one, the characterization had to be performed in a vehicle on a chassis roll dynamometer. That phase was split into two different sessions: one to characterize the engine sensors and actuators as well as general engine operation, the second session characterized the engine overall emissions and fuel economy.

A 2010 Chevrolet Equinox LT equipped with our 2.4l Ecotec LAF research engine was leased for the purpose of that study. The engine operation characterization was performed on a Mustang Dynamometer (MD-AWD-500-SE) used in two wheel drive mode. Data was retrieved from the production sensors and actuators as well as from the production engine controller using a generic service tool. Some additional sensors (such as Air Fuel Ratio sensor) were fitted to complete the instrumentation set. Engine speed and load conditions were spanned to cover most engine operating points (20-100% load, 800 to 5000rpm). Data was logged and formatted to be used in the prototype controller in order to run the engine in steady state mode on a dynamometer test cell. Figure 1 shows the engine spark timing map as an example of engine data obtained during that phase.

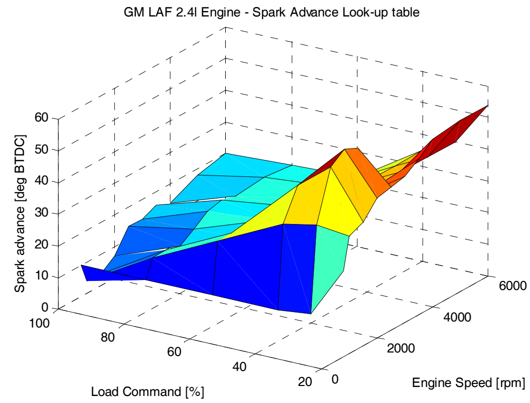

Figure 1. Spark advance timing map

Later on, engine emissions and fuel economy were assessed on ORNL' Burke E. Porter chassis dynamometer. The vehicle exhaust system was instrumented to measure raw engine out, raw tailpipe and diluted tailpipe out emissions while spanning the same engine operating conditions as during the engine mapping exercise (20-100% load, 800 to 5000rpm). Total hydrocarbons, CO, NOx, CO2 and O2 were logged. These results will constitute the reference points to calibrate to when the prototype controller replaces the original production controller. Figure 2 show total hydrocarbon engine out emission flow as an example of emissions obtained during that study.

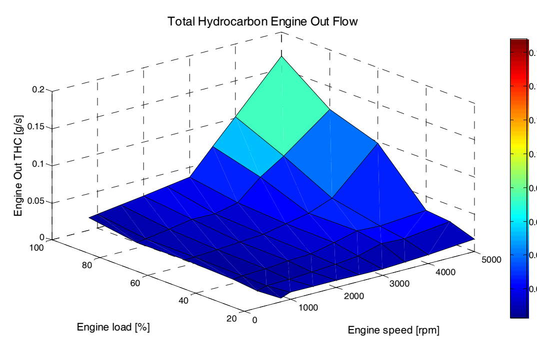

Figure 2. Total hydrocarbon engine out emissions on LAF engine

Open Source Prototype Controller Development

The prototype engine controller hardware is a Woodward production intend module. The fuel injectors are controlled by that module via an external power stage supplied by Continental specifically designed for solenoid type direct injection gasoline injectors. The production engine harness has been adapted to interface the production engine with the Woodward module.

The prototype engine strategies are implemented within The Mathworks Simulink environment and integrated into the Woodward controller using Woodward's Motohawk tool suite. This provides a seamless transition from the off-line simulation environment to the real world application environment since Simulink is used in both cases to implement the high level control strategies.

Engine control strategies have been designed to handle steady state operation based on the engine characterization performed earlier on. Cold start and catalyst heating strategies will be developed during FY11.

Engine Set-Up On Dynamometer Cell

The University of Tennessee, Knoxville (UTK) is designated as a DOE Graduate Automotive Technology Education (GATE) center concentrated on hybrid powertrains and control systems. This resource will be leveraged to support this project, including training graduate students in some of the unique aspects of advanced powertrain control development. The experimental phase of this project will be conducted at UTK's Advanced Powertrain Controls and System Integration (APCSI) facility.

An Ecotec LAF crate engine has been procured and installed in the APCSI engine dynamometer test cell. The prototype controller and harness have been fitted to the engine for commissioning.

Conclusions

The first year of this three-year project has seen the selection and characterization of the GM Ecotec LAF engine as the research engine to optimize cold start emissions on PHEV applications. An open source prototype controller has been developed with baseline engine strategies. This sets up the next phases of the project due to occur during FY11: engine commissioning on the University of Tennessee APCSI facility and development of engine warm-up and catalyst heating strategies before creating a hybrid powertrain Hardware-In-the-Loop system to test the newly developed engine control strategies with previously developed hybrid supervisory strategies.

E. CoolCab – Truck Thermal Load Reduction Project

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Objectives

- To identify or develop market-viable technologies that keep the truck cab comfortable without the need for engine idling, helping to reduce the 838 million gallons of fuel used for truck overnight idling
- To determine the potential fuel saving from reducing the truck cabin thermal load through testing and analysis
- To develop a tool for industry to use that predicts HVAC load reduction in truck cab/sleepers

Approach

- Work closely with industry to research, evaluate, and develop commercially viable idle-reduction technologies
- Build upon existing tools and test methods to develop truck cab specific analysis tools and test techniques that assess the impact of technologies that reduce the thermal load, improve the climate control efficiency, and reduce vehicle fuel consumption

Accomplishments

- Completed thermal testing of Volvo 770 and Kenworth T660 truck cabs
- Added and improved CoolCalc functionality
- Completed initial CoolCalc validation
- Developed air conditioning system model framework and integrated with CoolCalc
- Developed an initial data transfer process between Autonomie and CoolCalc
- Shared Beta version of CoolCalc with industry partners for review and feedback

Future Directions

- Release first public version of CoolCalc, based upon improvements from the Beta version feedback
- Expand the FY10 A/C framework model to a complete light-duty vehicle (LDV) air conditioning (A/C) model
- Collaborate with heavy-duty vehicle (HDV) A/C suppliers to obtain HDV A/C component data and build a HDV A/C model
- Work with industry partners to test and improve advanced idle reduction technologies
- Assist truck manufacturers by using NREL’s analysis tools and test methods, to implement advanced idle reduction technologies that reduce thermal loads and truck idling fuel use

Introduction

Heating and air conditioning is one of the primary reasons for long-haul truck main engine operation when the vehicle is parked. In the United States, trucks that travel greater than 500 miles per day use 838 million gallons of fuel annually for overnight idling [1]. Including workday idling, over 2 billion gallons of fuel is used annually for truck idling [2]. By reducing thermal loads and improving efficiency, there is great opportunity to reduce the fuel used and emissions created by idling. Reducing the thermal load for truck cab/sleepers will enable cost-effective idle reduction solutions. If the fuel savings from new technologies can provide a 3-5 year payback time, fleet owners will be economically motivated to incorporate them. This provides a pathway to rapid adoption of effective thermal load reduction solutions.

The U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) CoolCab project is researching efficient thermal management systems that keep the cab occupants comfortable without the need for engine idling. The CoolCab research approach is to reduce thermal loads, concentrate on occupant thermal comfort, and maximize equipment efficiency. By working with industry partners to develop and apply commercially viable solutions that reduce idling fuel use, both national energy security and sustainability will be improved. To achieve this goal, NREL is developing tools and test methods to assess idle reduction technologies. The truck cab industry needs a high level analysis tool to predict thermal loads, evaluate load reduction technologies, and their impact on climate control fuel use.

To meet this need NREL has developed CoolCalc, a software tool to assist the industry in reducing climate control loads for heavy-duty vehicles. CoolCalc is an easy-to-use physics-based HVAC load estimation tool that enables rapid exploration of idle reduction design options for a range of climates.

Approach

Coolcalc model development

CoolCalc is an easy-to-use simplified physics-based HVAC load estimation tool that requires no meshing, has flexible geometry, excludes unnecessary detail, and is less time intensive than more detailed Computer Aided Engineering (CAE) modeling approaches. It is intended for rapid trade-off studies, technology impact estimation, preliminary HVAC sizing design, and to complement more detailed and expensive CAE tools.

CoolCalc is built on NREL's OpenStudio platform. This was done to accelerate development and leverage previous and ongoing DOE investments. OpenStudio was developed at NREL and released in 2008. It is a plug-in extension of Google's SketchUp software. DOE's EnergyPlus is used as the heat transfer solver. EnergyPlus is a DOE funded software, designed for building efficiency analysis, which was found to be general enough to extend to truck cab thermal modeling.

Unlike previous building thermal simulation programs, EnegyPlus provides a fully integrated simulation, where the building HVAC zones, system, and plant (source) are solved simultaneously. This provides a more physically realistic solution and allows for more detailed control implementation. Heat transfer is described by a set of time dependent energy and moisture balances and the resulting ordinary differential equations are solved using a predictor-corrector approach. For solar loading, an anisotropic radiance model is used allowing the superposition of three components: isotropic radiance, point source circumsolar brightening at the sun, and horizon brightening. The sun position is tracked as a function of geographic location, time of year, and time of day. A shading model is implemented that accounts for shadowing of surfaces by other surfaces. EnergyPlus's window model is based on Lawerence Berkeley National Laboratory's (LBNL) WINDOW program algorithms and uses solar transmittance, reflectance, and absorptance properties. Full spectral analysis is also possible. All surfaces are treated as gray bodies. The external surface heat transfer balance includes shortwave solar radiation, longwave thermal radiation, convection, and conduction through the walls. Conduction is one dimensional through the thickness of a wall. Walls are defined using a series stack up of materials that allow for thermal storage. The interior surface heat transfer modes include shortwave solar radiation from windows, longwave radiation, and convection. The internal radiation view factors are approximated by a ratio of "seen" areas, then corrected for reciprocity and completeness. A detailed description of EnergyPlus's modeling and solution methods is beyond the scope of this paper, for further details see the extensive documentation available [3].

While CoolCalc is flexible and does not dictate a specific process, a typical workflow (illustrated in Figure 1), might begin with the creation of geometry using the Parametric Cab creation tool (Figure 2). The Parametric Cab creation window has a series of tabs across the top, one for each air zone in the model. Each tab has a list of available parametric variables which will modify the geometry. These variables and the parametric geometry relationships are determined by a model definition file created in the geometry coding framework. The user can also switch between the available parametric cab models to find one that that best suits their needs. To the right of the units, the allowable variable range is displayed. To illustrate this parametric capability, the windscreen angle was changed from 60° to 80° (Figure 3). The cab model quickly updates, allowing for fast modification of the geometry.

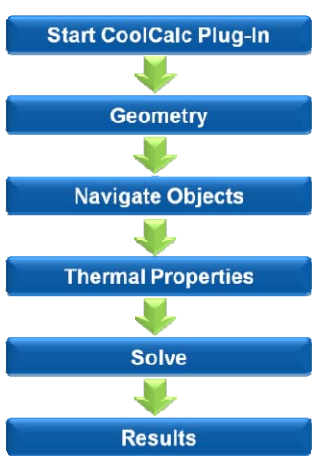

Figure 1. Typical CoolCalc Workflow

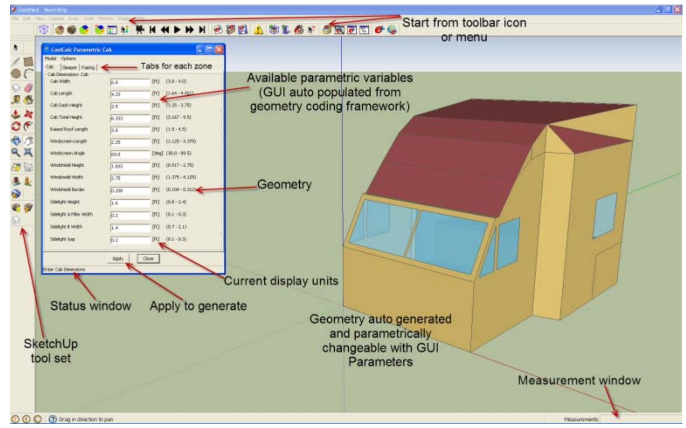

Figure 2. Parametric Cab Geometry Creation

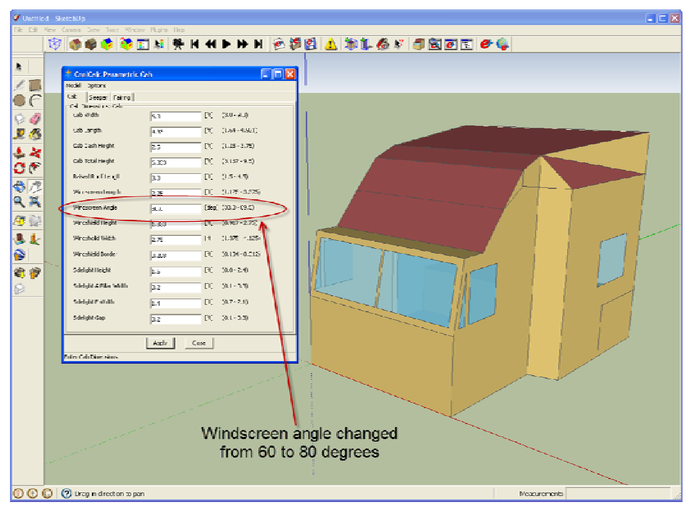

Figure 3. Parametric Cab with Modified Windscreen Angle

Once the cab geometry is established using the Parametric Cab tool, it can be manually modified by the user. Figure 4 shows an example of a user adding an additional sidelight to the sleeper cab. The sleeper cab sidewall was activated by double clicking on the surface. Once activated, the SketchUp drawing tools can be used to modify the geometry. The dashed lines are construction lines that were created to help quickly draw the sidelight and can be easily hidden or deleted later. The pencil tool was then used to trace out the construction lines. The pencil tooltip icon can be seen in the top left corner of the sidelight. Once the window shape is closed by the pencil tool, it is automatically recognized as a window and assigned default properties.

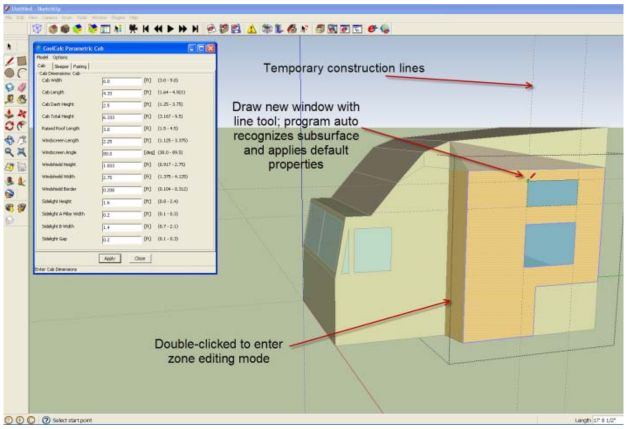

Figure 4. Manual Modification of Geometry - Adding a Sidelight

In EnergyPlus, every component of the model, e.g. walls, materials, location, and solver time step, is treated as an object. In CoolCalc, to modify or define new objects the Object Browser tool is opened (Figure 5). On the left side of the Object Browser window is the object tree, which shows all the objects that are available in the model and allows the creation of new objects. Below the object tree is the library window. The library window allows the user to load and manipulate additional libraries of objects. These objects can then be added to the current model by dragging and dropping them into the object tree. Below the specific object window interface, to the right of the object tree, is the text editing window. This window allows for the manual modification of the current object, giving full control to advanced users. For objects where no specific interface has been developed, the text editing window will comprise the entire right side of the split window. All object windows also provide an "add comment" option in the upper right corner to help users document their object assumptions.

To modify or define new materials, a material object is selected in the object tree (Figure 5). Based on this object tree selection, the material definition window is displayed on the right. The material definition window provides text boxes or pull-down menus for all the basic material thermal properties: name, roughness, thickness, conductivity, density, specific heat, and radiation absorptance.

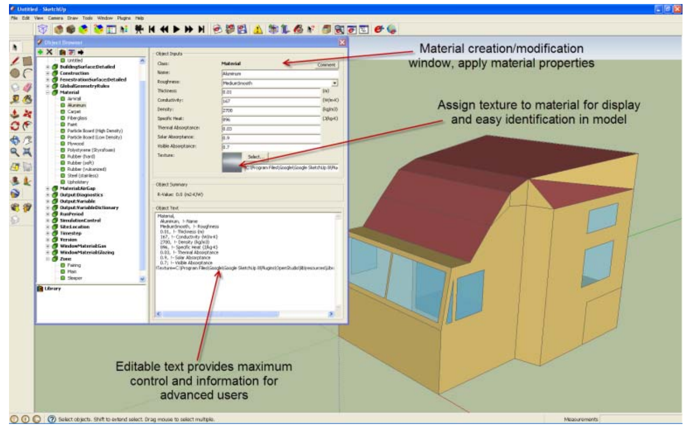

Figure 5. Object Browser and Material Definition Window

Each surface in CoolCalc is treated as multiple layer one-dimensional conduction, forming a "sandwich" type structure. To define this layered structure, a construction object is used. Once again navigating the object tree, a construction object is selected. This changes the current object window (right side) to display the construction definition window (Figure 6). In this window the user selects the materials to include in the construction and can change their order.

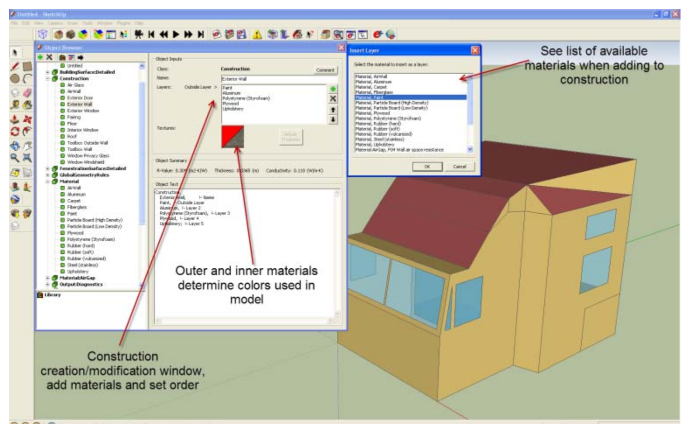

Figure 6. Construction Definition Window

Figure 7 shows the model in construction rendering mode. In this mode, the inner and outer surfaces are colored by their respective construction's material textures. The window to the left of the cab is the Construction Palette. It allows the sorting and selection of constructions and their application to the model using a point and click paint can tooltip.

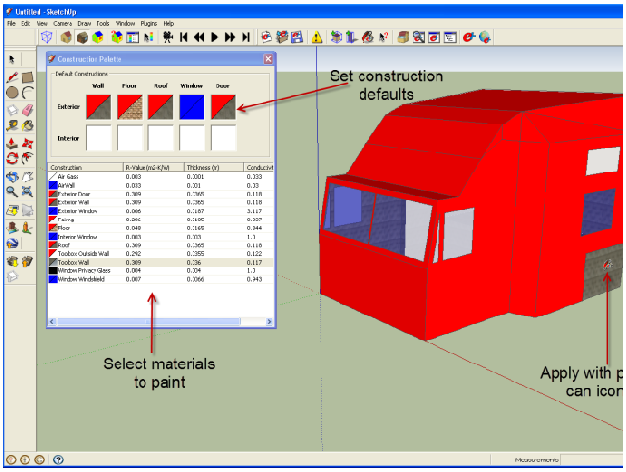

Figure 7. Construction Palette Window and Texture Rendering Mode

Before solving the model, a weather file is selected. There is currently Typical Mean Year (TMY) data available for 2100 locations worldwide. Custom weather data can also be entered. A simulation period of one day to one year is also selected. Once the model is solved, the results can be displayed within the interface. Figure 8 shows the exterior temperatures on the truck cab/sleeper. In addition to temperatures, the climate control loads can be calculated. To determine the impact of the thermal loads on engine power and ultimately vehicle fuel use, an A/C model was developed.

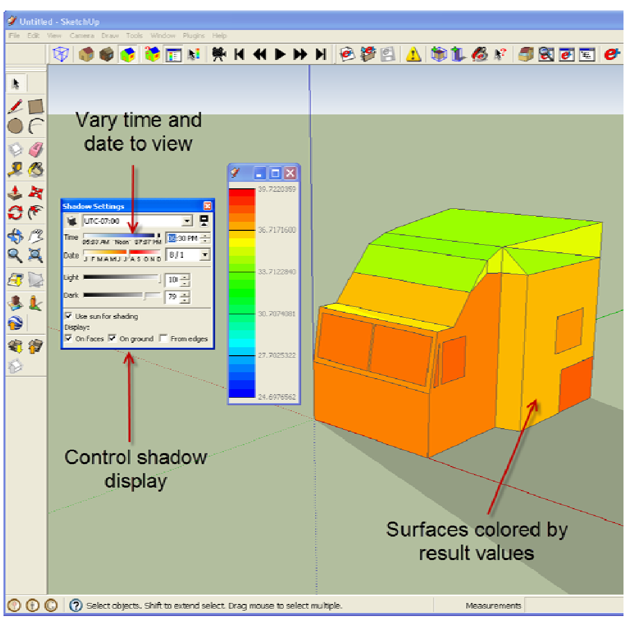

Figure 8. Example Temperature Distribution

A/C model Development

The A/C model shown in Figure 9 was developed in the MATLAB/Simulink modeling environment and was converted into executable code using the Real Time Workshop module of MATLAB. Since CoolCalc uses this executable, a CoolCalc user does not need to have a MATLAB license. The CoolCalc preprocessor is able to edit the input file and to read and process the output file of the A/C model. The CoolCalc preprocessor runs the A/C model multiple times to create a table of compressor powers as a function of operating conditions. This table is then used as a lookup table during the main time sweep of the CoolCalc run. Thereby, the overall A/C model run-time is reduced.

The current version of the A/C model calculates the steady state system performance. A/C system definition and operating conditions are input parameters and the steady state (or continuous 100% duty cycle) performance of the system is output.

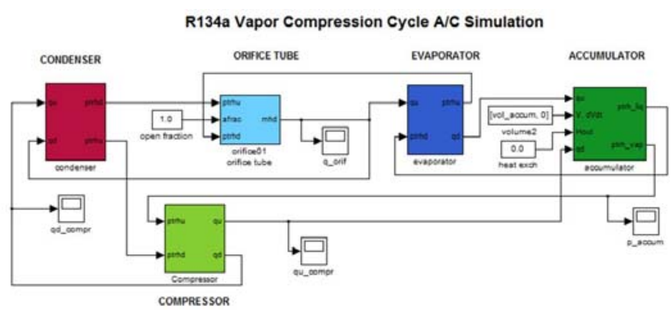

Figure 9. The Top Level of the Simulink A/C Model

The A/C system model requires definition of the condenser and the evaporator geometry, expansion device, and compressor. In addition, the air flow velocity and temperature over the condenser and evaporator must be set. Since the current definitions are broad approximations, the current A/C model should be considered a framework until real components can be created.

Currently, the condenser and evaporator are modeled as parallel tube heat exchangers (Figure 10) with up to four rows (one pass per row). The tube dimensions and number of tubes per row are variables. The change in temperature of the airflow as the air passes through the consecutive tube rows is accounted for. In the current framework, the heat exchanger fins are not modeled. The air-to-tube heat transfer is modeled as a bare tube in crossflow (Eq. 7.53 from [4]) and the tube-to-refrigerant heat transfer calculation uses the Dittus-Boelter equation (Eq. 8.58 of [4]).

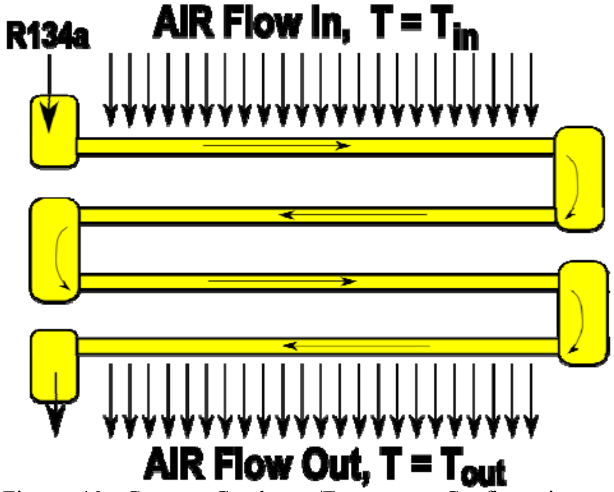

Figure 10. Current Condenser/Evaporator Configuration (Each Layer of Tubes is Represented with one Tube only in this Sketch)

The expansion device is currently an orifice tube, defined with diameter and discharge coefficient only. The mass flow rate through the orifice tube is calculated using a choked-flow equilibrium model. This model was checked against the measured data published in [5]. Further improvement of the model that accounts for non-equilibrium behavior is planned.

The compressor model assumes a positive displacement device. The compressor speed and displacement per revolution are inputs and adiabatic compression is assumed. The effect of irreversibilities is incorporated through an adiabatic efficiency parameter.

The A/C model currently uses R134a refrigerant. R134a thermodynamic and transport properties are determined from density and the internal energy because these are the two states calculated by the model in each of the control volumes. Lookup tables were generated using the REFPROP software [6].

The A/C model starts out from a standard initialization and uses a time relaxation method to iterate to the steady state operation of the system. Various relaxation factors aid achieving quick convergence, although further optimization of these factors will result in considerable improvement in execution speed. Figure 11 shows the thermodynamic results for a series of ambient temperatures.

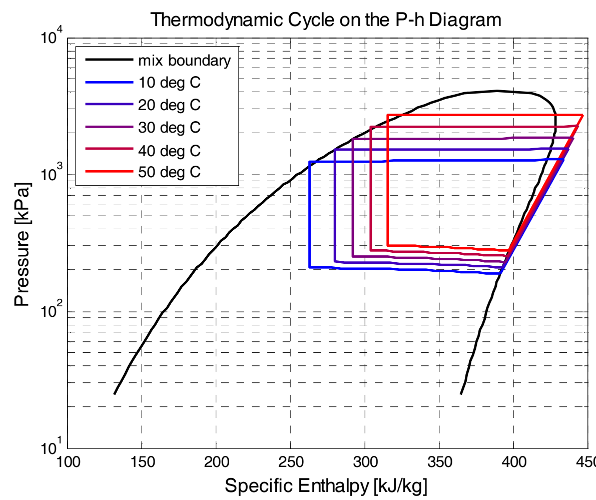

Figure 11. Output from A/C model shown on a P-h Diagram for a Series of Ambient Temperatures

The A/C system model will serve as a framework for future development. More advanced heat transfer equations on the air side and two-phase flow equations on the refrigerant side will be implemented. More work remains to optimize the performance of the model and to verify the results. Verification will be achieved through comparison with both test data and results generated with other A/C system simulation software. Time accurate simulation of transient heat transfer in the A/C system will be an important future improvement to the model.

Vehicle Thermal Testing

An outdoor test program was conducted to collect data for CoolCalc validation, characterize truck cab/sleepers, and provide high quality thermal performance data for production vehicles to industry partners. Kenworth and Volvo participated in the test program providing T660 and 670 sleeper cab trucks, respectively. Experimental evaluation of the trucks was conducted at NREL's Vehicle Thermal Soak Test Facility at an elevation of 5853 feet, latitude of 39.7 degrees, and longitude of -105.2 degrees.

The two industry provided trucks were used as test vehicles while a third, an NREL owned truck, was used as an experimental control. Each vehicle was oriented due south and separated by a distance of twenty feet to prevent cross shadowing. The test and control trucks were evaluated simultaneously to ensure exposure to similar environmental conditions (Figure 17).

Instrumentation distributed throughout each truck included 42, k-type thermocouples consisting of 14 exterior and 28 interior air and surface locations. Surface thermocouples were adhered using an Omega thermally conductive epoxy, while radiation shields were used for air thermocouples to minimize errors due to direct solar radiation. Each thermocouple was calibrated in a NIST traceable bath to minimize measurement error.

A pyranometer was placed on the instrument panel of each vehicle to confirm sunrise times and humidity measurements were taken. Two IOTech LogBook 360 data acquisition systems were used and located in each truck's toolbox. Data was collected every second and reduced to one minute averages over 24-hour periods. Solar radiation, wind speed, cloud coverage, relative humidity, and wind direction were also measured at NREL's Solar Radiation Research Laboratory which is located near the test site.

Figure 17. Test trucks at NREL's Vehicle Thermal Soak Test Facility

A test matrix was designed in close coordination with industry partners and the CoolCab team. The matrix consisted of baseline characterization, air infiltration, overall heat transfer coefficient (UA), thermal soak, and infrared imaging tests.

The baseline characterization data was used to quantify the differences between the test truck and the control truck (Figure 13). Thermal soak and air infiltration data were used to validate CoolCalc, and quantify the thermal performance of production vehicles. In addition to thermal soak tests, thermal load reduction opportunities were identified through overall heat transfer coefficient (UA) testing and infrared imaging.

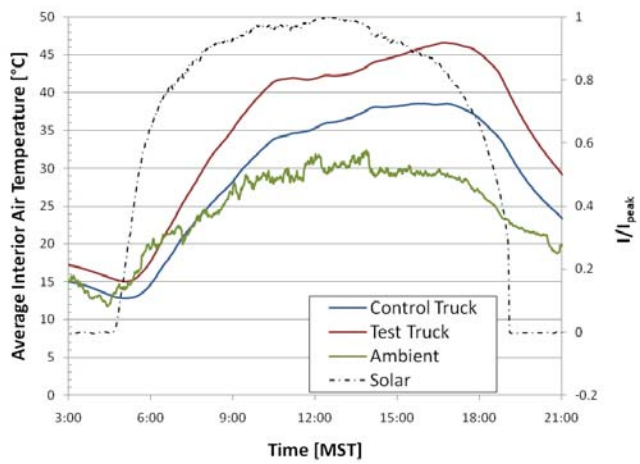

Figure 13. Baseline Characterization, Thermal Soak

To measure the overall heat transfer coefficient (UA) of the vehicle, electrical heaters were used to supply a constant heat load to the cab/sleeper interior. Heater power, interior air temperatures, and ambient air temperatures were measured. The overall heat transfer coefficient, UA, was calculated using Equation 1 to quantify thermal load reduction opportunities in the test truck.

$$UA = \frac{q_{heater}}{\bar{T}_{air,truck} - \bar{T}_{air,ambient}} \quad (1)$$

Average truck air temperatures, $\bar{T}_{air,truck}$ were calculated by averaging 14 interior air thermocouples positioned at ceiling, breath, and foot levels inside the cab and sleeper of each truck. Average ambient air temperature, $\bar{T}_{air,ambient}$ was calculated by determining the mean of 5 exterior air thermocouples.

To eliminate the impact of the solar load, nighttime tests were conducted so the only heat load was from the electrical heaters. The data from the 1:00-3:00 am MST time period was stable and used to calculate the average UA.

Infrared imaging and overall heat transfer coefficient test results were analyzed to identify opportunities for thermal load reduction in each truck. The overall heat transfer coefficient, (UA), characterizes the truck's heat transfer and can be used as an approximation to quantify heat loss or gain for a vehicle. Minimizing UA will reduce the amount of energy consumption when operating climate control systems to meet thermal comfort requirements.

RESULTS – Overall Heat Transfer Coefficient and Infrared imaging

A summary of multiday average overall heat transfer coefficients is shown in Table 1. Truck C had significantly higher UA values in comparison to trucks A and B and therefore would consume more energy to control the interior air temperatures. Opportunities to reduce UA and climate control energy use will be investigated in future phases of the project.

Table 1. Summary of Overall Heat Transfer Coefficients

	UA [W/K]	UA [W/K]	UA [W/K]
	Truck A	Truck B	Truck C
Average	51.7 ± 2.4	65.9 ± 0.5	90.0 ± 1.1

Infrared imaging was used to identify opportunities to reduce the overall heat transfer coefficient (Figure 14). During the IR tests, a heater was operated to impose a steady state gradient between interior and exterior air temperatures. Once a target temperature gradient was established inside the vehicle, a FLIR thermal imaging infrared camera was used to capture images internally and externally. These could then be used to identify areas with higher heat transfer and were considered opportunities for reducing heat transfer.

Figure 14. Infrared Image – Surface Temperatures

Coolcalc Validation Model

To validate the CoolCalc simulation approach, a Kenworth Truck Company T660 thermal model was developed. When available, information from Kenworth or testing was used, otherwise engineering estimates were applied. Since CoolCalc does not use meshing, all surfaces must be planar. Therefore, the computer-aided design (CAD) model provided by Kenworth was simplified. Figure shows the model geometry compared to a photograph of the vehicle. The red lines indicated the domain boundary used for the model. This simplification process inherently requires some approximation; however, effort was made to accurately represent the geometry.

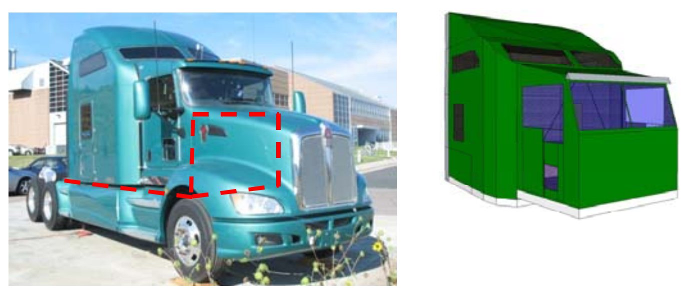

Figure 15. CoolCalc Validation Geometry

The vehicle was modeled with four air zones: Cab, Sleeper, Fairing and Toolbox. The full EnergyPlus exterior radiation calculations were used; however, a simplified version of the interior radiation calculations was applied to increase geometry flexibility. The simple interior radiation model assumes that all beam radiation that passes through the windows falls on the floor of that zone and any reflected radiation is uniformly distributed on all interior surfaces. A case study was conducted which indicated that this results in increasing, but acceptable differences during winter months due to changing sun angle. The detailed surface convection algorithms were used which account for both natural and forced convection. The model timestep was set to 1 minute intervals.

The glass properties for the cab and sleeper were obtained from Kenworth and suppliers; as were the materials and constructions for the vehicle walls. The overall resistivity of the walls was reduced to account for impacts of structural members and other disruptions to insulation that were observed in the vehicle IR imaging. The paint properties were not available and were estimated based on previous experience with vehicle paints.

Four internal masses were defined to represent interior objects. The first represents the seats in the cab. Data on vehicle seats was used to estimate the size, weight, and material properties. The next two internal masses represent the dashboard and the sleeper closets. Both were assumed to be polyurethane plastic and the volume and surface area of each was estimated using truck geometry. Lastly, the two beds were modeled. Information on these was supplied by Kenworth. It was found that internal mass assumptions can have a significant impact on thermal results and further work on internal mass modeling approaches is planned.

Since the chassis and hood would normally shade the underlying surfaces and were excluded from the solution domain, solar load was removed from both surfaces. The firewall boundary condition was set to represent natural convection at 20% above ambient temperature. The exterior surfaces of the vehicle floor were exposed to wind at ambient temperature.

The measured air infiltration rate, as described in the experimental section, was applied to the cab and sleeper. Since this model does not include a fluid flow solution, the cross-mixing between zones had to be estimated. Incorporating a simplified means for estimating this is another possible improvement for the future.

Results –Validation (Thermal Soak)

The CoolCalc concept was validated by comparing the Kenworth T660 thermal model results with experimental temperature and on-site weather data. Figure shows the weather data used for the three consecutive validation days. The data has been normalized at the request of industry partners. This data set captures a range of conditions. The first day was overcast, cooler, and had low wind. The second two days were both clear, but had different wind and temperature behavior.

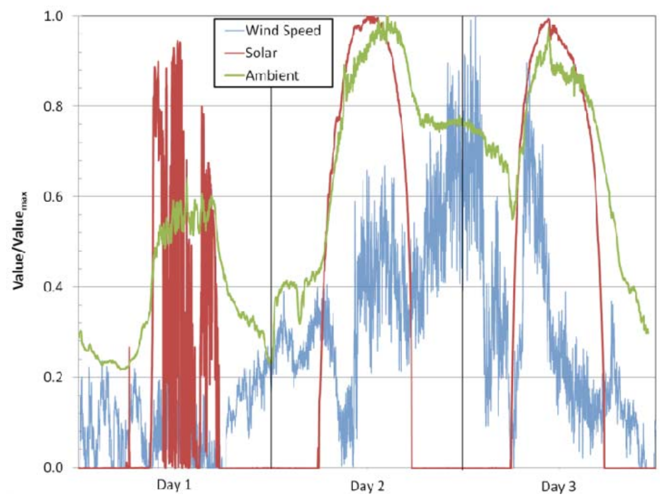

Figure 16. Normalized Weather Data for 3 Validation Days

Figure and Figure show a comparison between the model and the measured air temperatures. These graphs demonstrate good agreement between model and experimental data, both in the peak soak temperature and the overall trends. The experimental averages for the cab and sleeper are an average of 6 and 8 distributed air temperatures respectively.

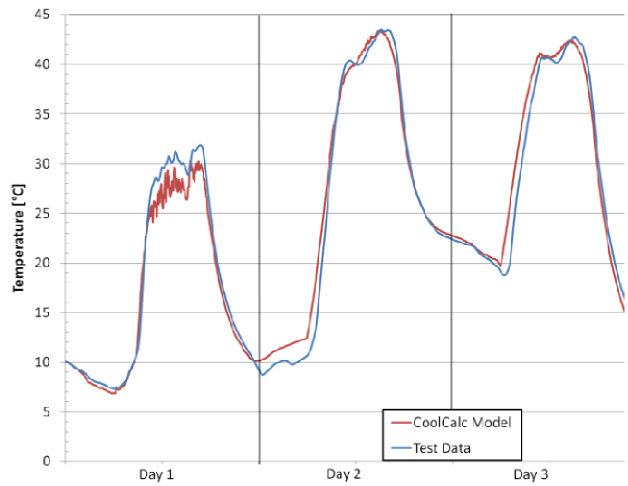

Figure 17. Cab Average Air Temperature Comparison

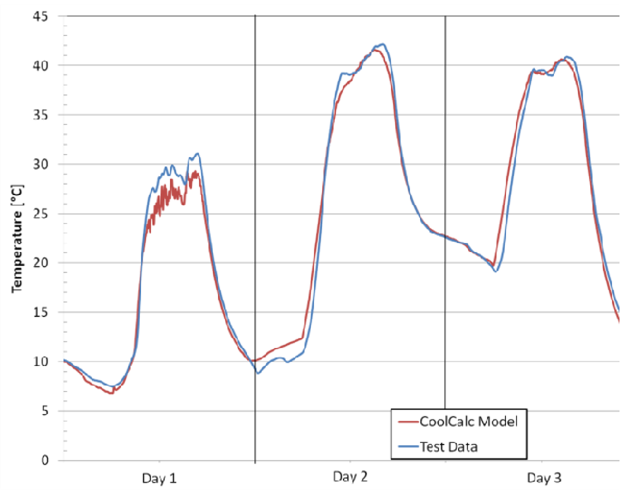

Figure 18. Sleeper Average Air Temperature Comparison

Figure summarizes the temperature difference between the model and test data for the time average (2-4pm) sleeper and cab air temperatures. The maximum interior air temperatures occurred during this time interval and therefore represent peak soak conditions. For the sunny days, the temperature difference was less than 0.4°C. On the cloudy day, the temperature difference between the data and model was 2°C. While the average peak soak temperature for day two compares very closely with experimental data, the differences with time can be seen in the previous two figures.

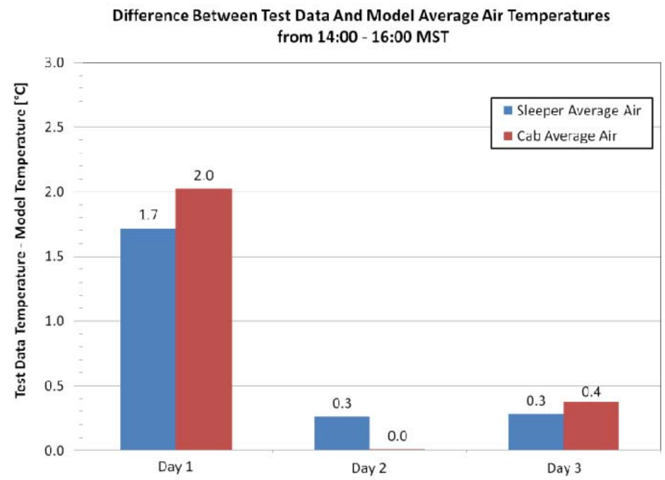

Figure 19. Comparison of Test Data and Model, Time Average from 2-4 pm

The predicted exterior surface temperatures were also compared to experimental results. Figure shows results for the driver and passenger sleeper side wall surface temperatures. Since the truck is south facing, the driver side surface temperatures rise in the morning, peak and decline as the sun passes over the vehicle. Likewise, the passenger side surfaces rise in the afternoon, peak and decline as the sun goes down. The temporal variability seen in the afternoon temperatures for both the experimental and model results were caused by passing clouds on that particular test day. On day three, a larger error is seen between the model and experimental data. Based on the high solar load and low wind speed, one possible cause for this could be that the natural convection portion of the heat transfer is under estimated in these conditions. Further investigation, however, would be needed to confirm this.

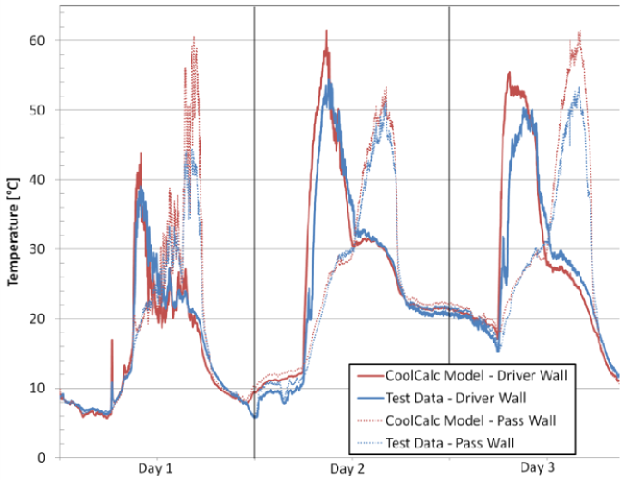

Figure 20. Sleeper Driver and Passenger Exterior Side Walls

The concept validation results also show good agreement between the model and experimental data for the other surfaces that were compared. Figure 21, shows the inside surface of the sleeper side windows. The model tends to overestimate the temperature and respond faster. EnergyPlus does not currently have thermal mass for windows; therefore, this behavior is expected. This could also account for the higher sensitivity to transients, such as passing clouds on Day1.

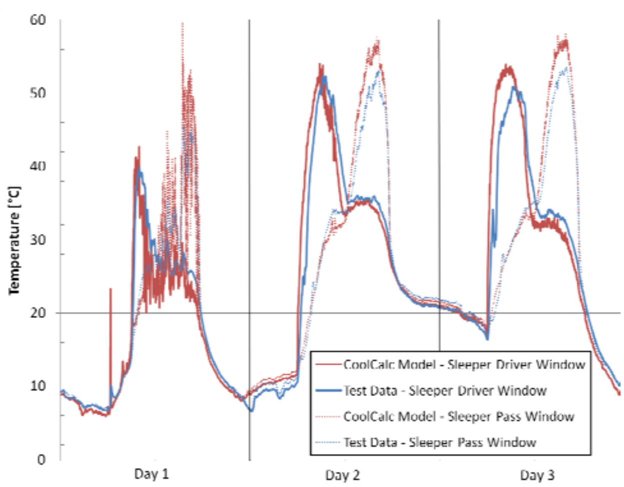

Figure 21. Comparison of Sleeper Interior Side Windows

One of the larger differences between the model and experimental results is the windshield, shown in Figure and Figure . The temporal shift is more noticeable on the windshield exterior. This might also be caused by the lack of window thermal mass.

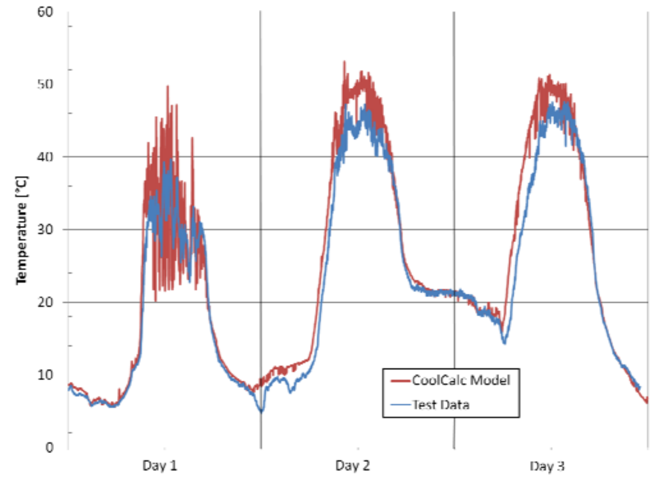

Figure 22. Comparison of Windshield Exterior

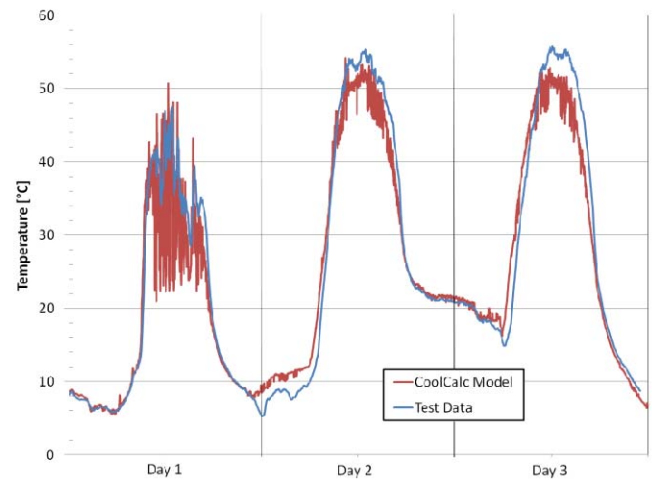

Figure 23. Comparison of Windshield Interior

These validation results demonstrate that the CoolCalc modeling tool can quickly and accurately estimate vehicle temperature distributions for air, surfaces, and glass. Experimentation has been completed for a second validation case study and modeling will begin shortly. This validation will have a larger data set and will include various thermal load reduction configurations. Air conditioning test were outside the scope of this first validation study. Matching the interior temperatures well during a thermal soak provides some confidence that the predicted air conditioning evaporator load is realistic. Previous work on simulation of military type vehicle geometry indicated that the evaporator thermal load calculations were reasonable. Future work will validate load calculations in more detail.

Summary/Conclusions

To help develop solutions that reduce the 838 million gallons of fuel used by long-haul trucks annually for overnight idling in the United States; the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) CoolCab project has developed a HVAC load estimation software tool called CoolCalc. Vehicle geometry is first created using parametric and manual tools. The user navigates and modifies solver objects using the Object Browser as needed to define model parameters. Once the model is setup, the weather file is selected and the model is solved. Results can be displayed within the software environment or post-processed in detail using output files.

Detailed experimental testing of a Kenworth T660 sleeper cab truck was done at NREL to validate CoolCalc. A model of this vehicle was developed using information provided by Kenworth Truck Company, testing, and engineering assumptions. Comparison between the model and experimental results over three days shows good agreement both in trends and peak temperature values for a variety of weather conditions. The difference between experimental and model peak soak air temperature, an average from 2-4pm, was less than or equal to 0.4°C for the sunny days and 2°C for the cloudy day. Surface temperature comparisons show that the effect of solar position was captured accurately. Experimental testing for a second validation case study has been completed and modeling is planned for the near future.

An air conditioning model framework was developed to provide a pathway for determining the impact of climate control thermal loads on vehicle fuel use. The model calculates compressor power that can be applied to a vehicle simulation.

The ability of CoolCalc to quickly and accurately estimate vehicle thermal temperature distributions has been demonstrated. Methods and tools are currently being developed to link CoolCalc thermal load estimates to vehicle fuel use. The next step will be to apply CoolCalc to study the impact of thermal load reduction technologies on idling and vehicle fuel use. This will fill an important role in the CoolCab project's suite of experimental and analytical tools which are being used to develop commercially viable idle reduction technologies in collaboration with industry partners.

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F. Smart Charging Demonstration

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Objectives

- Demonstrate the Grid Friendly Charger Controller prototype in one or more vehicles in preparation for customer acceptance testing. This technology demonstration will leverage the Office of Electricity's R&D investment in FY2009
- Employ the emerging communications standards (SAE J2836 and SAE J2847) into the prototype to convey charging strategies to the test vehicle.

Approach

- To demonstrate the Office of Electricity's FY09 investment of a grid-friendly charger controller, Pacific Northwest National Laboratory (PNNL) integrated and tested the controller prototype in a system that included a Toyota PRIUS PHEV retrofitted with a Hymotion L5 battery and a Coulomb Technologies Level 2 charging station. The vehicle and the charging infrastructure were provided by PNNL. PNNL collaborated with the National Renewable Energy Laboratory (NREL) to demonstrate the grid-friendly charger controller in a NREL-vehicle as well.

Accomplishments

- Vehicle to Charging Station communication was successfully implemented with Power Line Carrier communication technology using the SAE J1772 connector, SAE J2836 Use Cases, and SAE J2847 messages. Implementation was performed both in the lab and in PNNL's test vehicle.
- The full feature set of the grid-friendly charger controller was demonstrated in PNNL's test vehicle using SAE J1772 connector and SAE J2847 messaging.

Future Directions

- The FY2011 plan includes a joint testing effort with NREL and outreach to organizations involved in ARRA activities to jointly test customer acceptance of developed technology.

Background

As electric vehicles become more popular, they will make greater demands on the electric power system. Yet the electricity needs of about 70 percent of all U.S. light-duty vehicles could be met by the existing power grid infrastructure if battery charging was managed to avoid new peaks in electricity demand . Recognizing the importance of load management for this emerging new customer segment, the Office of Electricity Delivery and Energy Reliability (DOE/OE) funded PNNL to develop Smart Charger Controller technologies for electric vehicles. The result of this technology development activity is a prototype that offers two key features:

- Price-based charging strategies that determine optimal start/stop times to minimize the cost for charging to the vehicle owner. The controller will connect to a network to receive current electricity price information and rate schedules and develops an optimal charging schedule based on customer preferences.

- Embedded "regulation" services that support integration of intermittent renewable resources. This feature will control the charging current in accordance to the system needs to minimize the imbalance between load and generation.

Both features have been successfully tested in the lab. Through this project, PNNL will be able to demonstrate the utility of the smart charger in a real PHEV or EV. This demonstration will leverage about $1 million of DOE/OE's investment in the technology development. This project also leveraged PNNL's standards work with the Society of Automotive Engineers (SAE) that identified and tested hardware methods to implement current SAE communication standards.

Introduction

PNNL's FY2010 effort identified and successfully tested hardware methods commercial entities could use to implement current SAE communication standards into the vehicle charging process. PNNL tested these methods using a commercially available charging station, vehicle, and charger; developed a human-machine-interface (HMI) for controlling and monitoring the charging process; and incorporated PNNL's smart charger controller (now called Grid-Friendly Charger Controller). The communication standards implemented included over 25 of the SAE J2847 messages, incorporated SAE J2836 use cases, and transmitted the messages using Power Line Carrier technology. The SAE communication standards were designed to allow the development of utility programs to enable consumers to charge their vehicles at the lowest cost during off-peak hours and help the utilities reduce grid impacts by minimizing electric vehicle charging during peak periods. "The biggest challenge for utilities is managing the grid during peak times, a time when energy is the most expensive and demand is greatest," said Rich Scholer, chair of SAE's Hybrid Task Force and sponsor of SAE J2836/1.

Hardware to implement SAE communications standards

Two-way communication between vehicle and charging station was demonstrated using Echelon's Power Line Carrier technology, a 2009 Toyota PRIUS retrofitted with the Hymotion (A123) 5.5 kW battery pack and a SAE J1772 charging connector; and a UL-certified Coulomb Level 2 charging station; and PNNL developed HMI and charger controller interface. This hardware configuration allowed testing of the HMI and the charging system, user-friendliness of the HMI, and monitoring of the elapsed time between vehicle connection to the Charging Station and completion of the SAE J2836 process from *registration* through *binding*. Even with the low data rate powerline carrier communication hardware, measured times for the *registration* through *binding* processes were typically a few seconds.

SAE J2836 Use Case Implementation

The SAE J2836 Process begins with the vehicle connecting to the Charging Station, obtaining Authorization for charging, Binding communications, Charging, Billing, and disconnecting as shown in Figure 1.

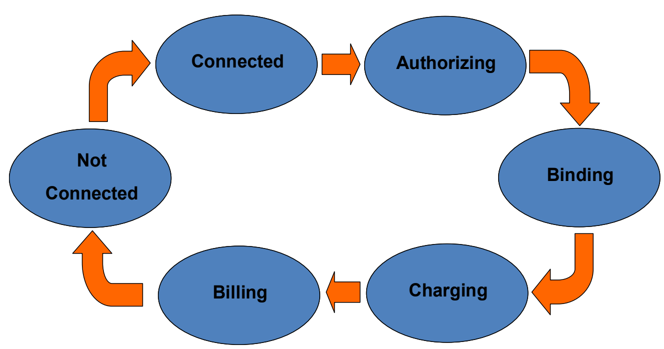

Figure 18. SAE J2836 Process

The SAE J2836 Use Cases implemented included the General Registration and Enrollment Process (E); TOU Program (U1), Direct Load Control Program (U2), Real Time Pricing (RTP) Program (U3), Critical Peak Pricing (CPP) Program (U4), Optimized Charging Program (U5), Level I (S1 - 120VAC), and Level II (S2 - 240VAC). The Enrollment

Process and Program Selections are controlled by the HMI shown in Figure 2.

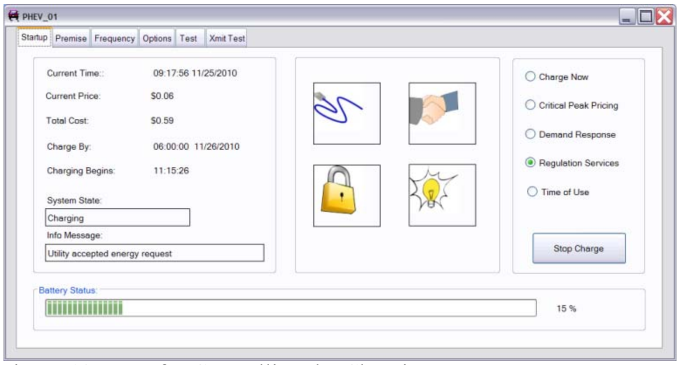

Figure 19. HMI for Controlling the Charging Process

The panel on the left shows the price information obtained through the SAE J2836 Authorization and Binding processes and shows the total charging cost. The icons in the middle panel indicate progress through the SAE J2836 process including Connection, Authorization, Binding, and Charging. The only required user interaction is to select a charging program on the right panel of Figure 1. Selection of a different charging programs initiates communications to obtain pricing for the selected program and informs the user of the price associated for that program. The time by which the vehicle is expected to be charged is set as a default value and globally available to all pricing options.

An additional display for the "Time of Use" program is shown in Figure 3's Charging Profile display. The black line shows a fairly complex sample pricing tariff and the red region shows the results of where the price optimization calculation shows when the vehicle should be charged so that it is available at the user determined time of 6a.m. The charger controller calculates a new charging profile each time charging is started, the price is changed, or the user specifies a new charge complete time.

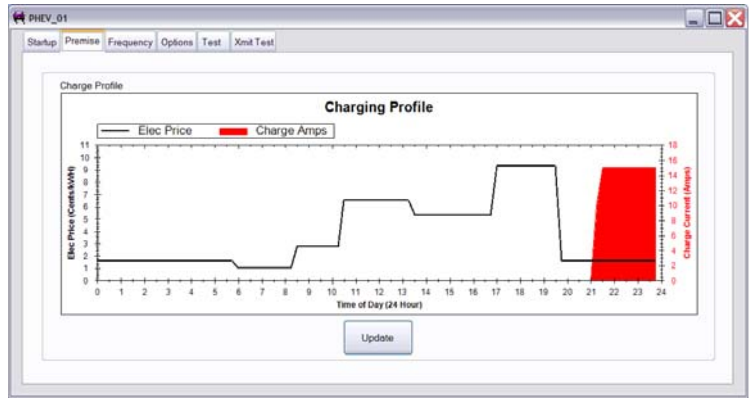

Figure 20. Time of Use Charging Profile

Smart Charging Demonstration using PNNL's Test Vehicle

The technology demonstration was developed with the following requirements:

1. All electronics in the vehicle were powered from the charging station and vehicle electronics were minimized.

2. Commercially available modules were used to the maximum extent possible and custom-designed module use was minimized.

3. All safety related aspects of the SAE J1772 standard were maintained and implemented (especially de-energization of AC power as soon as J1772 connector was being removed from the vehicle).

4. Package the controller so that outside connections are minimized (i.e. communications and A.C. power) and it's suitable for transport and demonstration.

5. Enable implementation of PNNL's Grid-Friendly Charger Controller technology in the Charging Station (EVSE) and communicate varying charge rates to the vehicle's controller conforming to the SAE J1772 standard.

6. Implement an interface to the J1772 Control Pilot and Proximity Detect signals.

7. Provide the hardware interface to perform Power Line Carrier technology data rate and error rate testing.

8. Provide a communications interface to the HMI and respond to user selections made on the HMI.

9. Implement the SAE J2847 messages and SAE J2836 Use Cases.

10. Interface with Echelon's Power Line Carrier communication technology, Maxim's Power Line Carrier technology, a ZigBee Modem, two CAN buses (one for the vehicle CAN bus and one for the battery management system CAN bus), and have the capability of an Ethernet interface.

11. The battery charging rate could be controlled using the battery management system's CAN bus.

12. The processor chosen should cost less than $5 each in large quantities.

13. Explore and provide potential solutions to issues that might preclude implementation of the standards as written.

These requirements were implemented using an ARM7 evaluation board (MCB2300), Echelon's PL3170 Power Line Carrier, Maxim's MAX2991 Power Line Carrier, a motherboard to make interconnections more rugged, and in firmware. The final prototype packages were ~8-1/2 x 11" x 3". One was installed in PNNL's test vehicle; the other outside the Coulomb Technology charging station.

Figure 21. PNNL Test Vehicle

Price-based Charging

The full set of time-variant prices of the SAE J2836 use cases were implemented in the controller. Figure 22 shows the control strategy for a Critical Peak Pricing event. After receiving an price update, the charger controller re-optimizes the charging profile to provide load relieve and still insures that the vehicle is fully charged by the user specified time (i.e. 6 a.m.).

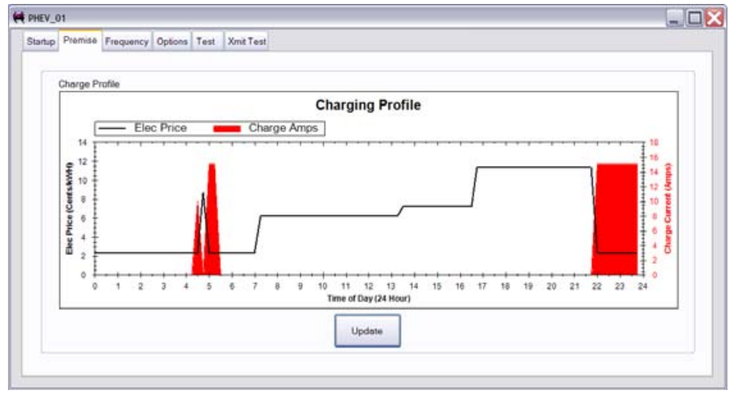

Figure 22. Critical Peak Pricing Charging Profile

The charging profile changes occur autonomously to insure that the vehicle is fully charged when needed at the minimum cost. This charging profile display provides a simple and convenient method for the user to review when charging will occur.

Regulation services to support integration of variable renewable energy resources

Regulation services can be provided to grid operator with electric vehicles during the charging mode without reversing the flow of electricity out of the battery back into the grid. The electric vehicle would provide regulation services as a load and only as a load. We call this mode "V2G-Half" because only half of the regulation capacity can be provided to the grid (only between 0 charging and full charging as opposed to full charging to full discharging). However, no IEEE interconnection requirements apply, nor are there any uncertainties with battery warranty when exposing the vehicle battery to grid operations.

The *V2G Half* battery charging method varies the charging rate (Figure 23 - red line) as the grid frequency (Figure 23– black line) varies. Grid frequency is a key indicator used by electricity balancing authorities to add or reduce grid generating capacity. The *V2G Half* charging mode was successfully demonstrated in the PNNL test vehicle.

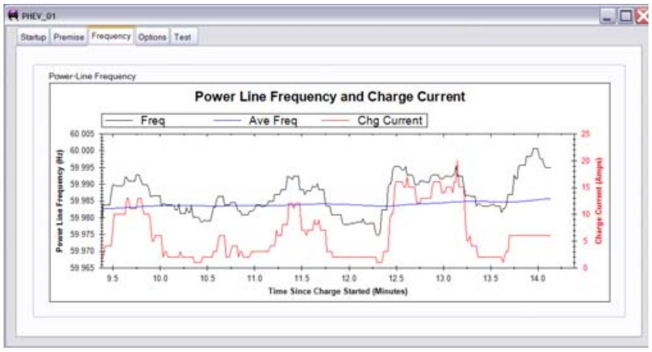

Figure 23. V2G-Half

Lessons-learned from the technology demonstrations

There were several challenges associated with installing the charging station and implementing the charger controller with the SAE J1772 connector, the SAE J2836 Use Cases, and the SAE J2847 messages including:

1. The PRIUS Hymotion retrofit kit has a standard 120VAC receptacle and the J1772 Level II standard (240VAC) uses a different receptacle. Users may want the capability to charge using both methods, but there is potential for inadvertently connecting a 120VAC source and a 240VAC together. A switch was added to the vehicle to allow the user to select between 120VAC receptacle and the J1772 receptacle.

2. The PNNL system was designed so that the vehicle communications module received all its power from the AC power line. This requires that the contactor in the charging station be closed prior to Power Line communications beginning. A simple circuit (in addition to the J1772 standard) was added to the vehicle's communication module to assert the Control Pilot signal and communicate to the charging station that a vehicle is connected.

3. The SAE J1772 standard uses the Control Pilot to signal the Charging Station that a vehicle is connected. AC power is supplied only when a vehicle is connected. A second part of the safety design is that when the connector's switch (see Figure 24 - orange button) is depressed (Proximity Detect), the Control Pilot signals the Charging Station that a vehicle is no longer connected and AC power is no longer supplied. This circuit design was required to be added to the systems installed at PNNL since J1772 compliant chargers were not available.


Figure 24 – Yazaki SAE J1772 Connector

4. The SAE J1772 Control Pilot signal has an additional function in addition to indicating that the vehicle is connected. This function is to communicate a variable charge rate from the EVSE to the vehicle. External control of this signal was not available in the equipment supplied. PNNL obtained access to this signal and designed their Charger Controller use this path to communicate a variable charge rate signal from the Charger Controller on the Charging Station to the Charger Controller in the vehicle.

5. The battery charging rate from Hymotion L5 battery charger can be externally controlled using the battery management system's CAN-bus. PNNL's vehicle Charger Controller interfaced with the battery management system CAN bus and the SAE J1772 Control Pilot signal to control the battery charging rate.

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VII. CODES AND STANDARDS

A. Electrified Vehicle Codes and Standards Technical Support

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Objectives

- Provide technical expertise to guide the responsible Society of Automotive Engineers (SAE) committees towards the development of a system of Codes and Standards for use with electric vehicles (EVs) that connect to the utility grid for charging their battery systems. By enabling any EV to be compatible with every charging station installation in any location around the world, this project will provide alternatives to help improve the accessibility and convenience of performing vehicle charging. Achieving global harmonization of these electrical codes and standards will contribute to the widespread adoption of electric-drive transportation
- Recommend the appropriate communication methods and protocols needed to transfer status/accounting/control information back and forth from the grid operators to the vehicles/consumers.
- Support specifications that ensure standardized vehicle charging systems and the vehicle connectors that can accommodate a wide variety of charging rates and available power.
- Determine methodologies for providing flexible vehicle communication systems with the ability to reconfigure itself, such as with Internet protocols that "figure it out on their own" when first plugged in. Likewise, vehicles with advanced communications technology, such as software-defined radio (SDR), can reconfigure "on the fly" by asserting firmware stored in a vehicle's memory to literally define the functionality of the wireless communication standard implemented via software.

Approach

- Provide technical support to the SAE Committees involved in establishing codes and standards requirements related to EVs.
- Facilitate exchange of information with other standards-setting bodies — such as the Institute of Electrical and Electronics Engineers (IEEE), International Engineering Consortium (IEC), International Standards Organization (ISO), and Japan Automobile Research Institute/Tokyo Electric Power Company (JARI/TEPCO) — to ensure harmonization and synchronous evolution of EV-related standards.
- Interact with National Institute of Standards and Technology (NIST) on Priority Action Plan (PAP-11) as part of the mandate of NIST to coordinate all smart grid-related standards and developments. Develop a white paper on EV charging coupler requirements that is not technology or region specific and that can be used as a technology-based reference to evaluate proposed AC and DC coupler standards worldwide.

- Participate in the Electric Power Research Institute Infrastructure Working Group (EPRI-IWG), whose participants are drawn from utilities, municipalities, industry, and government. This group identifies the need for standards within the context of EV charging infrastructure development and deployment.
- Liaise with SAE battery standards committees to exchange standards requirements on overlapping areas, such as state-of-charge (SOC) reporting, acceptable charging rates, and impact of battery technology on charging standards.
- Evaluate and validate hardware and communication protocol proposals. Engage with suppliers, academia, the automotive industry, and government officials to continuously assess state-of-the-art approaches.

Accomplishments

- **SAE J1772™** *Electric Vehicle Conductive Charge Coupler* standard for AC connection was balloted and approved in January 2010 after three years of revision meetings to update the original J1772™ standard (initially ratified in 1998). The combination AC and DC hybrid coupler design, which has synergy with an AC coupler (allowing compatibility in the AC and DC coupler interface), is in process. Revision to the published SAE J1772™ standard is in process to accommodate details of communication and other evolving standards.

- Provide contemporary status reports to DOE to track standards development progress and direct future DOE support. The status of other related/support SAE standards is as follows (listed numerically):

  – **SAE J2344** *Guidelines for Electric Vehicle Safety*: published March 2010.

  – **SAE J2836/1** *Use Cases for Communication Between Plug-in Vehicles and the Utility Grid*: published April 2010.
  (There are a total of five sections for this standard. **J2836/2** *Use Case with Electric Vehicle Supply Equipment [EVSE]* was at the pre-ballot stage as of October 2010. Three other documents are in various stages of completion.)

  – **SAE J2847/1** *Communication Between Plug-in Vehicles and the Utility Grid*: balloted and published in June 2010. (There are five sections total for this standard. It is anticipated that **J2847/2** *Communication between PEV and Off-board DC EVSE/Charger* will be submitted to ballot by January 2011. Three other documents are in various stages of completion.)

  – **SAE J2894/1** *Power Quality Requirements for Plug In Vehicle Chargers-Requirements*: started March 2009, in pre-ballot phase. Argonne supplied charger bench test data, as well as vehicle test data, to the task force and played a notable role on this small team.

  – **SAE J2894/2** *Power Quality Requirements for Plug-In Vehicle Chargers—Test Methods*: draft is started. Argonne again is expected to play a meaningful role in providing best practices, along with vehicle and component level validation data, on production-oriented EV charging equipment (both on-board and DC off-board).

  – **SAE J2907** *Power Rating Method for Automotive Electric Propulsion Motor and Power Electronics Subsystem*: draft document has been created. Update process has involved many interactions with industry representatives from automotive OEMs and motor suppliers. We are working in coordination with ORNL on defining requirements for document. Analysis work is being performed on stray loss separation in stator and rotor for high-speed motors to better refine models to predict and identify limitations to peak/continuous motor operation.

– **SAE J2908** *Power Rating Method for Hybrid Electric and Battery Electric Vehicle Propulsion*: draft document has been created. We have held meetings with OEMs to identify system-level limitations on motor rating standards. Argonne supplied relevant PHEV and BEV dyno test results.

– **SAE J2931/1** *Digital Communications for Plug-in Electric Vehicles*: methodology overview has been used as working reference document for other standards and industry input; currently in draft form and will remain so.
SAE J2931/2 *Inband Signaling Communications for Plug-in Electric Vehicles*: Argonne has performed bench-level proof of concept implementation of a digital form of inband signaling based on a less-than-$1, single programmable system on chip (PSOC) mixed signal device. By modulating the negative portion of the SAE J1772 1-kHz dedicated/point-to-point conductor, additional communications for the association of the vehicle to its EVSE are provided while eliminating any chance of "cross-talk" or accidental communication with other vehicles/chargers. J2931/2 is in draft form while industry representatives decide on bandwidth, security, and performance requirements.
SAE J2931/3 *Power Line Carrier (PLC) Communications for Plug-in Electric Vehicles*: Argonne evaluated one demonstration version of the PLC by Echelon that uses the LONworks operating system. We also participated in creating requirements for EMC testing and reviewed test results from contractors. J2931/3 is in a long-term elimination of 16 proposed vendor solutions via closed-door meetings with OEMs and peer review of results. The committee is focusing on five final competing technologies, as well as on a universal base-band communication IC approach to accommodate differences between EU countries and the United States.

– **SAE J2853** *Plug-in Electric Vehicle (PEV) Interoperability with Electric Vehicle Supply Equipment (EVSE)*: standard has a status of pre-draft, with meetings to establish specifications and requirements. Given that there are 4,400 utilities in the United States, 30+ EVSE manufacturers, and up to 20 vehicle OEMs, there is great uncertainty about how to ensure interoperability among these three elements when they are connected into one system. Argonne has created a test fixture that contains the basic elements of a vehicle-side emulator with a battery SOC computer, CAN bus, and other physical control elements. The test fixture also contains an Itron Centuron smart meter-based grid emulator, end-use monitoring device (EUMD), and EVSE emulator.

– **SAE J2954** *Wireless Charging of Electric and Plug-in Hybrid Vehicles*: document started in September 2010. Establishing minimum performance and safety criteria for wireless power transfer to EVs. Presentations by vendors are peer reviewed to compare and contrast common elements, as well as safety issues for each. Argonne's past contributions include performing research and a 1-kW demonstration. The published work is used as an information reference to this document.

- Initiated and managed subcontracted projects for grid connectivity technology development and validation of vehicle charging messages.
- Demonstrated Phase 1 limited capability grid connectivity of EV charging infrastructure by using lower cost, secure, universalized wired and wireless communications technologies (e.g., PLC modem, UMAN, Zigbee).

- Produced a functional demonstration of SDR technology in a low–cost, field-programmable gate array (FPGA) device by implementing a vehicle-to-grid Universal Metropolitan Area Network (UMAN), thereby enabling interoperability of widely varying infrastructure resources. These components relate to SAE J2931 and J2847 vehicle communication technologies.
- Defined specifications for planar implementation of a non-contact, non-ferrite, concentrator-based current sensor (flux gate magnetometer) and signal processing electronics, as part of SAE J2847 regarding EUMD.

Future Directions

- Continue to investigate limitations and propose solutions for vehicle-grid communications technologies, with emphasis on interoperability between countries as well as regions (utility districts).
- Implement other internationally compatible communications protocols in SDR technology.
- Validate interoperability and communications performance targets in a systems context.
- Address power electronics and energy storage technology standards.
- Expand benchmark hardware experiments to support validation of methods used to determine electric motor rating standards, with emphasis on cooling methods and impact.

Conclusions

- EV-related codes and standards support has benefited the vehicle electrification activities as a whole by creating a set of harmonized standards that allows interoperability between the various components needed to charge and drive EVs.
- Connector standards are supported, completing the SAE J1772™ AC Level 2 standard, and we are forging ahead on the DC coupling challenges. Solar-tied charging stations will likely use this standard to minimize the number of conversion steps between electricity production (and possible local storage) and distribution to the vehicles. Off-board DC chargers are a likely mainstay of longer-range EVs as on-board chargers become larger and prohibitively heavy/expensive.
- Communication standards are supported in use-case, messaging, and communications physical hardware. Just as has occurred with the expansion of the information age — where everyone expects ubiquitous seamless communication technology to be available at a low cost — EV communication will be used as part of the management of the Smart Grid and will encompass providing real-time pricing information, transparent billing systems when drivers are away from home, demand management, and possibly even the use of EVs to stabilize the grid in times of distress or disruption of services.
- Software-defined radio is expected to be the next generation of communications networking solution platforms that can be adapted to each installation location by utility provider, region, or country. SDR can reprogram the communications network "on the fly" to adapt to a variety of communications infrastructure options.
- Sensor technologies, such as planar-coreless flux gate magnetometers and low-cost robust signal conditioning, may open new markets and opportunities for branch energy measurement. The State of California is mandating the use of EUMD sub-metering for every EV for emissions accounting and compliance with CARB mandates.
- Equipment validation and interoperability standards supported under this work allowed for the creation of test fixtures that may be used to assess and test the interoperability of utilities, EVSE, and EVs.
- Pursuit of wireless charging of EVs is the next chapter in designing EV infrastructure. Many of the automotive OEMs are exploring the limits and feasibility of the current wireless power-transfer technologies. In proportion, vendors are exploring new ways to capitalize on potential new infrastructure markets in

wireless charging. Safety, communication, and performance benchmarking will all be important elements of this work in progress.

Papers/Presentations

1. White paper NIST PAP-11: *NIST Smart Grid Interoperability Priority Action Plan 11 — Plug-in Electric Vehicles DC Charging Coupler White Paper.*
2. Paper: *Transposition Effects on Bundle Proximity Losses in High-Speed PM Machines,* IEEE Energy Conversion Conference and Expo (ECCE), Oct. 1, 2009, in San Jose, CA.
3. Paper: *Modeling and Analysis of Proximity Losses in High-Speed Surface Permanent Magnet Machines with Concentrated Winding,* IEEE Energy Conversion Conference and Expo (ECCE), Sept. 14, 2010, in Atlanta, GA.
4. Presentation/Paper: *Electric Vehicle Infrastructure Opportunities Leveraging Light-Duty Standards,* Industrial Utility Vehicle Conference, Oct. 7, 2009, in Louisville, KY.
5. Presentation: *Vehicle Electrification and Minimizing Impact on the Grid,* COP-15 Climate Change Conference Bright Green Expo, Dec. 12–13, 2009, in Copenhagen, DK [http://www.brightgreen.dk].
6. Presentation: *Clean Cities Plug-in Vehicle and Infrastructure Community Readiness Workshop,* U.S. Department of Energy, Washington, D.C., infrastructure preparation workshop/support [http://www1.eere.energy.gov/cleancities/plugin_vehicle_infrastructure.html].
7. Presentation created for NFPA Electric Vehicle Safety Summit: *Vehicle Standards Update- Hybrid Vehicles,* Oct. 19-20, 2010, in Detroit, MI.
8. Presentation created for EVS-25: *EVSE Interoperability; Verifying Compatibility and Compliance*, Nov. 8-9, 2010, in Shenzhen, China.

B. Provide Technical Data Support and Leadership to SAE Test Procedures for Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs)

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Objectives

- Chair the industry/government task force and successfully complete the rewrite of SAE J1711, the standard for hybrid electric vehicle (HEV) test procedures, specifically addressing plug-in hybrid electric vehicles (PHEVs).
- Publish revised version of the SAE document, SAE J2841, which defines the "Utility Factor" (UF) that can be referenced by the U.S. Environmental Protection Agency (EPA) and is referenced by California Air Resources Board (CARB) legislation.
- Co-chair SAE J1634 task force for electric vehicle dynamometer test procedures. Provide ideas and valuable test data critical to its completion.
- Ensure that all stakeholders, including JARI-ISO, CARB, and EPA, are in consensus on the general direction and goals of the testing procedure.

Approach

- Chair the J1711 SAE task force committee, set agendas, and facilitate decision making.
- Assume leading role in the development of J1634 using concepts learned from extensive lab testing and lessons learned in support of the SAE J1711 test procedure.
- Use the vehicles available through the Advanced Vehicle Testing Activity (AVTA), the Argonne-instrumented Prius, the Modular Automotive Technology Testbed (MATT) platform, and the Through-the-Road (TTR) prototype vehicle to help validate the various test procedure concepts.

Accomplishments

- The task force met every two weeks near the end of J1711 writing. Many important additions were included before the final draft of SAE J1711 was sent to ballot. Among others, they include specific direction for state of charge (SOC) corrections and an accurate method for calculating the end of charge-depleting operation (for EPA label).
- Successfully balloted SAE J1711 in June 2010.
- Based on the subcontract with Georgia Institute of Technology managed by Argonne last year, the new and more realistic UFs were incorporated into a revised SAE J2841 UF calculations document. This new version was successfully balloted. These UF curves are suitable for EPA to reference for label fuel economy.
- Argonne has provided input and important suggested changes to the ISO 23274PHEV test procedure standard by attending ISO meetings.

Future Directions

- Although the SAE J1711 document is complete, supporting the effort by explaining and interpreting specific issues and practices will be an important role for Argonne as the procedures are adopted across the EPA and the industry. This support requires continued coordination among the informed stakeholders. This effort includes helping EPA and NHTSA develop MPG labeling methods and test procedures that are accurate and representative to facilitate the smooth market acceptance of electrified vehicles.

- Also being revised are other SAE standards that have a major impact on advanced vehicles. The introduction of these vehicles requires that standards not impede the widespread development and deployment of advanced technologies.
- SAE J2711 Heavy Duty Hybrid Electric Test Procedures – the same concepts used in J1711 can be applied to the heavy-duty test procedure. Differences in heavy-duty test objectives will be carefully considered.
- SAE J1715 Hybrid Terminology – clear and useful definitions improve communication and clarify technology.
- SAE J2951 Dynamometer Drive Quality Metrics – test-to-test variability can be explained by driver influences. If these influences can be quantified, better test results will be available industry-wide.
- Argonne will continue to work collaboratively on assessing consumer driving behavior related to the development of improved utility curves and labeling procedures.

Introduction

During the mid-1990s, the SAE J1711 task force (chaired by General Motors) developed the original J1711 procedure document. However, at that time, no production HEVs or PHEVs existed. In fact, GM performed procedure validation with student competition vehicles from the University of California, Davis (PHEV) and the University of Maryland (charge-sustaining HEV).

By 2004, like all SAE J-documents after five years, the original J1711 had expired, requiring re-approval as-is or after some updating. The fundamental procedures used for HEVs are not in contention; it was the PHEV procedures that drew attention. In the literature and in stakeholder focus groups (like those held at the DOE in 2006), many widely accepted assumptions for how PHEVs should be tested deviated from the assumptions given in the original J1711. Soon after the DOE stakeholder meeting, the industry called on Argonne to chair the SAE J1711 session, make the PHEV section current, and support consensus decisions with reliable PHEV data.

The SAE J1711 reissue effort has spanned from late 2006 to the current FY 2009. In FY08, the focus was on helping CARB with their procedures and freezing the J1711 test concept. In FY09, the focus was on solving open issues, refining the document for balloting, and evaluating the procedures using OEM-, aftermarket-, and Argonne-built PHEVs. Final calculation methods and approaches were written into the document and the procedure balloted in FY10.

Approach

Many of the existing testing programs at Argonne are heavily leveraged by the test procedure development activity. Because engineers have had more than a decade to test PHEVs and BEVs, the Argonne input is key in the development of advanced vehicle test procedures. Argonne staff spent a significant effort assessing data and specifying new experiments to support major procedure decision points. Many of the small investigative experiments were aimed at looking at the impact of various decisions—in other words, asking such questions as “How important or sensitive is the outcome for each procedure or calculation option?”

Argonne has attained several important achievements during FY10 in the areas of test procedure and standards development for advanced vehicles. This report highlights some of those advances in greater detail.

SAE J1711 State of Charge (SOC) Correction Methodology

The concept of SOC corrections was first proposed during the early 1990s. It is found in drafts of J1711 and was used by Argonne for student competition vehicle testing. The method is employed when HEV test results are not sufficiently charge-balanced to accept the fuel consumption as tested. By using regression techniques, the fuel consumption results can be "corrected" to find a result associated with zero battery energy contribution.

While SOC corrections have been used in some research circles, they are not widely used for the fuel economy testing of production charge-sustaining hybrids. However, in the case of PHEVs with large batteries, the industry indicated that production hardware and software may not reliably charge-balance during routine testing in the charge-sustaining mode. It was decided that before the revised J1711 was balloted, the very loose reference to SOC corrections found in the original J1711 needed to be refined to the point where a robust procedure could be followed and used effectively for PHEV testing. The analysis began in FY09 and the specifications were finished in FY10 and written into the procedure document.

In the literature, several researchers in Japan and in the Netherlands have suggested some statistical criteria to perform SOC correction regressions, but these techniques were not fully developed in the context of HEV test results. Argonne has perhaps the world's largest open database of hybrid test results. These data were mined to determine how to extract the most robust final answer with the least amount of test data. In addition, Monte Carlo techniques showed how much error is possible using various regression specification options (how many data points, how far from charge-balanced to be valid, etc.). Figure 1 gives an overview of the correction procedure that uses several measured data points to fit a regression curvewithin a certain energy envelope to estimate the fuel consumption at zero battery energy usage.

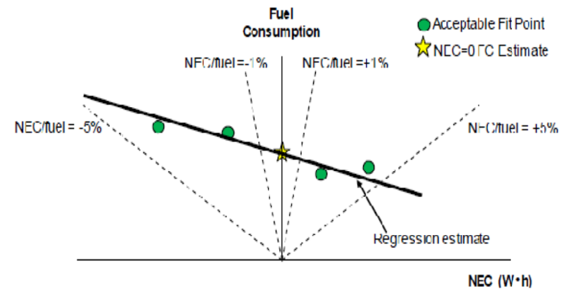
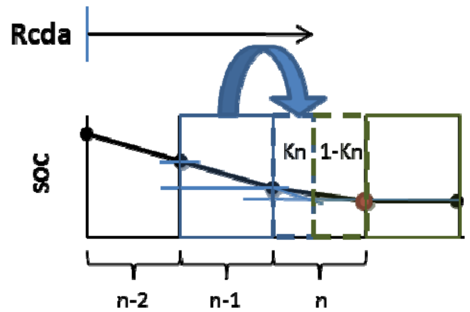


Figure 1. J1711 SOC Correction Specifications

J1711 Alternative Results Calculations

As J1711 was nearing balloting, several interesting developments played out behind closed doors and in the media. Ahead of any standard provided by EPA on how PHEVs' miles per gallon (MPG) will be evaluated and reported, some original equipment manufacturers (OEMs) announced MPG claims that used draft elements of J1711 (a specific UF method). In one case, the numbers were very high and it appeared that because of this, J1711 should include a method of reporting only the charge-depleting fuel and/or electric energy consumption without merging with the charge-sustaining results. By using some concepts found in the Japanese PHEV methods, a sound method of extracting the fuel and electric energy consumption was developed that could be used for any PHEV type. SAE J1711 was sent to ballot very soon after the new results-calculation methods were written into the document. This newly developed metric is shown below in the diagram and equations of Figure 2.



$$FC_{CD} = \frac{\left[\left(\sum_{i=1}^{n-1} Y_i\right) + Z_n * Y_{n-1}\right]}{R_{cda}}$$

where,

FC_{CD} = Fuel consumption rate (per unit distance)

Y_i = Fuel consumed in cycle *i*

Y_{n-1} = Fuel consumed in cycle prior to transition cycle *n*

Z_n = Depleting fraction of transition cycle (cycle *n*)

n = Transitional cycle

R_{cda} = Actual CD range

Figure 2. Method for Finding Total Charge-Depleting Fuel and Energy Consumption

SAE J1711 Final Ballot

The additional concepts explained above were included in the document, and subsequently several review periods were conducted. The document was balloted in May; however, a couple of small editing errors worthy of correction were found, and it was decided to correct these and do what is called a “14-Day” ballot — basically a chance for voting members to confirm that the changes are satisfactory. The document was finally published in June 2010.

SAE J2841 Revision Ballot

In FY09, a new family of Utility Factors was developed to address many possible analysis perspectives. These include UF curves specifically suited for city or highway driving cycles. We used some of the best multi-day, multi-driver on-road data available from Georgia Tech to support our findings. After many discussions and draft iterations, the inclusion of these curves and careful support explanations in J2841 were negotiated to everyone’s satisfaction. It was decided to include several UF options with the intention of assuring that users know what they are doing.

J1634 Battery Electric Vehicle Test Procedure

Just as J1711 needed to be revisited because of production intent OEM vehicles, so too did the BEV procedure, SAE J1634, need to be updated and revised. Led by Ford and Argonne, the task of updating the procedure included many meetings and rounds of testing, showing many successful applications of the new procedure ideas.

The existing J1634 test procedure takes a direct approach to finding the electric energy consumption and range of a BEV. In essence, the procedure details vehicle testing according the Urban Dynamometer Driving Schedule (UDDS) and the Highway Fuel Economy Test (HWFET). This worked satisfactorily 20 years ago for BEVs whose expected range was about 30–50 miles. In fact, the advanced original GM EV1 was tested only to a range of 78 miles [2]. However, many new electric vehicles with high energy density lithium-ion (Li-Ion) batteries will likely offer ranges of at least 100 miles. For example, Tesla claims its Roadster can achieve up to 245 miles on a single charge. Whereas performing a dynamometer test for a vehicle with a 78-mile range would take about five hours, performing the same procedure on a 245-mile vehicle becomes a two-shift, late-night, 16-hour endeavor. It is apparent that a new procedure is needed to test the next generation of advanced BEVs.

The new test must be performed in a much shorter time, and it must be more practical than a full-range test, which is currently the basis for determining a vehicle’s energy efficiency. The desired outcome is to be able to run abbreviated tests dedicated to finding energy efficiency and then to use a calculation method to estimate the range. This section will discuss the procedures that will yield the energy efficiency results.

One simple approach to a shortened test method uses the same principle as the long test but simply drives less than the full range to determine the AC power consumption vehicle efficiency in watt-hours/mile (Whrs/mi). This raises the issue of what constitutes an adequate test distance. Analysis of daily driving distances and the required amount of depletion for adequate recharge energy was decided at four cycles.

A second option for testing a BEV is to run it in a way similar to that of conventional cars. The cycles run back-to-back with intra-test pauses also similar to conventional vehicle testing. The difficulty is apportioning the recharge energy to each cycle, reflecting its contribution to energy consumption. This problem was solved by using methods explored in J1711 for PHEVs.

To extrapolate total vehicle range, the total capacity of the battery pack must be depleted by using a dedicated capacity test. This was decided to be a 55 MPH steady-state speed test. Next, the range is extrapolated by using several options that are currently being explored. BEV testing conducted at Argonne (and at other test labs participating in J1634) showed promise for predicting range from shortened methods. Figure 3 shows the results of various short-cut methodologies for a tested electric vehicle.

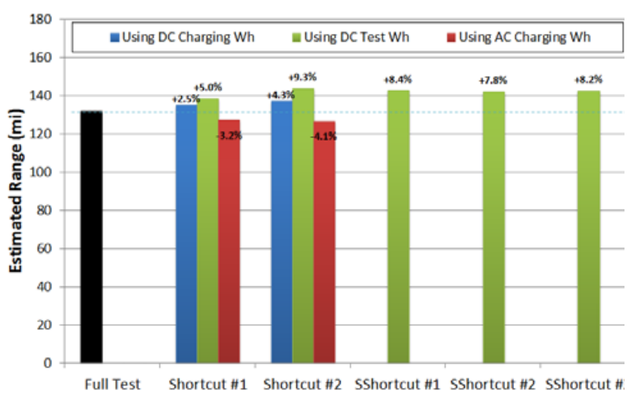


Figure 3: UDDS Cycle Range Extrapolation Results for Various Calculation Methods

Data and analysis are needed to complete the J1634 concept. There may be ways to shorten the procedure even further by combining the capacity test with the consumption test. Final concept and balloting is expected in December 2010 or shortly thereafter.

SAE J1715

Argonne participated in other task force activities important to the development of advanced vehicles; SAE J1715 was another such effort. Rapid advances in PHEV and BEV technology require that their terminology documents be revised. Some OEMs attempted to include terms that perhaps were more suitable for marketing use than necessary as technical terms. Having Argonne staff on the committee keeps the discussion balanced and reflective of the past committee efforts (like J1711, in this case). The document will be finished and balloted sometime in the beginning of FY11.

Conclusions

Argonne's 16 years of experience in fuel economy and emissions testing of HEVs and PHEVs are unmatched in the DOE system, if not the world. This expertise is the reason that industries regularly turn to Argonne and the DOE to help lead test procedure efforts.

Two major pieces of work were principally authored and balloted in FY10. Successes in the efforts were validated by EPA referencing J1711 and J2841 in their Notice of Proposed Rule Making (NPRM) for advanced vehicle MPG labeling in September of 2010. Argonne has taken a lead role in ensuring that advanced vehicle technology is tested, evaluated, and rated in the most technically rigorous and equitable manner. A smooth introduction and market adoption depends upon accurate information describing the various advanced vehicle technologies that will be available to the consumer within the next few years (starting with the Chevy Volt PHEV in November 2010).

As in previous years, Argonne works hard in the open standards committees and offline with individual OEMs and suppliers. Several OEMs have brought their protected and secret vehicles to Argonne to ensure that they obtain the best data in the world. Argonne benefits from analyzing test methods, and the OEMs get educated on the methods and gain access to high-quality data.

Through Argonne's hard work, knowledge, and perseverance, the SAE J1711 and J2841 rewrite documents completed ballot in FY10. Furthermore, Argonne's standards development activity has contributed immensely to a greater understanding of advanced vehicle technology within the industry as well as within the national laboratory system and the general public.

Publications/Presentations

1. Duoba, M., "PHEV MPG: Standard Test Results versus Expectations of Real-World Benefits," SAE HEV Technology Symposium, San Diego, CA, February 2010.
2. Duoba, M., "The Battle Over Batteries: What's the Right Way to Compare Fuel Economy?" SAE Congress panel discussion moderator presentation, SAE Congress and Expo, April 2010.
3. SAE J1711, "Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-in Hybrid Vehicles," HEV Test Procedure Task Force, June 2010.
4. SAE J2841, "Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data" HEV Test Procedure Task Force, September 2010.
5. Lohse-Busch, H., and Duoba, M., "Mini E Testing and Analysis," presentation to BMW, Munich, Germany, February 2010.

C. Vehicle-Grid Connectivity & GITT Supplemental Projects

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Objectives

- Determine the most robust technologies that can minimize the negative impact of vehicle charging on the electrical grid while exploiting opportunities to stabilize demand on the grid.
- Support the goals of the DOE FreedomCAR Vehicle Technology Program Grid Interaction Tech Team (GITT).
- Create technical-solution proposals for grid-connectivity project research (i.e., Supplemental GITT-funded projects).
- Identify segments of vehicle-grid connectivity that require pre-competitive research support, such as sensor technology and communication.
- Provide leadership and technical data support to SAE subcommittees (Connector standards, SAE J1772; Communication protocols/standards, SAE J2847; Use-case scenarios, SAE J2836; Digital communication, SAE J2931; Electric-Vehicle Supply Equipment [EVSE]-Vehicle Compatibility, SAE J2953) via the grid compatibility evaluation test fixture.

Approach

- Create FreedomCAR GITT supplemental projects in 4 key areas: Software Defined Radio (SDR), current sensor and communication technology for compact metrology, home gateway, and power-line communication (PLC) validation of SAE J2847.
- Facilitate exchange of information with electric-vehicle equipment manufacturers, vehicle OEMs, utilities, and other stakeholders to disseminate information about grid interaction issues and technologies for synchronous development of vehicle-grid technologies.
- Provide technical support to the SAE subcommittees involved in the establishment of codes and standards requirements related to electrified vehicles (EVs).
- Provide status reports to DOE to track the progress of grid-connectivity-related standards development and to direct future DOE support.
- Interact with the National Institute of Standards and Technology (NIST) on Priority Action Plan (PAP)-11, as part of the mandate of NIST to coordinate all Smart-Grid-related standards and developments.
- Participate in the Electric Power Research Institute Infrastructure Working Group, which consists of utilities, municipalities, and industrial and government participants. This group identifies needs for

standards within the context of EV-charging infrastructure development and deployment. This group also consists of stakeholders in vehicle-grid interaction issues.

- Address codes and standards requirements to enable widespread adoption of electric-drive transportation with Smart Grid interoperability. Encourage consistency with international harmonization.

- Engage with suppliers, academia, the automotive industry, and government officials to continuously assess the state of the art.

- Evaluate and validate hardware and communication-protocol proposals.

Future Directions

- Continue to investigate limitations and propose solutions for vehicle-grid communications technologies, with emphasis on interoperability between countries as well as regions (utility districts).

- Implement other internationally compatible communications protocols in SDR technology.

- Validate, in a systems context, interoperability and communications performance targets.

- Expand vehicle-grid compatibility benchmark hardware experiments and test fixture to support evaluation of compatibility of grid-connected vehicle components.

- Implement Narrowband PLC with OFDM technologies. The existing G. Hnem draft follows Narrowband OFDM standards such as G3 and Prime, validating global trends toward this approach.

- Leverage previous work to provide the hardware platform for this new generation of "Flex Radio."

- Take advantage of a new flexible baseband chip which is coming to market in 2011 (engineering samples for silicon available in March 2011). Transfer existing FPGA implementation of Narrowband OFDM engine into flexible-frequency-band solution and apply multiple modalities including PLC and sub-GHz wireless.

Accomplishments

GITT Support

- Provided meaningful support in creating GITT meeting agenda items and execution of GITT meetings both in person and via web-connected conference calls.

- Publicly presented GITT supplemental project results in several global forums such as the SAE Government-Industry Workshop, US-China Workshop, Clean Cities Infrastructure Workshop, Business of Plugging In Conference, and EVS-25 Shenzhen, and conducted one-on-one interactions with stakeholder representatives from utilities, industry, government and academia.

Test Equipment Development

- Created a PC-based Vehicle-EVSE-Grid compatibility evaluation test fixture, as shown in Figure 1, that allows emulation of utility messages via Itron AMI meter, Greenwave Reality home gateway, EVSE with compact metrology, various vehicle-grid communication devices, and an emulated electric-vehicle environment. The fixture also incorporates the SAE J1772™ coupler set. (HAN: Home Area Network.)

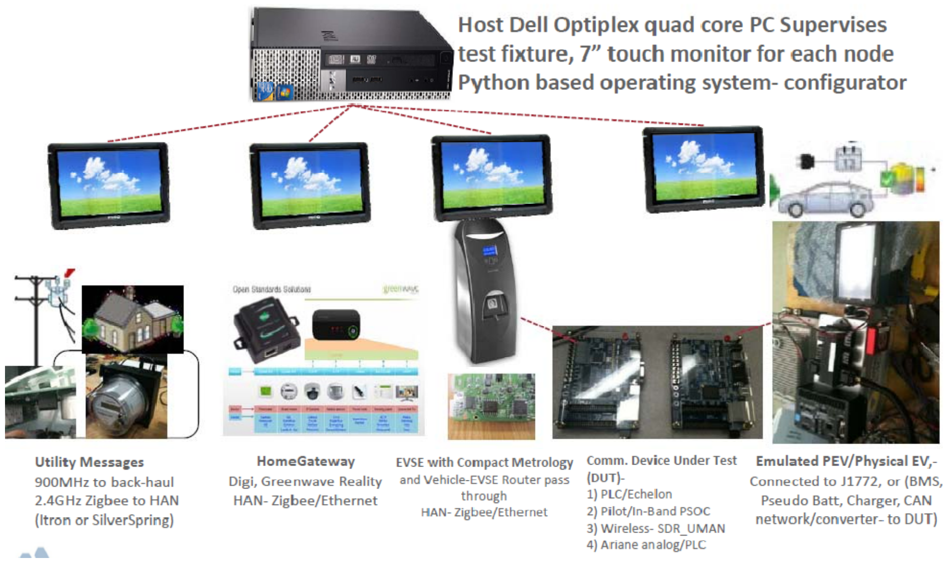
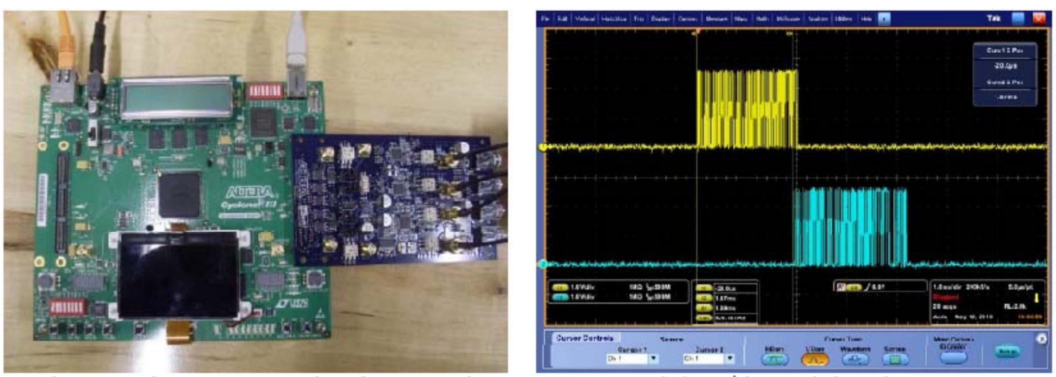


Figure 1 Vehicle-Grid compatibility evaluation test fixture

- Demonstrated implementation of Orthogonal Frequency Division Multiplexing (OFDM) modulation in a 16,000-gate space on a field-programmable gate array (FPGA) device compatible with Zigbee (IEEE 802.15.4-2006) or Universal Metropolitan Area Network (UMAN, IEEE 802.15.4g), as shown in Figure 2.



Altera Cyclone III FPGA development kit Modulate/demodulate bit stream

Figure 25 Software-Defined Radio hardware and output waveforms

- Demonstrated Zigbee (IEEE 802.15.4-2006) radio-based meshed communication network using Digi International modem and Itron Centron AMI grid-emulation device, shown in Figure 3 with a diagram of its topology

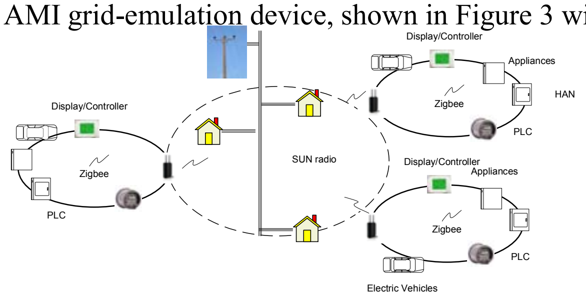


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Figure 26 Digi International Zigbee communication port used in meshed communication and topology

- Developed software for a pre-production prototype home gateway (by Greenwave Reality) to communicate with other HAN devices in the home as well as the Smart Meter. (Figure 4 below).

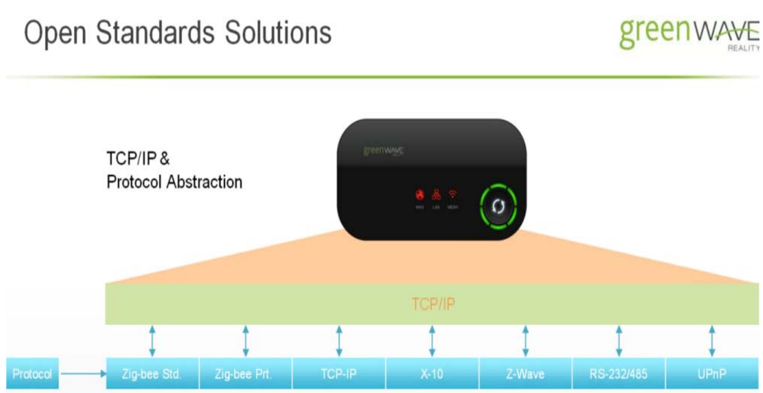

Figure 4 Pre-production home gateway device

- Developed and demonstrated a hand-built flux-gate-magnetometer-based current sensor, shown in Figures 5 and 6 below. The sensor technology is capable of better than 0.1% accuracy. These devices can be produced for less than $0.30 each, which is approximately 1/10th the cost of a current transformer with similar accuracy, yet the flux gate has significantly better linearity over the full temperature range. A plot of the linearity is shown in Figure 7.

Figure 27 Flux-gate-magnetometer-based current sensor and signal conditioner

Figure 6. Flux-gate-magnetometer current sensor installed in low-cost UL-approved 60A-rated package

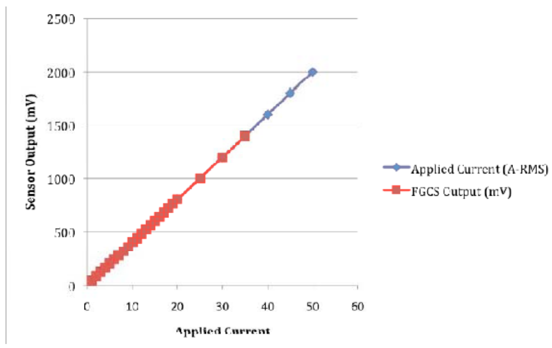

Figure 7 Output linearity of flux-gate-magnetometer current sensor

SAE Standards

This project supported the following SAE standards, listed by number:

- **SAE J1772** *Conductive Charging Coupler for Plug-in Electric Vehicles*

- **SAE J2836/1** *Use Cases for Communication Between Plug-in Vehicles and the Utility Grid*: published April 2010
  (5 sections total for this standard. J2836/2 *Use case with EVSE* is in pre-ballot status as of Oct 2010. The other three documents are in various stages of completion.)

- **SAE J2847/1** *Communication Between Plug-in Vehicles and the Utility Grid*: published June 2010, balloted (5 sections total for this standard. J2847/2 *Communication between PEV and Off-board DC EVSE/Charger* is anticipated to be submitted to ballot by Jan. 2011. The other three documents are in various stages of completion.)

- **SAE J2931/1** *Digital Communications for Plug-in Electric Vehicles*: methodology overview — used as working reference document for other standards and industry input; currently in draft form and will remain so.
  SAE J2931/2 *Inband Signaling Communications for Plug-in Electric Vehicles*: ANL has performed bench-level proof-of-concept implementation of a digital form of inband signaling based on a single programmable-system-on-chip mixed-signal device costing less than $1. By modulating the negative portion of the SAE J1772 1-kHz dedicated/point-to-point

conductor, additional communication capability for association of a vehicle with EVSE is provided with no chance of cross-talk or accidental communication with other vehicles/chargers. J2931/2 is in draft form while industry decides on bandwidth, security and performance requirements.
SAE J2931/3 *Power Line Carrier Communications for Plug-in Electric Vehicles*: ANL evaluated one demonstration version of PLC by Echelon using the LONworks operating system, participated in creating requirements for EMC testing, and reviewed test results from contractors. J2931/3 is in a long-term elimination of 16 proposed vendor solutions by means of closed-door meetings with OEMs and peer review of results. The committee is focusing on the final 5 competing technologies, as well as a universal base-band communication IC approach to accommodate differences between EU countries and the US.

- **SAE J2853** *Plug-in Electric Vehicle (PEV) Interoperability with Electric Vehicle Supply Equipment (EVSE)*: In pre-draft status, with meetings ongoing to establish specifications and requirements. With 4400 utilities in the US, 30+ EVSE manufacturers, and up to 20 vehicle OEMs, there is great uncertainty about ensuring interoperability among these three elements when connected as a system. ANL has created a test fixture that contains the basic elements of a vehicle-side emulator with battery state of charge (SOC) computer, controller–area network (CAN) bus and other physical control elements. The test fixture also contains an Itron Centuron Smart Meter-based grid emulator, End-Use Monitoring Device (EUMD), and EVSE emulator.

Results

- Demonstrated Phase 1 limited-capability grid connectivity of electric-vehicle charging infrastructure using lower-cost, secure, universalized wired and wireless communications technologies (PLC modem, UMAN, Zigbee)

- Produced functional demonstration of SDR technology in a low-cost field-programmable gate array (FPGA) device implementing UMAN vehicle-grid, enabling interoperability of widely varying infrastructure resources. These activities relate to SAE J2931 and J2847 vehicle communication technologies.

- Defined specifications for planar implementation of a non-contact, non-ferrite concentrator-based current sensor (flux-gate magnetometer) and signal-processing electronics, as part of the J2847 EUMD.

Conclusions

- Communication standards are supported in use-case, messaging and communication physical hardware. Just as the expansion of the "information age" has created the expectation of ubiquitous seamless communication technology at a low cost, electric-vehicle communication will be used as part of the management of the Smart Grid — from real-time pricing information, transparent billing systems when drivers are away from home, and demand management to possibly even the use of electric vehicles to stabilize the grid in times of distress or disruption of services.

- SDR is expected to be the next generation of communication networking solution platforms that can be adapted to each installation location by utility provider, region or country. SDR can reprogram the communication network on the fly to adapt to a variety of communication infrastructure options.

- Sensor technologies such as planar-coreless flux-gate magnetometers and low-cost, robust signal conditioning may open new markets and opportunities for branch energy measurement. For example, the State of California is mandating the use of EUMD sub-metering for every electric vehicle for emissions accounting and compliance.

- Equipment validation and interoperability standards supported under this work allowed for the creation of test fixtures that may be used to assess and test the interoperability of utilities, EVSE, and electric vehicles.

Papers/Presentations

1. Presentation: June and Sept. 2010, DTE Allen Road Advanced Meter Lab, Detroit. GITT Projects Hardware Progress Review.
2. Presentation: US-China Workshop, Aug. 31–Sept. 1, 2010 at ANL. “Grid Connectivity Related Standards.”
3. Presentation: SAE Government-Industry Meeting, January 2010, Washington, DC. “Proposed U.S.-China Cooperative Standards Activities.”
4. Presentation: COP-15 Climate Change Conference Bright Green Expo, Dec. 12-13, 2009, Copenhagen, Denmark. “Vehicle Electrification and Minimizing Impact on the Grid.” http://www.brightgreen.dk
5. Clean Cities Plug-in Vehicle and Infrastructure Community Readiness Workshop, January 2010, USDOE, Washington, DC. Infrastructure preparation workshop/support http://www1.eere.energy.gov/cleancities/plugin_vehicle_infrastructure.html
6. Presentation created for EVS-25, November 4, 2010, Shenzhen, China. “EVSE Interoperability; Verifying Compatibility and Compliance.”

D. Support for Green Racing Initiative

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Objectives

- Incentivize OEMs to develop and validate advanced technology relevant to production vehicles in major racing series.
- Increase the use of renewable fuels and advanced propulsion systems in racing.
- Use racing as a platform to educate the public on the acceptability of renewable fuels and the capabilities of advanced vehicle technologies through highly visible demonstrations of their performance.
- Diversify the Green Racing Initiative in its present form beyond sports cars to include other racing series with even greater potential for wider participation and visibility.
- Increase the acceptance of "green racing" in the United States and internationally.
- Maintain collaborative partnership with the U.S. Environmental Protection Agency (EPA) and SAE International.

Approach

- Work with the American Le Mans Series (ALMS) to strengthen its green racing program.
- Refine scoring system; move to an energy consumption scoring basis.
- Increase outreach to teams to encourage renewable fuel use.
- Recommend HEV rules that create incentives for use, emphasizing safety.
- Improve visibility and understanding of Green Challenge scores with media and race fans.
- Increase DOE visibility at ALMS events.
- Increase availability of second-generation biofuels.
- Provide technical support for Project G.R.E.E.N sponsored by Circle Track Magazine.
- Demonstrate the feasibility of accurate fuel control and aftertreatment for racing applications.
- Promote the adoption of renewable fuels for grassroots racing across the United States.

Accomplishments

- Dramatically increased the number of teams using renewable fuels in ALMS racing from 5 to 16, including all major OEM Grand Touring class teams.
- Improved Green Challenge scoring system; will be used in a simplified form in the EU and Asia.
- Increased Green Challenge visibility with media, especially with respect to television coverage.
- Increased DOE visibility at ALMS races and on air by more than two times compared to FY 2009.
- Developed E85 HEV race car simulation based on video game and displayed it at five ALMS races.
- Made second-generation biofuels available for all E85 teams at Petit Le Mans.
- Performed comparative dynamometer and track testing with E10 and E85 in a stock car using carburetion and fuel injection.

- Made first-ever emissions measurements on stock car race engine on the dyno and short track with and without exhaust catalysts.
- Attracted first OEM HEV race car (Porsche 911 GT3 RSR Hybrid) to the United States and unveiled it at DOE's Washington, D.C., headquarters, which resulted in outstanding national press coverage.
- Arranged to obtain actual race data from the Porsche HEV race car to assist in developing future sporting regulations for electric assist vehicles.

Future Directions

- Refine the Green Challenge scoring system in ALMS to make it more transparent.
- Expand outreach to race fans and public on core energy and environmental messages.
- Support the use of energy recovery technology in race cars.
- Work with sanctioning bodies to recommend ways to incorporate advanced technology and renewable fuels into racing.
- Support use of renewable fuels at the grassroots level in American short track racing.
- Provide technical support and recommendations to sanctioning bodies and rulemakers concerning Green Racing content.
- Support the development of more accurate on-vehicle fuel use measurement and a feasible energy allocation system.

Introduction

The Green Racing Initiative is a collaborative effort led by DOE in partnership with the U.S. Environmental Protection Agency. SAE International, while it is a silent partner in this initiative, is lending its support. FY 2010 was the second year of significant activity in this program signified by the second full season of the Green Challenge award in the American Le Mans Series. A major new element of the initiative developed in FY 2010 in the form of *Circle Track Magazine's Project G.R.E.E.N* series of articles challenging the status quo in American short track racing. Through Argonne National Laboratory, DOE provides technical assistance, instrumentation, and analysis for this paradigm-shifting project. This fiscal year, the Green Racing initiative made major strides in taking advantage of the racing's huge potential for rapid technical development and the equally large potential to achieve the objectives of DOE's R&D plans through public outreach.

Approach

Motor sports are the only professional sports that can help attain critical national energy and environmental objectives. Such racing-based events can help achieve these objectives by directing the vast creativity and engineering talent, significant spending, and rapid developmental cycles in racing toward the use of technology and fuels that reduce our dependence on petroleum and lower the carbon footprint of vehicles – while still providing the entertainment and drama that has made racing one of the largest and most followed forms of sports around the world. Because of these unique attributes, racing is one of the biggest and best platforms for reaching a large audience with the message that, through advanced vehicle technologies and renewable fuels, we can maintain the personal mobility we want while moving toward energy security and sustainability.

Racing uses the crucible of competition to bring out the best in the machinery and the people – a core cultural value that resonates with the public – adding to the interest, drama, and entertainment. Racing also inherently values efficiency, an attribute that underpins our national energy and environmental objectives. By building on this core value in racing for high-performance machinery and people – and adding renewable fuels and advanced technology as ways to achieve it – we have developed the Green Racing Initiative with our partners.

Results from the 2010 American Le Mans Series Season

The Green Racing Initiative has become an integral part of the ALMS, the world leader in green racing. The 2010 season was a testament to growth and acceptance of green racing activities in the series.

A number of significant firsts were achieved; the most prominent of which were the first overall victories by cars in the Prototype class that used renewable fuels. The diversity of cars and technologies in the ALMS was shown by the differences between the two winning cars: the Dyson Mazda, a turbocharged 2–liter, four-cylinder winning vehicle that uses a BP-developed isobutanol fuel, and the Drayson Judd, a naturally aspirated V10 that uses second-generation cellulosic E85 fuel (see Figure 1). In addition, cars using a significant portion of non-petroleum fuel won the series' two marquee races: the world-beating Peugeot diesel-powered prototypes that employed GTL-enhanced diesel fuel in their victories in the 12 Hours of Sebring and the 1,000 mile Petit Le Mans. In total, four prototypes used GTL diesel, three used E85, and one used isobutanol; only three prototypes used E10 fuel. More than half of the vehicles in the Prototype field used fuels with significant non-petroleum content.

Another important development was the widespread adoption of E85 as the fuel of choice in the ultra-competitive GT class. The GT class is based on cars that are on the road today and pits the largest and most sophisticated OEMs in door-to-door competition that may be the most competitive class in racing anywhere in the world.

Figure 1. Photo of the Dyson Mazda turbocharged 2L at speed (top left) and the driving team on the winner's podium at the Mid-Ohio ALMS race (top right). Next (bottom left), the Drayson-Judd naturally aspirated V10 driving team on the winner's podium and (bottom right) during the race.

The GM factory-backed Corvettes were the only cars using E85 in this class in the 2009 season. The 2010 season began with the Porsche factory cars switching to E85 for the first race at Sebring. Close behind were the factory BMW and then Ferrari cars as the season unfolded, the latter being a four-car effort. By the end of the season, independent Robertson racing had begun to convert their Ford GTs to run on E85. The number of cars using second-generation cellulosic E85 at the end of the season had grown from two to 11 the previous year. Only three GTs used E10 by the end of the season. This change was motivated both by the performance potential of this excellent fuel and its energy security and environmental advantages.

In total, the amount of petroleum displaced by advanced fuels exceeded 38% at the season finale at Petit Le Mans as compared to what the same cars would have used running conventional race fuels. Greenhouse gas emissions were also reduced by more than 37%.

Other significant accomplishments included the development of a vehicle driving simulator at

Argonne based on an arcade game that cleverly incorporated both an engine map using E85 fuel from the stock car program and a program that captured braking energy and turned it into available power, as shown in Figure 2.

Figure 2. The racing driving simulator developed by Argonne that incorporates a program that displays the amount of regenerative braking energy captured during two laps of simulated racing. This simulator was set up at a number of ALMS races in 2010 and served as a notable means of disseminating the DOE Green Racing's key message that the use of renewable fuels and hybrids can displace a substantial amount of petroleum fuel.

A portable display designed around the simulator was constructed, and this display was sent to five ALMS races, where it was well received by fans and competitors alike. Prior to being allowed to drive the simulator, demographic and contact information (e-mail) data were collected from the participants. These data will be made available to the program sponsors. The simulation consisted of drivers completing two laps of a pre-defined race course. The simulator then allowed users to store some regenerative energy from braking and use this energy for boosted acceleration (similar to the hybrid racing systems being developed). The fuel usage was then calculated, and the fuel savings using the regenerative system versus non-regenerative systems was compared. Included was a simulation of the petroleum displaced by using E85 as compared to traditional racing fuel; a message to this effect was displayed at the conclusion of the race.

This year brought more visibility for DOE's involvement in the ALMS Green Challenge awards, with more television time devoted to its explanation and the broadcast of more direct interviews with DOE sponsors, including radio and live television segments with Deputy Assistant Secretary Kathleen Hogan at Petit Le Mans (Figure 3).

Figure 3. DOE Assistant Deputy Kathleen Hogan provides interviews explaining the benefits of the Green Racing Program to the media during the ALMS Petit Le Mans event.

A major improvement to the Green Challenge scoring system was made at the beginning of the season with a change to energy consumption as the key metric that drives the score. During the season, refinements were made to the scoring system by incorporating updates to the well-to-wheel petroleum and greenhouse gas calculations using the latest GREET model release. Technical adjustments were also made to the scoring to better represent virtual make-up laps added to the scores for those cars finishing off the lead lap. As a result of these changes, winners of the Michelin Green X Challenge, the best Green Challenge scores at each race, went to 12 different cars from 10 teams from seven vehicle manufactures – a clear indication of the fierce competition in ALMS and the fairness of the scoring system across the five available fuels and multiple vehicle technologies. In addition, the energy efficiency element of the Green Challenge scoring system is being considered for implementation at the Continental Cup in Europe and Asia, a further validation of the quality of this system developed for the Green Racing Initiative.

The DOE/EPA/SAE International's season-long Green Challenge awards were given to the manufacturer that consistently placed the best – week in and week out – in Green Challenge scoring. This year, the winner in the Prototype class was Honda Performance Development for its championship-winning P2 Acura run by Highcroft Racing (Figure 4). In the GT class, Porsche won for its 911 GT3 RSR cars that were fast and efficient all season (Figure 5).

Figure 4. Steve Eriksen, Assistant Vice President from Honda Performance Development, receives the Green Challenge Championship trophy from Karl Simon (EPA), Tim Mellon (SAE International), and Lee Slezak (DOE).

Figure 5. Harmut Kristen, Director of Porsche Motorsports Worldwide, accepts the Green Challenge Championship trophy from Karl Simon (EPA), Tim Mellon (SAE International), and Lee Slezak (DOE).

An important element of the Green Racing Initiative is to promote the use of energy recovery systems in racing. Major steps toward this goal were achieved this year with significant input provided to the Automobile Club de L'Ouest (ACO), the sanctioning body for international sport car racing, regarding safety considerations and recommendations for incorporation of hybrid electric technology into the Prototype class. For example, Argonne produced and distributed a revised white paper recommending an approach to implementing energy recovery over the entire scope of motor sports. This white paper focused on influencing content of future rules packages for both GT and Prototype cars that will encourage energy recovery from braking and waste heat sources. Progress in this area was made through meetings with key stakeholders, culminating in accelerated development of hybrid electric technology in an important initial test bed by Porsche in the 911 GT3 RSR Hybrid. This rolling test bed used electromechanical flywheel energy storage and was the focus when it was unveiled at DOE headquarters before its North American debut at Petit Le Mans, shown below in Figure 6. These successful events were attributed to the efforts of the Green Racing Initiative and represent a large step forward in opening the door for advanced technology development in racing.

Figure 6. The Porsche 911 GT3 RSR Hybrid, the first OEM hybrid electric racing car to join the Green Racing project, on display at DOE headquarters (left) and in action on the race track (right).

<u>Results from the Stock Car Program and Project G.R.E.E.N</u>

To demonstrate the viability of the program, *Circle Track Magazine* partnered with GM Performance Division, Mast Motorsports, Sensors, Inc., and DOE's Green Racing

Initiative through Argonne National Laboratory to begin a series of technical articles dubbed Project G.R.E.E.N. These articles, published in *Circle Track Magazine*, were intended to demonstrate the viability of racecars based on renewable fuels and modern engine technology using a neutral, scientific approach. The program, which began in earnest September of 2009, was broken into three main parts: engine testing at Mast Motorsports in November 2009, on-track testing at New Smyrna Raceway in July 2010, and a full race demonstration in La Crosse, Wisconsin, in October 2010. The following sections highlight the accomplishments to date. DOE/Argonne provided technical guidance and support, instrumentation, analysis. Argonne also was instrumental in bringing in technical partners, such as Sensors, Inc., for emissions testing support.

1. Engine Testing

A production GM Performance Parts circle track-525 LS3 engine was converted to run on fuel-injected and carbureted fueling systems using both race fuel and E85. This engine may be purchased through GM Performance Parts for less than one-fourth the cost of typical race engines to be used in the class of cars in the race series, and its design is based solely on the production-based 6.2L engine sold in the Chevrolet Camaro and Corvette. A Mast Motorsports fuel injection system and calibration was utilized for testing. The engine was mounted to a dynamometer at Mast Motorsports, and a matrix of tests was conducted to benchmark performance measures on such dimensions as fuel injection vs. carburetion, E85 vs. 100-octane race fuel, and catalytic convertors vs. non-catalytic convertor setups. One catalyst contained a 100-cells-per-inch (CPI) and the second a 300-CPI substrate. The testing setup may be seen in Figure 7.

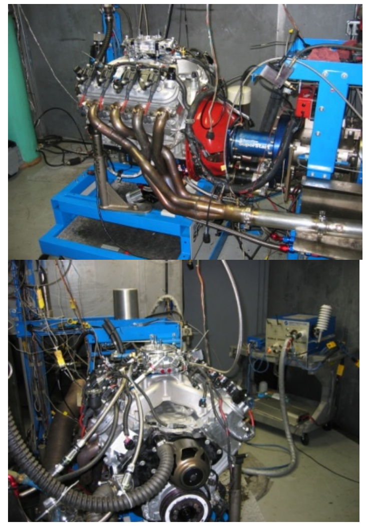

Figure 7. Dynamometer testing configuration for the circle track-525 LS3 engine (top and bottom). MAST Motorsports engine is shown on the right with the SEMTECH DS portable emissions measurement system (PEMS).

After completion of the tests, analysis was conducted to benchmark the gains when using these various technologies. Results of these tests are summarized in Figure 8. The dynamometer testing revealed that the E85-powered, fuel-injected configuration generated approximately 7% greater torque across a majority of engine speeds in the engine's range. Even when catalysts were used, the E85-powered, fuel-injected version showed significantly greater torque benefits over the carbureted, race fuel-powered engine configuration.

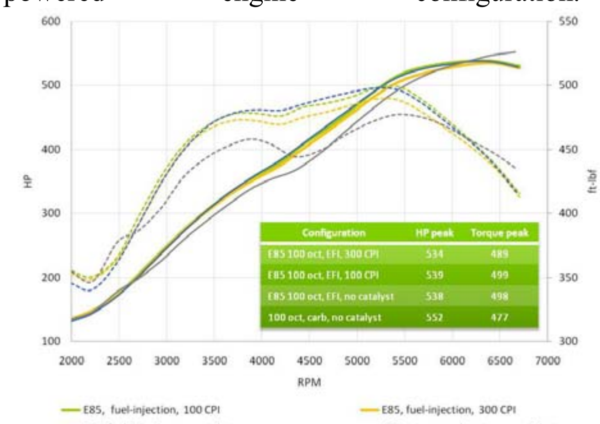

Figure 8. Engine dynamometer full-load, pull-testing results obtained at Mast Motorsports in November 2009.

On Track Testing

The Project G.R.E.E.N team installed, in vehicle, the Sensors, Inc., SEMTECH DS portable emissions measurement system (PEMS). This unit allowed real-time criteria emissions measurements with the vehicle operating at the track as it would in a race. Coupling this equipment with a GPS and a data acquisition system that allowed for temperature measurements and engine control unit (ECU) codes, the team tested each configuration twice over a series of five laps (for a total of 10 laps) by running nearly identical lap profiles. Testing required use of the exact same engine; the only changes occurred when swapping out the fuel induction system (i.e., from carburetor to fuel-injection), switching between fuels (race fuel, E85), and installing catalysts. In order to facilitate quick changes and ensure that the test fuels were not mixed, the Zehr Racing Camaro test vehicle was equipped with two fuel cells: one for race fuel and the other filled with E85. Figure 9 shows the installed system, and Figure 10 shows the course on which the tests occurred.

Figure 9. Pictured in the foreground with the Zehr Racing Camaro test vehicle are Argonne National Laboratory Research Engineers Danny Bocci (left) and Forrest Jehlik (right), with *Circle Track Magazine* editor Rob Fisher in the background. On-board is the SEMTECH DS PEMS courtesy of Sensors, Inc.

Figure 10. New Smyrna raceway. Red lines indicate the recorded position of the car over five laps. Two warm up laps were allowed that preceded five laps of full effort tracing the same path, followed by one coast-down lap before re-entering the pit lane.

Performance Results

Figure 11 shows the average time per lap, where it can be seen that the slowest average lap time was logged by the carbureted race fuel configuration. Over the half-mile (oval) course, the average lap time was 19.2 seconds. The fastest average lap time – recorded using E85 and fuel injection (i.e., no catalytic converters for emissions control) – was 0.5 second faster per lap. Even when using catalytic converters with the E85 fuel-injected configuration, the average lap time was reduced by 0.2 second relative to the race fuel's carbureted counterpart using no catalysts.

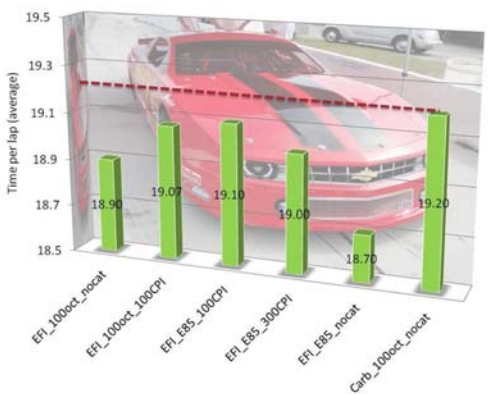

Figure 11. Results obtained on the New Smyrna 1/2-mile oval raceway. Bars indicate the average time per lap, in seconds, for each configuration.

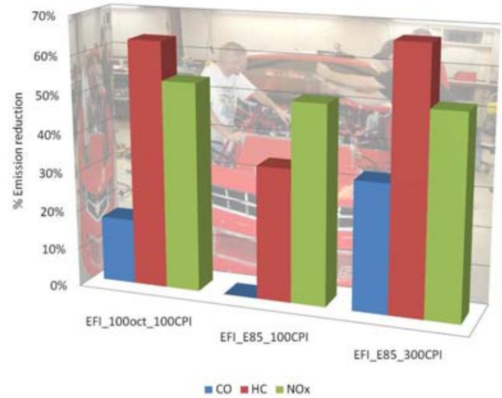

Figure 12. Catalytic convertor emissions reduction efficiencies, 100 CPI vs. 300 CPI (E85) vs. E85 (100 CPI) fuel-injected configurations.

In analyzing the results, it became clear that the reduction in the average lap time was simply a side effect of the increased performance of the fuel-injected and E85-powered configurations. At the conclusion of the on-board emissions lap testing, the Semtech emissions measurement equipment was removed, and the Project G.R.E.E.N team conducted a series of best effort laps with the fuel-injected, E85 configuration, which was contrasted against the carbureted race fuel configuration. Lap times for the fuel-injected E85 configuration were recorded at 18.20 seconds, with the carbureted configuration coming in 0.2 second slower per lap.

Emissions Results

Engine out emissions were recorded, and the effectiveness of utilizing two different catalytic convertors on reducing unburned fuel (e.g., hydrocarbons, HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) were calculated. Five-lap averaged emissions for each configuration are shown for contrast and comparison. The units shown are in grams of emission per mile traveled. These data (shown in Figure 12) were collected at the same time as the performance data.

From these results, it may be seen that all of the convertor configurations experienced modest or no CO reduction. However, on average there were realized reductions of more than 50% in HC emissions and more than 60% in NO_x emissions. The 300-CPI count catalyst exhibited significantly greater HC and CO reductions; the reduction for NO_x conversion, however, was nearly identical. An additional finding is that the conversion efficiency between the 100-octane, 100-CPI configuration is higher than that of the E85 configuration. Referring to back to Figure 11, these reductions do not come at the expense of increased performance.

This successful testing allowed the project to move forward to the next stage of Project G.R.E.E.N, which entailed a demonstration in a real racing situation.

Racing Demonstration

A third stage in the project involved demonstrating the competitiveness and durability of the production-based, ethanol-fueled powertrain in an actual race. In October 2010, the Project G.R.E.E.N Camaro was raced at the ½-mile La Crosse Speedway in La Crosse, Wisconsin, at the annual end-of-season Oktoberfest event, as shown in Figure 13. The car competed in three race stints composed of 33 laps each.

A successful event allowed us to collect valuable data. Competing against a field of 64 cars, the Project G.R.E.E.N Camaro placed 14th overall, a very good finish given the low cost of the engine consisting almost entirely of stock parts, and competing against blueprinted race engines costing more than four times as much. Of particular note was the successful use of E85 at $2.37/gallon compared to the race fuel used by the other competitors at $10.75/gallon. Our FY 2011 report will include a complete description of this very positive test during this part of the Green Racing Initiative.

Figure 13. The Project G.R.E.E.N. Zehr Racing Chevrolet Camaro at the 2010 La Crosse Oktoberfest race weekend.

Conclusions

In FY 2010, significant developments emerged in the Green Racing Initiative. Great advances were recorded in the ALMS program, such as achieving an oil displacement rate of 38%, experiencing several overall wins by cars powered by advanced biofuels, and realizing the near-complete conversion of the GT class to renewable fuels. Important developments in incorporating energy recovery into world-class sports car racing were achieved, and the first factory-backed HEV prototype GT car was raced in the United States. The stock car program blossomed from an intriguing idea into a successful program in partnership with *Circle Track Magazine* and directed by DOE/Argonne technical support, guidance, and instrumentation. The foundation was laid for a new grassroots movement in circle track racing that incorporates the use of renewable fuels, modern engine technology, and emissions control. The relationship between our partners at EPA and SAE International are strong, and many opportunities advance acceptance of green racing principals in other forms of racing lie ahead. This initiative continues to deliver high returns and value for DOE's modest investment.

E. Vehicle to Grid Communication Codes and Standards Development and Testing

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Objectives

- Contribute to Society of Automotive Engineers (SAE) and National Institute of Standards and Technology (NIST) activities to accelerate the development of vehicle to grid communication standards
- Facilitate standards harmonization among various communication protocols relevant for vehicle to grid communications (SAE, ISO/IEC, Smart Energy Profile (SEP 2.0) specifications).
- Test and validate communication messages in SAE J2836/J2847 standards
- Identify industry partners interested in testing and validation of SAE J2847/1 communication in a laboratory setting. Test various communication paths using wireless technologies (ZigBee) and power line carrier (PLC) communications technologies.

Approach

- Pacific Northwest National Laboratory (PNNL) actively participated in SAE and NIST standard development working group meetings to develop use cases and communication messages to establish standards and protocols for vehicle to grid communications. PNNL staff contributed to the production and review of standards documents as well as provided briefings on comparisons among other relevant or competing communications standards developments.
- PNNL worked with Argonne National Laboratory (ANL) and DOE's Grid Interaction Tech Team (GITT) members to develop communication standards verification and to explore interoperability testing options. As part of this effort, two PLC technologies were identified for developing prototype modules to test the J2847/1 messages. A laboratory test bench was assembled and a human-machine-interface (HMI) prototype was developed to demonstrate and test J2836/1 use cases.

Accomplishments

- Provided recommendations to SAE working group on public review drafts of IEC standard and Smart Energy Profile (SEP 2.0) specifications to define the scope for SAE's standards work.
- Developed functional requirements for Human Machine Interface (HMI) and implemented a prototype to test completeness of SAE communication standards.
- Implemented and tested twenty-five SAE's J2847/1 messages and use cases in a PLC communication module.
- Fabricated a test bench with charger, EVSE and monitoring equipment for data collection and testing; developed communication latency testing plan.

Future Directions

- Further testing of power line communication technologies will be continued in FY11 to support the SAE J2931 and J2953 standards. Field testing and demonstration of vehicle to utility advanced meter infrastructure (AMI) networks will be undertaken in partnership with vehicle manufacturers and utility partners.

Introduction

Several vehicle manufacturers have announced the launch of electric vehicles by 2011. Nissan is expected to deliver 20,000 vehicles and Chevrolet Volt is planning to deliver 10,000 vehicles in 2011. Other manufacturer including Mitsubishi, Tesla and Coda have plans to release limited number of vehicles in the near future. Several charging station manufacturers have announced availability of UL certified home and public charging stations. With ARRA funding, the EV Project partners are currently installing electric vehicle charging stations across the country to build the charging infrastructure. These charging stations are installed with cellular communications for vehicle to grid communication and data collection. However, the communication technology and protocols are proprietary to each vehicle manufacturer and charging station. The Society of Automotive Engineers (SAE) is developing communication standards for interoperability between various vehicle and charging station manufacturers, and support utility communication and control of charging stations for load control. This report summarizes PNNL participation and contribution to the development and testing of SAE communication standards.

Status of SAE Communication Standards

The SAE Hybrid Committee is developing a family of standards to address vehicle to grid connectivity and communication. The SAE J1772 connector for Level 1 and Level 2 charging was approved in late 2009, and manufacturers are currently producing connectors and couplers that can be installed in charging stations and vehicles. A hybrid connector update to J1772 is currently being finalized to support connectivity with off-board charging. Since the hybrid connector standard is not yet finalized, JARI/TEPCO connectors are used by some vehicle manufacturers at the present time.

In addition to the connector standards, a total of about 14 documents are expected to be published within the next two years for electric vehicle communication. A list of SAE communication standards is listed below:

- J2836 – General information and Use cases
- J2847 – Communication messages
- J2931 – Communication protocols
- J2953 – Interoperability requirements

J2836 and J2847 standards are further divided into <u>five</u> parts each aimed at specific aspects of communication: 1) utility programs, 2) off-board charger, 3) reverse energy power flow, 4) diagnostic messages and 5) customer home area network (HAN). J2931 standard is expected to have <u>four</u> parts: 1) general requirements, 2) in-band signaling, 3) powerline carrier (PLC) over main cabling and 4) wireless communications. J2953 is the most recent standards initiative to define the testing and certification requirements for interoperability between vehicles and charging stations.

During March 2010, SAE is finalized a draft of J2836/1 and J2847/1 documents for balloting and published it in May 2010. J2836//2 and J2847/2 documents are currently being finalized and expected to be published in early 2011. All other documents are planned for balloting by end of 2011 or early 2012.

PNNL's Contribution to Standards Harmonization Activities

As part of standards harmonization effort, PNNL participated in the NIST's Priority Action Plan 11 (PAP11) working group activities comparing the use cases in SAE J2836/1 and ISO/IEC 15118-Part 1 for vehicle to grid communications. PNNL analyzed the commonalities and differences between the SAE and ISO/IEC standards and provided SAE recommendations to respond to the public review draft of ISO/IEC 15118. The most significant difference identified by PNNL is the scope of ISO/IEC uses cases which is limited to vehicle to charging station communication. SAE J2836/1 use cases address the communication between vehicle and utility, and treat the charging station as an additional node in the communication path. Based on PNNL work, SAE has influenced the international standards organization (ISO/IEC) committee to broaden the scope of the standard to include the option of vehicle communication with the utility.

The ZigBee/HomePlug Alliance released Version 2.0 of Smart Energy Profile (SEP 2.0) communication standards during June 2010, which included electric transportation communication specifications. Smart Energy Profiles originally were intended to support home automation and energy management services in residential home environments. However, these standard developments have matured and are sufficiently relevant for SAE to consider. PNNL developed a relational mapping of J2847/1 messages to SEP 2.0 data items and identify gaps in the SAE J2847/1 data definitions. For instance, data items related to energy demand and electricity pricing were added to the SAE specification. PNNL continues work with the SEP 2.0 specification development team to address these items.

Vehicle to Grid Communication Testing

Development of a lab test bench for SAE standards testing

In 2010, SAE with consultation by the technology vendors expressed interest in exploring the applicability of low-cost, narrow-band powerline carrier (PLC) technology for the communication between the EVSE and the vehicle. In discussion with DOE's Grid Interaction Tech Team, Argonne National Laboratory (ANL) and other interested partners, PNNL proposed the development of communication module prototypes to implement the J2847/1 messages for testing the low-frequency, narrowband technologies. A laboratory test bench was fabricated with a charging station, battery, charger, and a computer set up to connect the communication modules to develop test procedures for SAE standards validations. Figure 1 shows the components of the laboratory test bench.

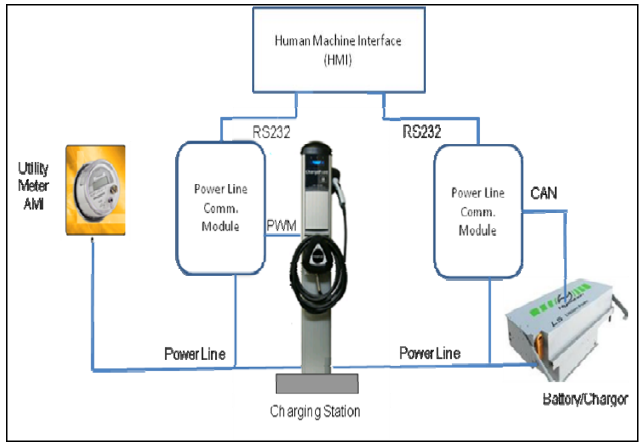

Figure 1: Laboratory test bench setup

Testing SAE standards completeness with development of human-machine-interface (HMI)

PNNL developed a draft version of a HMI to test completeness of the user-input data for executing use cases. All of the HMI display items are related to J2847/1 messages. Data items and their function related to the charging status, pricing information, charging status and others related to J2836/1 use cases are implemented in the prototype HMI.

The primary method for user interaction with the vehicle charger is typically through a touch screen interface in the vehicle or the charging station. The main screen in the HMI provides information on the status of their electric vehicle, and will display several basic elements to the user, display some additional items during vehicle charging, and may contain some user configurable optional information (see Figure 2). Upon activation of the screen, the user will be presented with a visual representation of the battery state of charge. Once the vehicle is plugged in, and the handshaking with the utility has been accomplished, the connection, handshaking and authentication icons in the middle of the display will be enabled indicating that the process was successful. This handshaking mechanism will be accomplished via J2847 compliant messages that will authenticate the vehicle with the utility, and transmit the rate table from the utility back to the vehicle. The screen will display the time by which the vehicle will be charged and the current system state, the current price of electricity, and the cost of the current charge session.

Figure 2: Sample HMI Screen

When the vehicle is plugged in and the handshaking with the utility is completed, the vehicle will immediately begin a charge session using the optimal charge scenario based on the TOU rate schedule and the "charge by" time set in the preferences screen. The user will also have the option to override the scheduled charge and begin charging immediately. The user also has the option to temporarily override the selected rate plan (for example, temporarily opt out of demand response programs). The interface provides “Startup” window, where default settings can be provided.

SAE Standards implementation and testing with PLC technology

PNNL worked with Echelon and Maxim to test PLC technology for implementability of J2847/1 messages between the EVSE and the vehicle. PNNL developed an application layer protocol that represents J2847/1 messages on Echelon’s networks. All J2847/1 messages for key use cases (U-1 to U-5) were implemented for testing.

PNNL test the PLC technology to communicate between a Coulomb Technology Level 2 charging station and a Hymotion battery charger (representing a vehicle). Results from these tests will provide a basis for SAE to make the final selection of PLC communication technology for automotive application.

Conclusions and Future Work

During FY10, PNNL developed the lab test bench to test and validate vehicle to grid communication messages. This provides an infrastructure to test various physical and application layer communication protocols for automobile applications. The SEP 2.0 application protocol is expected to be finalized in early 2011 and this needs to be tested for interoperability so that vehicle manufacturers, charging station manufacturers and utility AMI systems can begin to adopt the SAE Standards and develop communication modules. Recently, EPRI has begun a survey of automobile manufacturers to identify the physical layer and protocol preferences, and scope of communication messages and prioritize the standards development. In addition, SAE communication standards development requires further support to establish testing procedures, performance requirements and validation methods for communication modules.

During FY11, PNNL will work with industry partners to implement and test the new SAE standards and SEP 2.0 protocols to accelerate the communication module development such that the vehicle and charging station manufacturers can deploy communication modules by 2012 when the number of electric vehicles is expected to increase significantly.

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2. http://www.theevproject.com/overview.php
3. PAP11: Priority Action Plan 11: Common Object Models for Electric Transportation

VIII. HEAVY VEHICLE SYSTEMS OPTIMIZATION

A. DOE Project on Heavy Vehicle Aerodynamic Drag

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Contractor: Lawrence Livermore National Laboratory
Contract No.: W-7405-ENG-48, W-31-109-ENG-38, DE-AI01-99EE50559

Objective

The primary goal of this project is to reduce the aerodynamic drag of heavy vehicles for a significant impact on fuel economy while satisfying regulation and industry operational constraints. An important part of this effort is to expand and coordinate industry collaborations for DOE to improve the fuel economy of heavy vehicles and participate with industry in designing the next generation of highly aerodynamic class 8 heavy vehicles. Class 8 tractor-trailers consume 12-13% of the total US petroleum use. At highway speeds, more than 50% of the energy expenditure is used in overcoming the aerodynamic drag. The specific goals of this project include:

- In support of DOE's mission, provide guidance to industry to improve the fuel economy of class 8 tractor-trailers through the use of aerodynamic drag reduction
- On behalf of DOE to expand and coordinate industry participation to achieve significant on-the-road fuel economy improvement
- Demonstrate new drag-reduction techniques and concepts through use of virtual modeling and testing
- Full-scale wind tunnel validation of selected devices with industry collaboration and feedback
- Joined with industry in getting devices on the road
- Establish a database of experimental, computational, and conceptual design for aerodynamic drag reduction devices

Approach

- Simulate and analyze the aerodynamic flow around heavy vehicles using advanced computational fluid dynamics (CFD) tools
- Generate an experimental database for code validation and for understanding the drag producing flow phenomena
- Provide industry with design guidance and insight into the flow physics about a heavy vehicle from experiments and computations
- Investigate aerodynamic drag reduction devices (e.g., base flaps, tractor-trailer gap stabilizers, underbody skirts, wedges and fairings, and blowing and acoustic devices, etc.)
- Provide industry with conceptual designs of drag reducing devices

- Demonstrate the full-scale fuel economic potential of these devices

Accomplishments

For the fiscal year 2010, the Heavy Vehicle Aerodynamic Drag Project achieved two major accomplishments. The first is the completion of the full-scale wind tunnel study at the NFAC facility (80'×120') located at NASA Ames Research Center. Requiring more than a year of preparation, this test was completed over the course of two months during the early portion of 2010. During this study, the drag reduction properties of 23 devices were evaluated for heavy vehicle configurations consisting of a long-sleeper tractor with a 53' straight-frame trailer, a long-sleeper tractor with a 28' straight-frame trailer, a day-cab tractor with a 53' straight-frame trailer, and a day-cab tractor with a 53' drop-frame trailer (Figure 1). Approximately 140 wind tunnel runs were completed throughout the study.

In addition to the drag measurements, select runs were made to determine the acoustic properties of the flow over the heavy vehicle using a phased microphone array. A significant reduction in the aerodynamic drag was observed when the devices are used in combination with one another and we are therefore cautiously optimistic that a 25% drag reduction can be achieved through these vehicle modifications. Some preliminary results on the drag reduction properties of the trailer skirt devices are shown in Figure 2. This and other data are currently being post-processed and analyzed and will be summarized in an article submitted to a peer-reviewed journal.

The second accomplishment is the collaboration between Praxair and LLNL for the research and development of fairings to reduce the aerodynamic drag of tanker trailers. In addition to Praxair, we are beginning to discuss with Navistar and a third-party device manufacturer to evaluate and produce these fairings.

We have started to investigate the aerodynamics of tanker trailers in order to identify the major contributors to the drag on this type of vehicle. This was accomplished by simulating the flow over a highly detailed, full-scale day-cab tractor and tanker trailer operating within a 6 degree crosswind at highway speed (Figure 3a). The results of the simulations demonstrate that the major contributors to the aerodynamic drag are flow impingement upon the tractor grill, the transition of the flow from the hood to the windshield, flow entrainment into the tractor-tanker gap, and flow separation from the tanker base (Figure 3b). Starting with the tractor-tanker gap, we are planning to design devices that can mitigate these drag sources and thereby improve the fuel economy of tanker trailers.

Future Direction

- Complete the analysis of the NFAC full-scale wind tunnel test and summarize the study results in a peer-reviewed publication

- Perform track and on the road test of selected drag reduction devices suggested by the full-scale wind tunnel test data in collaboration with Navistar.

- Continue talks with Praxair and Navistar for the evaluation of fairings to reduce the aerodynamic drag of tanker trailers.

Acknowledgments

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Figure 1. Top) Long-sleeper tractor and 53’ straight-frame trailer in the 80’x120’ NASA Ames wind tunnel. Bottom) Day-cab tractor being lifted into the wind tunnel test section. The drop-frame trailer, straight-frame trailer, and long-sleeper tractor are visible at the bottom of the photo.

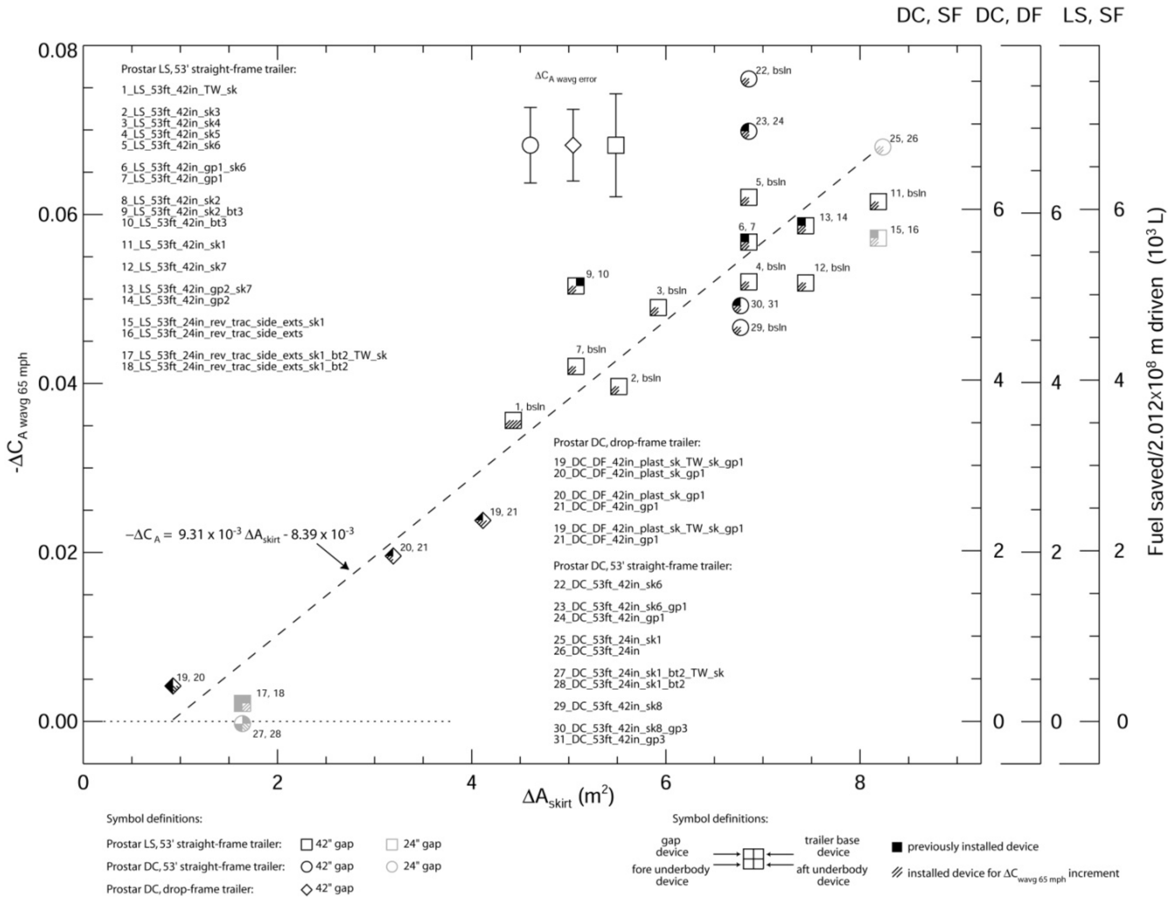

Figure 2. Reduction in the drag coefficient and estimated fuel usage for the various trailer skirts as a function of skirt area.

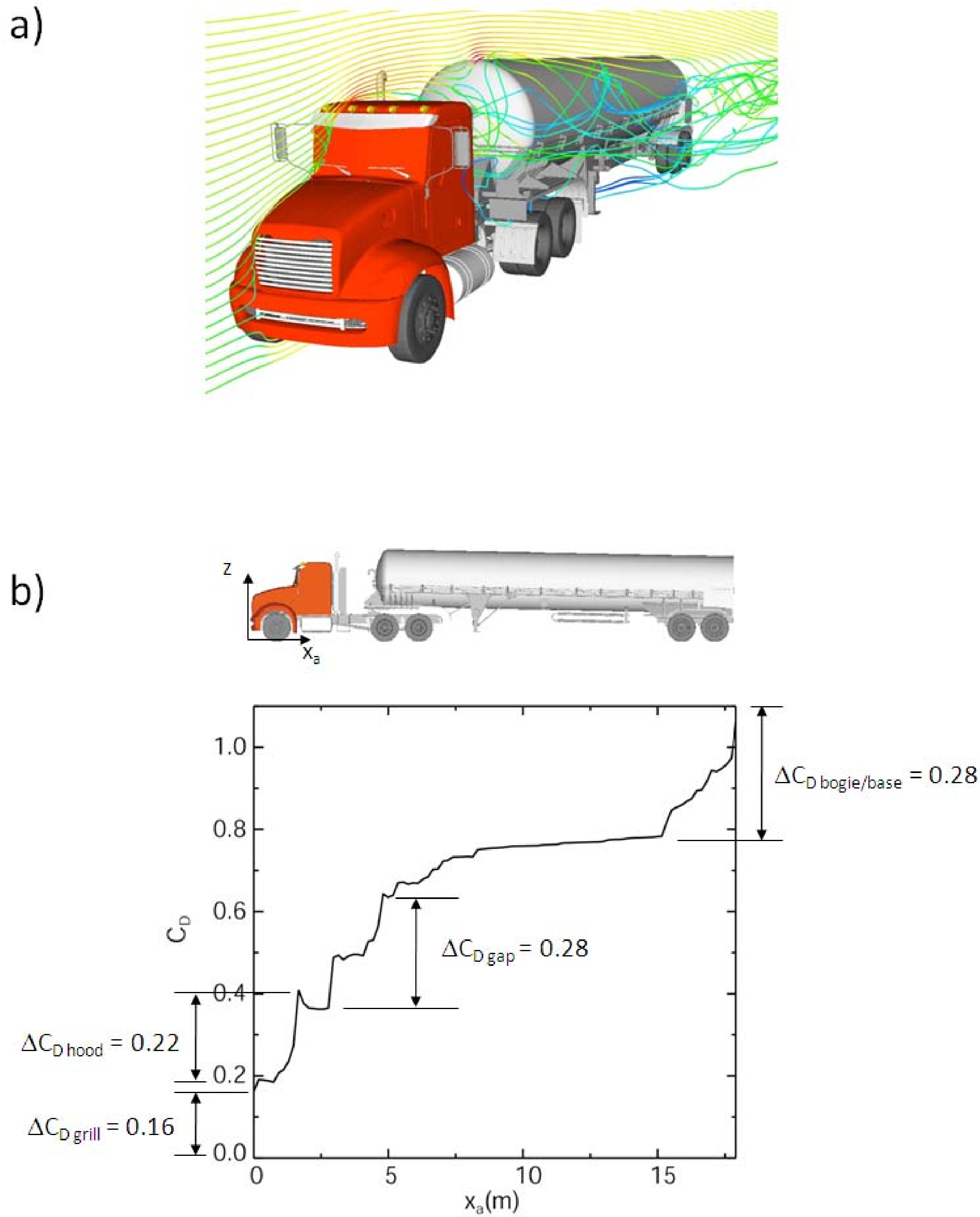

Figure 3. a) Velocity streamlines over a day-cab tractor and tanker trailer. b) Body-axis drag coefficient as a function of length along the tractor and tanker trailer.

B. Experimental Investigation of Coolant Boiling in a Half-Heated Circular Tube– CRADA with PACCAR

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Contract No.: DE AC03 06CH11357

Objective

- Understand and quantify engine coolant boiling heat transfer in heavy duty trucks.
- Experimentally determine boiling heat transfer rates and limits in the head region of heavy duty truck engines.
- Develop predictive mathematical models for boiling heat transfer results.
- Provide measurements and models for development/validation of heavy duty truck engine computer codes.

Approach

- Design and fabricate the experimental test facility with the test section sized to the specification of the cooling channel in the head region of heavy truck engines.
- Experimentally determine subcooled boiling heat transfer rates and critical heat fluxes with water.
- Experimentally determine subcooled boiling heat transfer rates and critical heat fluxes with a 50/50 ethylene glycol/water mixture.
- Experimentally determine subcooled boiling heat transfer rates and critical heat fluxes with a 25/75 ethylene glycol/water mixture.

Accomplishments

- Completed the concept and technical designs of the experimental test facility and support systems.
- Completed procurement of materials and components for experimental test facility.
- Initiated fabrication of experimental test facility and completed several subcomponents including the preheater component, the heat exchanger (cooler) component, the flowmeter component, and part of the test section component.

Future Direction

- Continue fabrication of the experimental test facility.
- Establish data acquisition hardware and software.
- Verify the experimental test facility through heat loss tests and single-phase heat transfer tests.
- Conduct subcooled boiling tests of water and ethylene glycol/water mixtures and perform experimental data analyses.

Introduction

Subcooled boiling is an important phenomenon that must be understood in order to design efficient diesel engine cooling systems. If the system fluid is at or below the critical heat flux (CHF), the cooling can be very efficient. However, if the system is allowed to go above the CHF, cooling becomes inefficient. Two-phase flow instabilities also lead to inefficiency. PACCAR/DAF is designing engines to take advantage of operation just below the CHF, but the CHF has not been determined under realistic conditions. This experiment will address this, using a design specified by our CRADA partner. The data will be used in computational fluid dynamics models and design by PACCAR/DAF with the objective of producing more efficient engines for heavy trucks.

Experimental Test Facility

The experimental test facility, shown in the Test Facility Schematic Diagram, was designed specifically for the boiling test program with PACCAR. The major components shown in the diagram either have been purchased and are being adapted for use in the facility or are in the process of being fabricated from specially purchased materials.

The pump has been purchased with flowrate and head in the range necessary for the desired test series. It was one of the first components ordered and received for the project.

The test fluid exiting the pump passes through two preheaters, Preheater 1 and Preheater 2 in the diagram. The purpose of these heaters is to raise the subcooled temperature of the fluid to desired levels for entrance into the test section. The preheaters, shown in the photograph, Preheater Component (Preheater 1 and Preheater 2), have been fabricated from stainless steel tubing that was specially bent. The tubes were fitted with piping connections and mounted on high temperature stands. Copper blocks were fabricated and electric cable end connectors were attached to each heater as seen in the photograph. These heaters will have electrically insulated thermocouples attached, and then they will be ready for assembly into the system. Thermal insulation will be applied last.

The test fluid exiting the preheaters flows to the test section seen in the photograph, Test Section Component. The test section is being fabricated from carbon steel tubing with fittings for connection to electrically insulating flexible tubing. Heat will be supplied by resistance heating wire seen in the photograph attached to specially fabricated copper blocks and electrical cable end connectors. Currently, thermocouples are being attached to the test section after which the heating wire will be electrically insulated and attached. (The clamps in the photo are temporarily holding the heating wire to the test section tube.)

The fluid exiting the test section will be reduced in temperature in the heat exchanger (cooler) shown in the photograph, Heat Exchanger (Cooler) Component. This plate-frame heat exchanger was procured and mounted on a high temperature stand. The inlet and outlet tubes have been fitted with appropriate tubing connectors. Under maximum test conditions, this heat exchanger is rated at 20 kW that matches the facility needs.

After flowing through the heat exchanger, the test fluid flows through the flowmeter before returning to the pump and thus completing the closed loop. The electro-magnetic flowmeter, shown in the Flowmeter Component photograph, has been mounted and fitted with appropriate tubing connections. The electrical output is shown on top of the flowmeter in the photograph.

Currently, thermocouples are being attached to components after which the components will be assembled into the system configuration shown in the schematic diagram. The electrically insulating tubing shown in the schematic as ISO has been identified, and special connections are being fabricated for its use. At the same time, we have started work on the data acquisition software for testing. The data acquisition hardware and software have been used previously in boiling experiments in our laboratory. It is only necessary to make adaptations to the new system and test section.

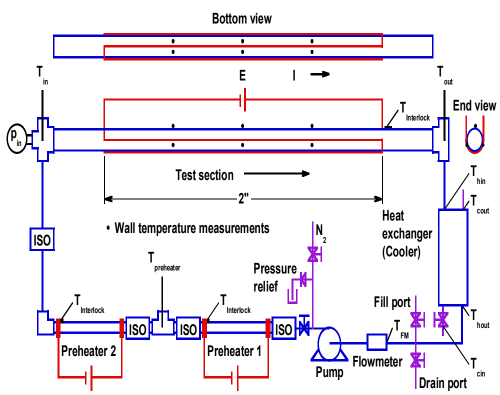

Figure 1. Test Facility Schematic Diagram

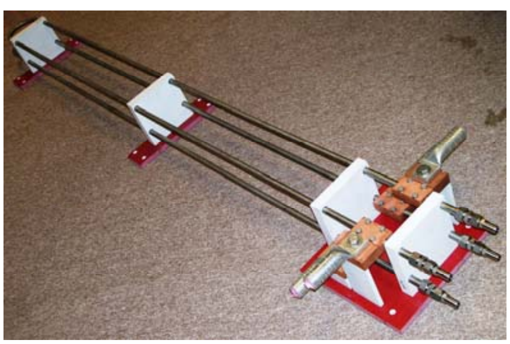

Figure 2. Preheater Component (Preheater 1 and Preheater 2)

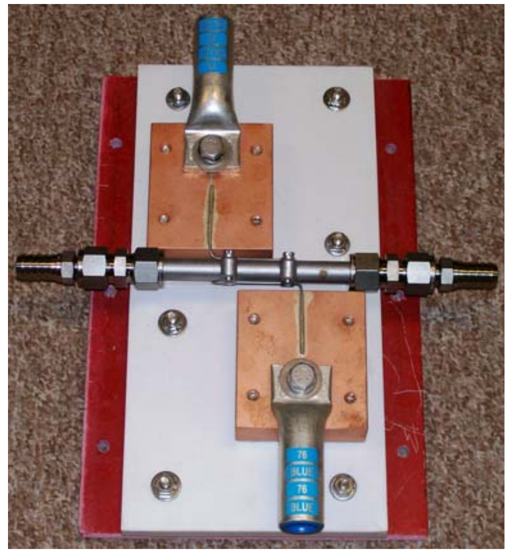

Figure 3. Test Section Component

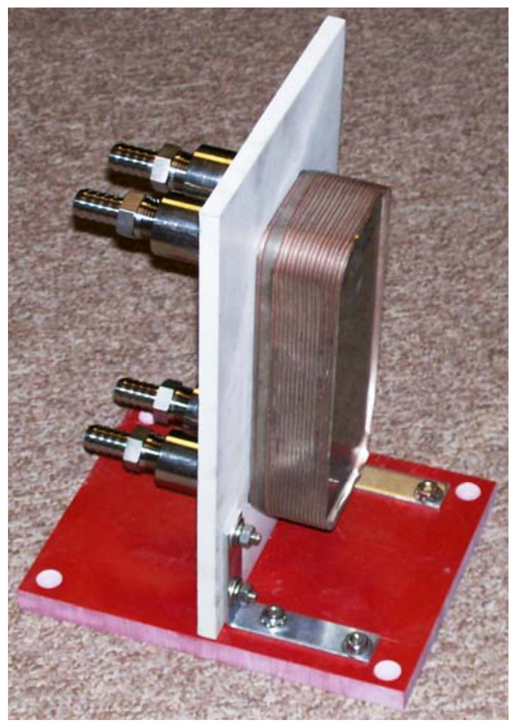

Figure 4. Heat Exchanger (Cooler) Component

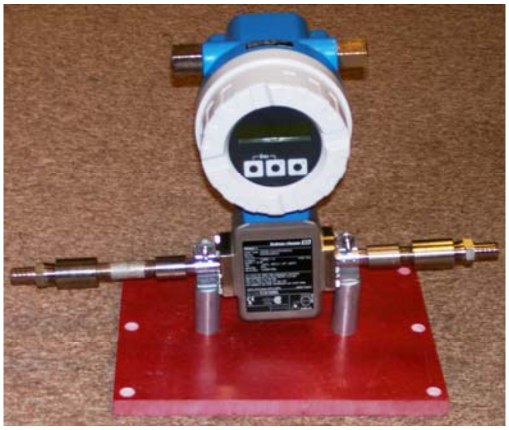
Figure 5. Flowmeter Component

Issues & Future Direction

Future work includes (a) Continuing and finishing the fabrication of the experimental test facility, (b) establishing and modifying data acquisition hardware and software to meet the requirements of this project, (c) verifying the experimental test facility through heat loss tests and single-phase heat transfer tests, (d) conducting subcooled boiling tests of water and ethylene glycol/water mixtures, and (e) performing experimental data analyses.

C. Boundary Lubrication Mechanisms

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Objective

Develop a better understanding of the mechanisms and reactions that occur on component surfaces under boundary lubrication regimes with the ultimate goal of friction and wear reduction in oil-lubricated components and systems in heavy vehicles. Specific objectives are

- Determine the basic mechanisms of catastrophic failure in lubricated surfaces in terms of materials behavior. This knowledge will facilitate the design of higher power density components and systems.
- Determine the basic mechanisms of chemical boundary lubrication. This knowledge will facilitate lubricant and surface design for minimum frictional properties.
- Establish and validate methodologies for predicting the performance, and failure of lubricated components and systems.
- Integrate coating and lubrication technologies for maximum enhancement of lubricated-surface performance.
- Transfer the technology developed to OEMs of diesel engine and vehicle components and systems.

Approach

- Characterize the dynamic changes in the near-surface material during scuffing. Formulate a material-behavior-based scuffing mechanism and prediction capability.
- Determine the chemical kinetics of boundary film formation and loss rate by in-situ X-ray characterization of tribological interfaces at the Advanced Photon Source (APS) of Argonne National Laboratory (ANL).
- Characterize the physical, mechanical, and tribological properties of tribo-chemical films, including the failure mechanisms.
- Integrate the performance and failure mechanisms of all the structural elements of a lubricated interface to formulate a method for predicting performance and/or failure. This task will include incorporation of surface coatings.
- Maintain continuous collaboration with OEMs of heavy vehicle systems to facilitate effective technology transfer.

Accomplishments

- Conducted extensive characterization of microstructural changes during scuffing of 4340 steel, using scanning electron microscopy (SEM) and X-ray analysis.

- For metallic materials, developed a model of scuffing initiation based on an adiabatic shear instability mechanism and scuffing propagation based on a balance between heat generation and heat dissipation rates.
- Characterized the mechanical properties and scuffing resistance of a graded nanocrystalline surface layer produced by severe plastic deformation resulting from the scuffing process.
- Conducted preliminary evaluation of scuffing mechanisms in ceramic materials.
- Extended scuffing mechanisms study into ceramics and metals contact pairs as well as cast iron –typically used as cylinder liner in diesel engine.
- Using X-ray fluorescence, reflectivity, and diffraction at the APS, demonstrated the ability to characterize tribo-chemical films generated from model oil additives.
- Designed and constructed an X-ray accessible tribo-tester for in-situ study of boundary film formation and loss rates.
- Characterized the structure of Tribochemical boundary films with different frictional behavior with a new technique that combines focused ion beam (FIB) milling, transmission electron microscopy (TEM) and grazing incidence x-ray diffraction (GIXRD) at APS.
- Initiated the measurement of nano mechanical properties of tribo chemical boundary films.
- Formulated the frame work for friction prediction of lubricated contact interface taking into account the contribution of fluid film, boundary film and the near-surface material.

Future Direction

- Continue refinement and validation of the comprehensive scuffing theory for various engineering tribo materials.
- Develop and evaluate methods and technologies to prevent scuffing in high power density oil-lubricated components and systems.
- Continue characterization of tribochemical films formed by model and commercial lubricant additives using FIB, TEM and x-ray based surface analytical techniques available at APS.
- Characterize the physical, mechanical, and failure mechanisms of tribochemical films with nano-contact probe devices.
- Evaluate the impact of various surface technologies, such as coating and laser texturing, on boundary lubrication mechanisms.
- Develop a technique to measure real contact temperature needed for tribochemical film formation.

Introduction

Many critical components in diesel engines and transportation vehicle systems such as gears and bearings are lubricated by oil. Satisfactory performance of these components and systems in terms of efficiency and durability is achieved through the integration of materials, surface finish, and oil lubricant formulations often using Edisonian trial-and-error approach. Indeed, experience is likely the sole basis for new designs and methods to solve failure problems in lubricated components. Because of the technology drive to more efficient and smaller systems, more severe operating conditions are invariably expected for component surfaces in advanced engines and vehicle systems. The trial-and-error approach to effective lubrication is inadequate and certainly inefficient. Departure from this approach will require a better understanding of the fundamental mechanisms of both boundary lubrication and surface failure in severely loaded lubricated components.

Another major technical thrust area for the Department of Energy in the development of diesel engine technology for heavy vehicles is emission reduction. Indeed with the higher efficiency of diesel engines compared to gasoline engines, significant reduction in emissions will facilitate more use of diesel engine for automotive applications. Unfortunately, some essential components in oil lubricants and diesel-fuel additives (such as sulfur, phosphorus, and chlorine) are known to poison the catalysts in diesel engine emission-reducing after-treatment devices. Reduction or elimination of these additives will make emission after-treatment devices more effective and durable; it will however make the surfaces of many lubricated components more vulnerable to catastrophic failure. There is therefore a need to develop effective replacement for these essential lubricant additives. Again, such an Endeavour will require a better understanding of the mechanisms of boundary lubrication and the failures therein.

Increases in vehicle efficiency will require friction reduction and increase in power density in the engine and powertrain systems. Higher power density translates to increased severity of contact between many tribological components. This, again, will compromise the reliability of various critical components, unless they are effectively lubricated. The efficacy of oil additives in reducing friction and in protecting component surfaces depends on the nature and extent of the chemical interactions between the component surface and the oil additives. In addition to reliability issues, the durability of lubricated components also depends on the effectiveness of oil lubrication mechanisms especially under boundary conditions. Components will eventually fail or wear out by various mechanisms including contact fatigue. Wear is the gradual removal of material from contacting surfaces, and it can occur in many ways, such as abrasion, adhesion, and corrosion. Repeated contact stress cycles to which component contact surfaces are subjected can initiate and propagate fatigue cracks and, ultimately, lead to the loss of a chunk of material from the surface. This damage mode by contact fatigue is often referred to as "pitting." Wear and contact fatigue are both closely related to boundary lubrication mechanisms. Antiwear additives in lubricants are designed to form a wear-resistant protective layer on the surface. The role of lubricant additives on contact fatigue failure is not fully understood, although it is clear that the lubricant chemistry significantly affects contact fatigue. Again, lack of a comprehensive understanding of the basic mechanisms of boundary lubrication is a major obstacle to a reasonable prediction of the durability of lubricated components and systems.

Significant oil conservation benefits would accrue by extending the drain interval for diesel engine oil, with an ultimate goal of a fill-for-life system. Successful implementation of the fill-for-life concept for the various lubricated systems in heavy vehicles requires optimization of surface lubrication through the integration of materials, lubricant, and, perhaps, coating technologies. Such an effort will require an adequate fundamental understanding of surface material behavior, chemical interactions between the material surface and the lubricant, and the behavior of material and lubricant over time.

Some common threads run through all of the challenges and problems in the area of effective and durable surface lubrication of efficient and high power density engine components and systems briefly described above. The two key ones are lack of adequate basic and quantitative understanding of the failure mechanisms of component surfaces, and lack of understanding of the basic mechanisms of boundary lubrication, i.e., how lubricant chemistry and additives interact with rubbing surfaces, and how this affects performance in terms of friction and wear.

To progress beyond the empirical trial-and-error approach for predicting lubricated component performance, a better understanding is required of the basic mechanisms regarding the events that occur on lubricated surfaces. Consequently, the primary objective of the present project is to determine the fundamental mechanisms of boundary lubrication and failure processes of lubricated surfaces. The technical approach taken in this study differs from the usual one of posttest characterization of lubricated surfaces but, rather, will include developing and applying in-situ characterization techniques for lubricated interfaces that will use the X-ray beam at the Advanced Photon Source (APS) located at ANL. Using a combination of different X-ray-based surface analytical techniques, we will study, in real time, the interactions between oil lubricants and their additives and the surfaces they lubricate. Such study will provide the basic mechanisms of boundary lubrication. In addition to surface chemical changes, the materials aspects of various tribological failure mechanisms (starting with scuffing) will be studied.

Results and Discussion

Efforts during fiscal year 2010 (FY 2010) were devoted to the characterization and measurement of the mechanical properties of tribochemical boundary films. The new technique of combined focused ion beam (FIB) and transmission electron microscopy (TEM) that we developed for the analysis of tribochemical boundary films was described in details in the last annual report for this project. Details of the structure of three tribochemical films produced from three different lubricant formulations were analyzed with the new technique. The three films showed distinctively different friction behaviors as shown in Figure 1. Since these films were produced on the same material and from lubricants with same viscosity, differences in their friction behavior is attributed to differences in their structures and properties.

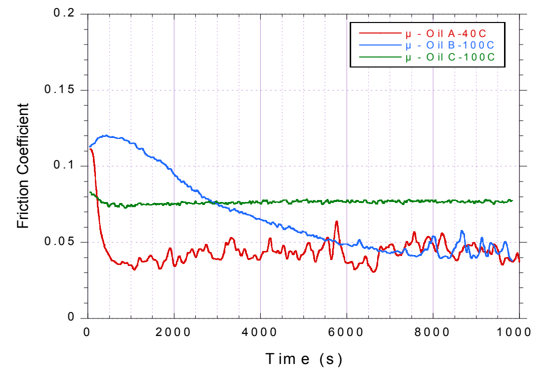
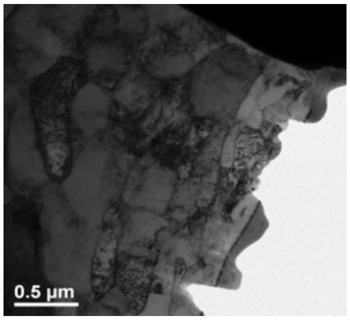
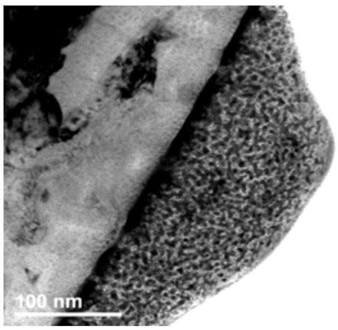


Figure 1: Friction behavior of three different lubricants with different additives

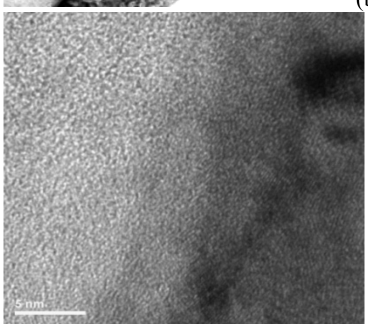
Figure 2 shows TEM micrographs from films produced from lubricant A, in which the friction coefficient decreased very quickly to a steady value of about 0.04 after the initial value of o.12. This friction behavior is attributed to a quick formation of the boundary film. Structural analysis showed that the film from lubricant A is monolayer and amorphous through its entire thickness. As shown in Figure 2c, there is a strong bond between the amorphous boundary films and the crystalline steel substrate material. It appears there is a transition zone of about 5 nm thickness between the ordered crystalline substrate and the disordered amorphous boundary film phase.



(a) Macroview



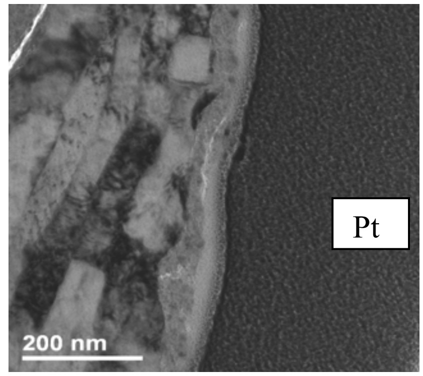
(b) Microview



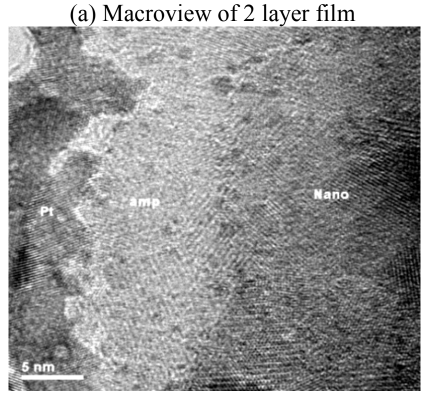
(c) Film-substrate interface

Figure 2: a Tribochemical film from Lubricant A is amorphous.

The tribochemical boundary film formed in oil B is bi-layer as indicated in Figure 3. The layer next to the substrate is primarily crystalline with grain size of order of 5-10 nm, while the layer at the top of the films is primarily amorphous as shown in Figure 3b.



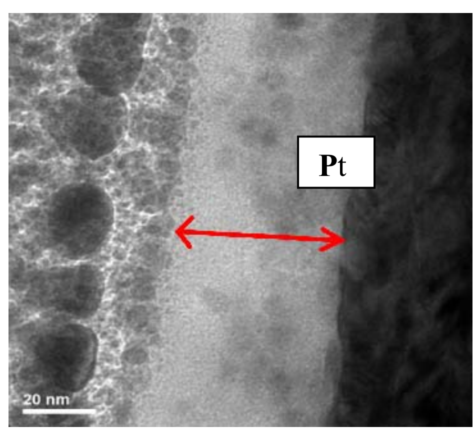
(a) Macroview of 2 layer film



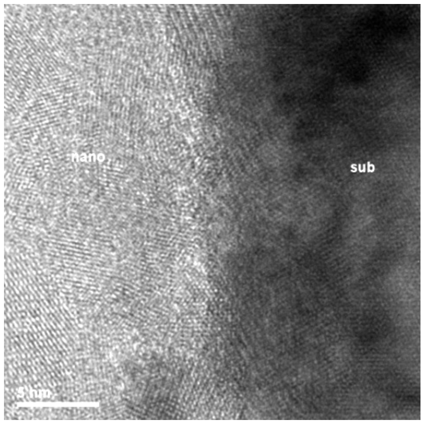
(b) Transition between crystalline and amorphous layer

Figure 3: Tribochemical films from lubricant B is bi-layer.

The films formed from lubricant C is a single layer and crystalline as Figure 4 shows. The interface between this boundary film and the substrate materials is continuous and without defect, as clearly seen in Figure 4b.



(4a)Macro view of film



(4b) Interface between film and substrate

Figure 4: Tribochemical film from lubricant C is single layer and crystalline

Although limited to only these three boundary films and hence preliminary, the results of the structural analysis of the three tribochemical films suggest a strong connection between the structure of the films and their friction behavior. The tribochemical film with crystalline structure exhibited relatively high and constant friction coefficient (oil C), while the films containing amorphous phase showed lower friction coefficient (oils A and B). In the film with a bi-layer mixture of phases, the friction started out relatively high, but decreased to lower values over time. This may suggest that the film in the early higher friction stage is primarily crystalline and that the formation of second amorphous top layer resulted in decrease of friction. If this observation is verified to be generally true, then, there is a pathway to sustainably reduce friction in lubricated contact through tribochemical boundary film structural design.

During FY10, efforts to measure the mechanical properties of tribochemical boundary films with nano mechanical probe system were started. The nano mechanical properties of the films were measured by Hysitron instrumented nano-indenter system shown in Figure 5. The hardness and elastic modulus of the films can be determined with this instrument. In addition, the mechanical behavior of the films can be extracted from the load-displacement curve during indentation loading and unloading cycle.

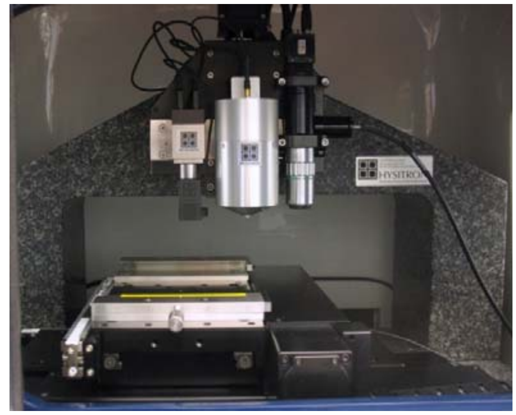
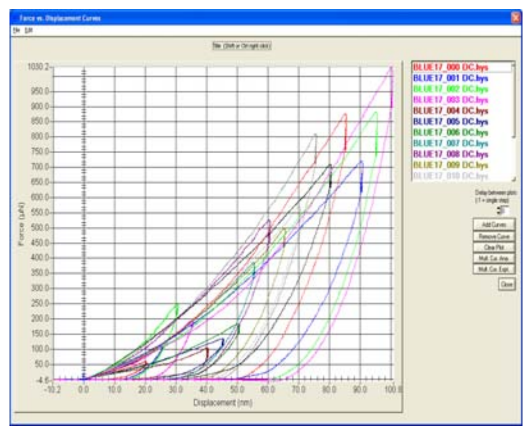
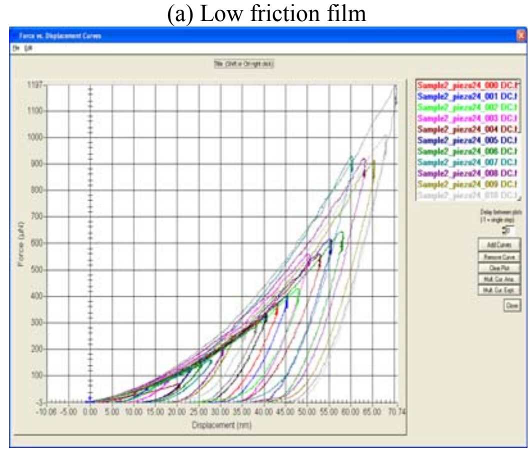


Figure 5: Hysitron instrumented nano mechanical probe system.

The force-displacement curves from nano indentation of two different tribo films are shown in Figure 6.



(a) Low friction film



(b) High friction film

Figure 6: Force-displacement curves from nano-indentation of tribochemical films

For the bi-layer low-friction film formed from oil B, the force-displacement curves showed a complex mechanical behavior (Figure 6a).

The average hardness of the film was 3.8 GPa while the elastic modulus was about 90 GPa. Both the hardness and the elastic modulus of this film are considerably lower than the hardness and modulus of the steel substrate with values of 7.8 GPa and 200 GPa for hardness and modulus respectively.

For the high-friction film with crystalline structure produced from oil C, the force-displacement curves indicate an elasto-plastic mechanical behavior (Figure 6b). The film hardness and modulus were determined to be 6.4 GPa and 152 GPa respectively; both of which are lower than the steel substrate, but higher than the values for the low-friction film.

Conclusions

During FY 2010, we made significant and important progress in characterizing the structure of tribochemical boundary films and connecting structure and friction behavior. Structures of three films with different friction behaviors were characterized by a new and unique technique of combination of FIB and TEM. The analyses showed that the film thickness is between 80-120 nm. The lower friction films are amorphous while the higher and constant friction film is nanocrystalline with a grain size of order of 5-10 nm. These results will provide guidance for lubricant and surface material integration for predictable and sustainable friction behavior. In addition to structural analysis, the nano mechanical properties of the tribochemical films were also measured by the instrumented nano mechanical probe system. The amorphous tribochemical film exhibited a complex mechanical behavior during indentation, while the crystalline tribochemical film showed an elasto-plastic mechanical behavior. Both films have lower hardness and modulus compared to the steel substrate. The amorphous film has lower hardness and modulus compared to the crystalline film.

Publications

1. O. O. Ajayi, C. Lorenzo-Martin,R. A. Erck, and G. R. Fenske, "Scuffing mechanism of near-surface material during lubricated sliding contact" *Wear Journal* (in press).

2. Lorenzo-Martin, O. O. Ajayi, R. A. Erck, and G. R. Fenske, "Effect of temperature in friction behavior under boundary lubrication regime" Presented at 2010 STLE Annual Meeting, Las Vegas, NV May 16-20, 2010.

3. Zhang, J. Han, G. Barber, Q. Zou, and O. O. Ajayi, "Comparative evaluation of scuffing mechanisms in carbon steel and cast iron" Presented at 2010 STLE Annual Meeting, Las Vegas, NV May 16-20, 2010.

4. Lorenzo-Martin, O. O. Ajayi, J. K. Lee and A. A. Polycarpou, "Frictional Behavior of Boundary Lubricated Contacts – Effect Tribochemical Surface Films" Proceedings 2009 ASME/STLE International Joint Tribology Conference.

5. O. O. Ajayi, C. Lorenzo-Martin, R. A. Erck, J. Routbort, and G. R. Fenske, "Boundary Lubrication Mechanisms" 2009 OVT Annual Report (2010), 323-330.

Patent Awarded:

1. Oyelayo O. Ajayi and Jeffrey Hershberger, "Method for Producing Functionally Graded Nano-crystalline Layer on Metal Surface" US Patent 7,682,650, March 23, 2010

D. Parasitic Energy Loss Collaboration

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Zoran Fillipe, University of Michigan

Objective

- Develop and integrate mechanistic models of engine friction and wear to identify key sources of parasitic losses as functions of engine load, speed, and driving cycle.
- Develop advanced tribological systems (lubricants, surface metrology, and component materials/coatings) and model their impact on fuel efficiency with a goal to improve vehicle efficiency by 2% in FY 2015.
- Develop engine component maps to model the impact on fuel efficiency for use in analytical system toolkits.
- Develop database of friction and wear properties required for models of mechanistic friction and wear of coatings, lubricant additives, and engineered surface textures.
- Validate mechanistic models by performing instrumented, fired-engine tests with single-cylinder engines to confirm system approaches to reduce friction and wear of key components.
- Identify common issues associated with commercial and military ground vehicles on the impact of low-friction lubricant technologies to reduce parasitic friction losses and vehicle efficiency.

Approach

- Predict fuel economy improvements over a wide range of oil viscosities by using physics-based models of asperity and viscous losses.
- Model changes in contact severity loads on critical components that occur with low-viscosity lubricants.
- Develop and integrate advanced low-friction surface treatments (e.g., coatings, surface texturing, and additives) into tribological systems.
- Measure friction and wear improvements on advanced laboratory rigs and fired engines to confirm model calculations.
- Develop component maps of parasitic energy losses for heavy-vehicle system models.

Accomplishments

- Modeled the impact of low-friction coatings and low-viscosity lubricants on fuel savings (up to 4%) and predicted the impact of low-viscosity lubricants on the wear and durability of critical engine components.
- Examined the impact of low-friction technologies on fuel efficiency under high idle conditions.
- Developed experimental protocols to evaluate the friction and wear performance of advanced engine materials, coatings, and surface treatments under prototypical piston- ring environments.
- Evaluated the impact of a commercial additive on the friction properties of base fluids and commercial heavy-duty engine lubricants.

- Modified a single-cylinder diesel test stand to measure cylinder-bore friction under .motored and fired conditions.
- Developed laboratory technique to simulate piston-skirt/liner friction using prototypic components.
- Evaluated the impact of lubricant additives on the friction between the piston skirt and cylinder liner.
- Established collaborative effort with the Department of Defense (DOD) and the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) to evaluate low-friction lubricant technologies.

Future Direction

- Apply superhard and low-friction coatings on actual engine components and demonstrate their usefulness in low-viscosity oils.
- Optimize coating composition, surface finish, thickness, and adhesion to achieve maximum fuel savings.
- Evaluate the impact of advanced lubricant additives on asperity friction.

Introduction

Friction, wear, and lubrication affect energy efficiency, durability, and environmental soundness of critical transportation systems, including diesel engines. Total frictional losses in a typical diesel engine may alone account for more than 10% of the total fuel energy (depending on the engine size, driving condition, etc.). The amount of emissions produced by these engines is related to the fuel economy of that engine. In general, the higher the fuel economy, the lower the emissions. Higher fuel economy and lower emissions in future diesel engines may be achieved by the development and widespread use of novel materials, lubricants, and coatings. For example, with increased use of lower viscosity oils (that also contain lower amounts of sulfur- and phosphorus-bearing additives), the fuel economy and environmental soundness of future engine systems can be dramatically improved. Furthermore, with the development and increased use of smart surface engineering and coating technologies, even higher fuel economy and better environmental soundness are feasible.

Integration of advanced lubricant chemistries, textured/superfinished surfaces, and advanced component materials and coatings necessitates pursuing a systems approach. Changes in one system component can readily change the performance of other components. For example, application of a hard coating on a liner to improve its durability may decrease the durability of the mating rings. Also, lowering the viscous drag will cause certain components (e.g., bearings) to operate under boundary lubrication regimes not previously encountered, resulting in accelerated degradation. A systems approach is required to not only identify the critical components that need to be addressed in terms of energy savings, but also to identify potential pitfalls and find solutions.

The main goal of this project is to develop a suite of software packages that can predict the impact of smart surface engineering technologies (e.g., laser dimpling, near frictionless carbon, and superhard coatings) and energy-conserving lubricant additives on parasitic energy losses from diesel engine components. The project also aims to validate the predictions by comparison with experimental friction and wear data from Argonne National Laboratory. Such information will help identify critical engine components that can benefit the most from the use of novel surface technologies, especially when low-viscosity engine oils are used to maximize the fuel economy of these engines by reducing churning and/or hydrodynamic losses. A longer term objective is to develop a suite of computer codes capable of predicting the lifetime and durability of critical components exposed to low-viscosity lubricants.

Starting in 2003, Argonne and Ricardo, Inc. have collaborated to identify engine components that can benefit from low-friction coatings and/or surface treatments. The specific components have included rings, piston skirts, piston pin bearings, crankshaft main and connecting rod bearings, and cam bearings. Using computer codes, Ricardo quantified the impact of low-viscosity engine oils on fuel economy. Ricardo also identified conditions that can result in direct metal-to-metal contacts, which, in turn, can accelerate engine wear and asperity friction. Efforts were also initiated to identify approaches to validate the predictions under fired conditions.

Argonne has focused on the development and testing of low-friction coatings under a wide range of sliding conditions with low- and high-viscosity engine oils. These coatings (such as near frictionless carbon) as well as laser-textured surfaces were subjected to extensive friction tests using bench-top rigs. The test conditions (i.e., speeds, loads, and temperatures) were selected to create conditions where direct metal-to-metal contacts will prevail, as well as situations where mixed or hydrodynamic regimes will dominate. Using frictional data generated by Argonne, Ricardo estimated the extent of potential energy savings in diesel engines and identified those components that can benefit the most from such low-friction coatings and/or surface treatments. Argonne developed a test rig to simulate engine conditions for piston rings sliding against cylinder liners – one of the major sources of parasitic energy losses identified in Ricardo's studies. The test rig is being used to identify candidate technologies (e.g., coatings and additives) that can provide not only the level of friction reduction assumed in the Ricardo models, but also information on the impact of the technologies on material and component wear/durability.

During FY 2009 Argonne analyzed earlier Ricardo simulation studies to determine the impact of (1) low-friction surfaces and low-viscosity fluids on the overall friction mean-effective pressure (FMEP) and (2) low-viscosity fluids on component durability. Argonne also initiated piston skirt/liner tests to determine the effect of several low-friction additives on skirt/liner friction.

During FY 2010 Argonne's activities on parasitic energy losses were modified to establish a collaborative effort between the DOE and DOD on the subject of parasitic losses and their impact on fuel economy. As part of these activities, discussions were initiated with TARDEC and DOD to identify areas of mutual interest related to mitigation of parasitic losses. Work also continued to investigate the potential of several advanced additives to improve scuffing resistance under severe tribological conditions.

Results and Discussion

Modeling Boundary Friction and Viscosity Effects

Phase I and II activities for this project focused on modeling the impact of low-friction surfaces and low-viscosity engine lubricants on friction losses and fuel economy. Figure 1 [1-3] summarizes the results of Ricardo's calculations on the impact of boundary friction and engine lubricant viscosity on the fuel economy of a heavy-duty diesel-powered vehicle. These curves are based on detailed calculations of the FMEP for the piston rings and skirt, valve-train components, and engine bearings under a range of driving conditions. The results predicted fuel savings up to 4-5%, depending on lubricant viscosity grade and asperity friction.

In FY 2009, we took a closer look at the role of boundary friction and viscous losses and their impact on FMEP. The results of the analysis suggest the following:

- Reducing asperity friction only can reduce fuel consumption up to 1%.
- Reducing lubricant viscosity only can reduce fuel consumption by ½%.
- Reducing both asperity and viscous losses can reduce fuel consumption up to 3-4%.

The fuel savings shown in Figure 1 are for a specific driving schedule in which the fuel consumed at each mode is weighted with respect to the fraction of time spent at each condition. The amount of time spent at idle (mode 1), where friction can account for more than 50% of the FMEP, significantly impacts the fuel savings – driving schedules with high idle times benefit more from low friction strategies than driving schedules with high-speed modes.

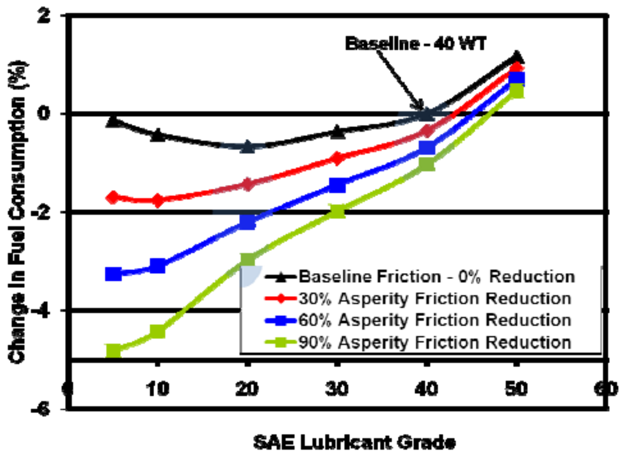

Figure 1.: Predicted change in fuel economy as a function of engine lubricant viscosity and boundary friction for an on-road driving schedule (federal test procedure).

The trends presented in Figure 1 are representative of a commercial heavy-duty truck for on-road conditions. This particular scheme uses Ricardo's eight-mode engine map to predict fuel economy for an on-road sequence. In FY2010, we used a similar approach to estimate the impact of boundary friction and lubricant viscosity for a driving schedule that would more closely represent an off-road driving mode for a military ground vehicle. Instead of the eight-mode map [1], the fuel consumption was estimated by a three-mode map, which was heavily weighted with idle, and two high-load, low/intermediate-speed operational conditions.

- Under these conditions, the results of the analysis led to the following observations (see Figure 2):
- Reducing asperity friction only can reduce fuel consumption up to 2% (compared to 1% for the case shown in Figure1).
- Reducing lubricant viscosity has no beneficial effect; it actually increases fuel consumption (compared to a reduction in Figure1).
- Reducing both asperity and viscous losses can reduce fuel consumption up to 4-5%.

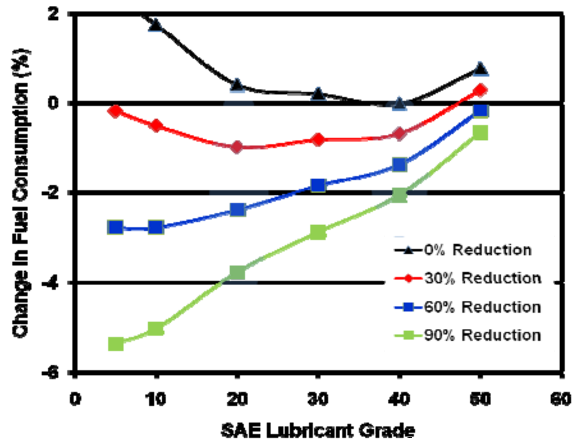

Figure 2: Predicted change in fuel economy as a function of engine lubricant viscosity and boundary friction for an off-road driving schedule (70% idle, mode 2 and 3).

The results suggest that the application of low-friction technologies should have a significant impact on the fuel consumption of military ground vehicles. Discussions with TARDEC were subsequently initiated to explore areas of common interest in the development of advanced lubrication systems. The results of these discussions identified a number of key drivers/issues that DOE and DOD are addressing in the development of advanced lubrication systems. These issues, which are summarized in Table 1, can be categorized into issues related to improving fuel economy/efficiency and issues related to reliability/durability. Of these, discussions with TARDEC indicated a strong interest in the development of advanced lubricants that improve the fuel economy of ground vehicles without compromising durability and reliability.

The collaborative effort with TARDEC continues to evolve in terms of defining specific approaches that will be further developed. Part of the activities involves identifying a range of operating conditions/modes and weighting factors that can be used to evaluate the impact of low-friction technologies on fuel savings. In that effort, we will attempt to define a typical duty cycle (or a range of duty cycles). While driving cycles have been developed for commercial/civilian applications, it may be difficult or impractical to define a specific cycle for military applications. In this case, we will rely on exploring limiting scenarios to define upper and lower limits on the impact of boundary friction and lubricant viscosity on parasitic engine friction and fuel economy.

Table 1. Attributes Impacting Development of Advanced Lubrication Systems for Commercial and Military Ground Vehicles.

Attribute	Commercial	Military
Fuel Consumption - Efficiency		
Driving Cycle	Primarily on-road – urban and highway 20-40 mpg passenger cars 6-10 mpg heavy trucks	Mix of highway, urban, off-road High level of idle High auxiliary power demands Fuel economy as low as 2 mpg
Fuel Delivery Infrastructure	Well-established infrastructure	Complex fuel delivery systems involving ground and aerial vehicles to deliver fuel to remote regions Infrastructure is vulnerable to disruption
Fuel Use	12-14 MBBD	0.4 MBBD
Fuel Cost	\$2.50 - \$3.50/gal at pump	\$35-\$40/gal average \$100-\$600/gal in remote regions
Durability & Reliability		
Emission Control Technologies	After-treatment devices limit use of beneficial lubricant additives Use of exhaust gas recirculation increases level of combustion products and soot into lubricants	National security exemptions can be requested on implementation of emission technologies
Extreme Tribological Environments		Accelerated wear of ground vehicles High operating temperatures – rapid degradation of lubricant properties Exposure to high concentrations of sand/grit – accelerated abrasion
Alternative Fueled Vehicles	Poorer lubricity of alternative, non-petroleum fuels Fuel dilution/degradation of lubricants	
Multi-Functional Lubricants		Single lubricant for both engine and transmission – compromised performance
Downsizing/Reducing Weight	Increased power density/stresses on critical engine and drivetrain components Poor tribological properties of lightweight material	
Loss-of-Lubricant Accidents		Survivability of engine, drivetrain, and other mission-critical systems/components when lubricant supply in disrupted/non-functional

Benchtop Studies of Advanced Tribological Systems

Experimental activities during FY 2010 focused on characterization of tribofilms produced with advanced additives and piston-skirt/liner testing. Results are presented below:

Block-on-Ring Scuffing Studies

A series of tests [4] was performed to evaluate the effect of five additives on the scuffing resistance and oil-off performance of a formulated mil-spec 15W/40 engine and transmission lubricant (and its base fluid). Details of the test protocols are presented in reference [4]. Results of the tests identified two promising additives (a commercial product, emulsion-based boric acid, and tricresyl phosphate) that increased the critical load for the onset of scuffing by 50 to 100% and significantly increased the time for scuffing onset under starved lubrication conditions.

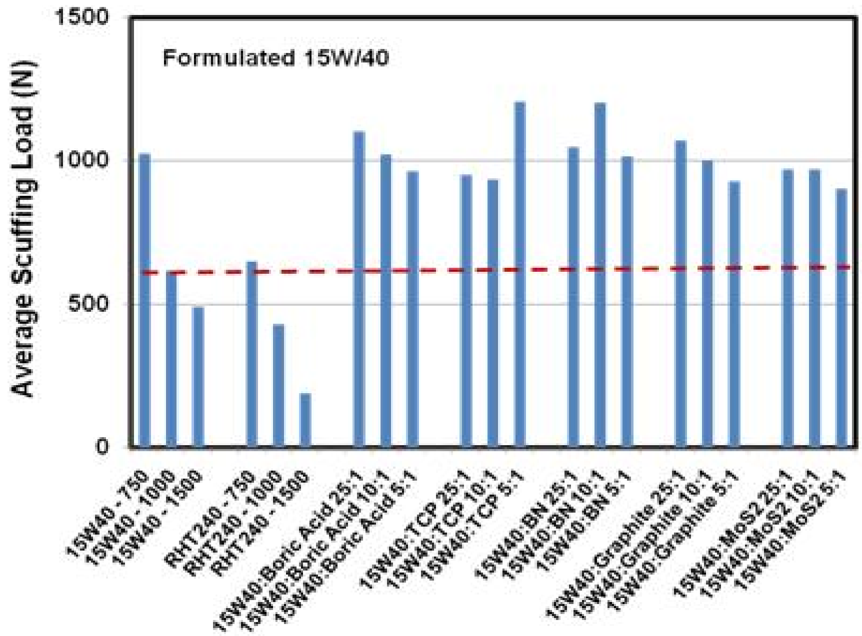

Figure 3: Average scuffing load of formulated 15W/40 and 15W/40 with additives.

Figure 3 shows an example of the impact of the additives on the scuffing resistance for the formulated 15W/40 lubricant. The additives are emulsion-based boric acid, tricresyl phosphate (TCP), boron nitride (BN), graphite, and MoS_2. The data in Figure 3 represent the average scuffing load obtained from a minimum of three repeat tests at each run. The first three tests show the impact of speed on scuffing, while the next three show the impact of speed (750, 1000, and 1500 rpm) on the scuffing load of the unformulated base fluid used in the as-received formulated oil. The remaining tests show the average scuffing load for the five additives at the three oil-to-additive levels. The dashed red line in Figure 3 represents the average scuffing load for the formulated 15W40 oil at a speed of 1000 rpm – the speed used for the tests with the different additives. As seen in Figure 3, all of the additives increased the scuffing load of the as-received formulated lubricant. The magnitude of the improvement ranged from 50% to 95%, depending on the additive and oil-to-additive level.

Results of the oil-off tests indicated that under certain conditions a low-friction tribofilm developed after the oil was drained from the test environment. he friction was reduced significantly (by a factor of 2 in many cases), and was often accompanied by a significant increase in the time for scuffing to occur.

To investigate further, an advanced surface analytical technique (focused ion-beam spectroscopy – FIBS) was used to characterize the structure and chemical composition of the thin (10- to 100-nm thick) tribofilms formed during the scuffing and oil-off tests. The FIBS process allows one to extract thin slices of material near the sample surface. The thin slices (approximately 10 µm x 5 µm x 0.1 µm) are transferred to a transmission electron microscopy (TEM) grid for subsequent imaging and analysis.

Figure 4 shows a low-magnification TEM image of a FIBS section extracted from a region that exhibited low-friction behavior prior to scuffing. The tribofilm is approximately 100-nm thick. The inset in Figure 4 shows a high-magnification dark-field image of the tribofilm. The inset reveals the presence of a large number of precipitates (10 to 20 nm in diameter) in the tribofilm. The film is heterogeneous, consisting of a matrix with smaller second phase material.

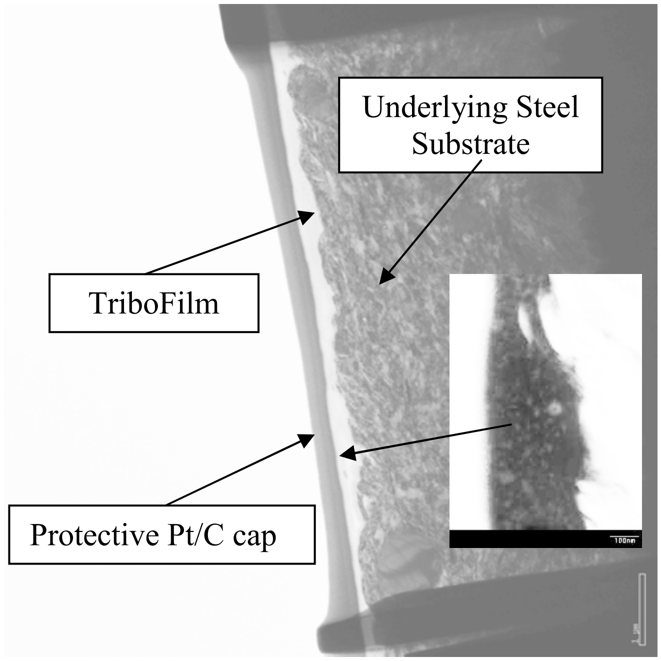

Figure 4. TEM image of tribofilm on steel block segment [4].

These samples, as well as samples from tests that did not exhibit low-friction regimes, were analyzed to determine if significant differences in the composition and structure of the precipitates and matrix of the tribofilm can account for the low-friction behavior.

It is anticipated that the information and knowledge gained from such studies will provide insight on the fundamental mechanisms involved in the complex chemical reactions that occur at tribological interfaces. Such information, coupled with nanomechanical properties (e.g., hardness and modulus) of the tribofilms, will contribute to the development of models of tribofilm formation and, eventually, the development of advanced additive packages optimized for specific environments. Additional details can be found in reference [4].

Reciprocating Friction Tests with Additives

Friction tests were carried out using PAO10 with 3 wt% BN and a surfactant at 20°C, 40°C, and 100°C. To establish a baseline, friction tests were also conducted using PAO10 with no additives at the same temperatures. The specimens used in this work were extracted from components in commercial heavy-duty diesel engines. During all machining operations the original surfaces of the piston and liner were protected to retain the original surface roughness and pattern. The material of the skirt specimens was an aluminum alloy.

Circumferential grooves were present on the surface of the skirt segments as an outcome of the manufacturing process. The liner was plateau honed (R_q= 1 μm). The liner segments were made of gray cast iron. The reciprocating frequency was 2 Hz. A small amount of oil (0.3 ml) was applied at the interface of the samples at the start of each test. A normal load of 250 N was applied. Each test at the temperatures specified was 3 hours, which was long enough to obtain representative data for the evolution of friction over time.

The friction tests results using PAO10 with 3 wt% BN and surfactant at 20°C, 40°C, and 100°C are shown in Figure 5. Also included for comparison are the results from baseline tests performed using PAO10. It can be seen that the friction coefficient increased as a function of temperature for both PAO10 and the formulation. This trend is most likely due to viscosity effects. As the temperature increases, the oil becomes less viscous, leading to a shift from a mixed lubrication regime toward the boundary regime, during which significant asperity interaction leads to higher friction.

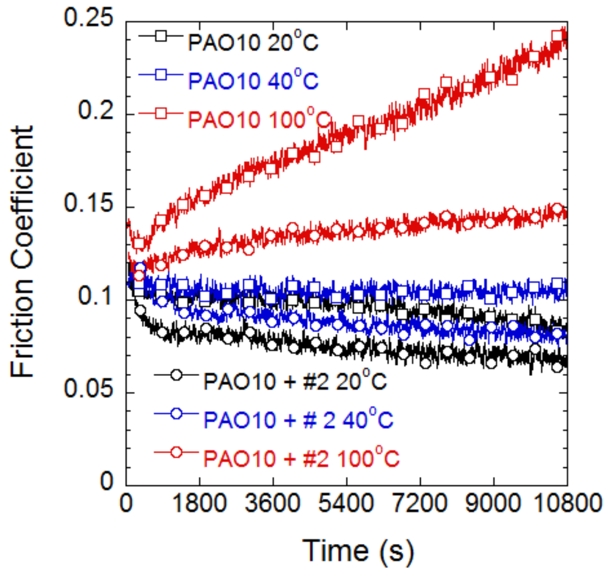

Figure 5: Friction test results for PAO10 and PAO10 containing 3 wt% BN/surfactant at 20°C, 40°C, and 100°C.

The friction was lower for the PAO10 formulation than for the baseline tests using PAO10. This behavior is consistent at each of the tested temperatures. This trend may be attributed to the combined effect of viscosity and additive interactions. The viscosity of the formulation is higher than that of the base PAO10. This difference would influence the friction behavior, especially at the lower temperatures of 20°C and 40°C. The effect of increased viscosity would be a lowering of the friction, as evident in Figure 5. At these temperatures the differences are not pronounced. However, at 100°C the results deviate significantly. The friction coefficient in the case of the base PAO10 increased dramatically during the test. Note that this increase was accompanied by excessive wear. In the case of the formulation, the increase was not as pronounced. That effect may be due to interactions with the additives in the formulation, which prevent the excessive wear observed for the base PAO10. Further investigation is necessary to examine the sample surfaces for formation of tribofilms by means of a surface analytical technique such as x-ray photoelectron spectroscopy.

A gradual decrease in friction was observed for both PAO10 and the formulation at 20°C and 40°C, while an increase was observed at 100°C. The combined effect of viscosity and morphological changes in the surface may be responsible for this behavior. As previously mentioned, excessive wear occurred in the case of PAO10 at 100°C. This wear, in turn, can influence the tribological behavior of the contact. Initially, the viscosity plays a more important role, determining the friction behavior at the beginning of the test. However, morphological changes due to the topmost features wearing off combined with viscosity effects determine the evolution of friction behavior.

Wear measurements of the samples tested using the base PAO10 and the PAO10 formulation are shown in Figure 6.

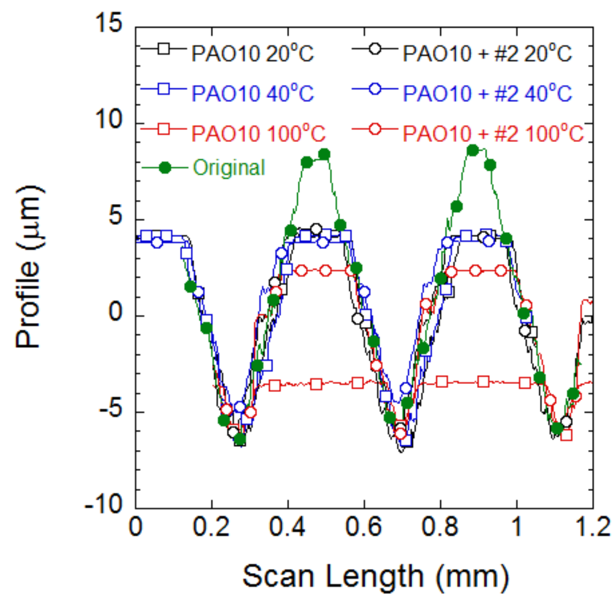

Figure 6: Wear measurements of samples tested using PAO10 and PAO10 containing 3 wt% BN/surfactant at 20°C, 40°C, and 100°C.

Superimposed on the graph, the original profile of the skirt specimens can be seen. The same sample was used at the three temperatures for testing with base PAO10, while a second sample with the same original profile was used for the PAO10 formulation. As expected, wear occurred in both samples. As seen in this plot, the wear at 20°C and 40°C is similar for all cases. After a run-in period during which the topmost asperities are sheared off, a plateau was reached. The plateau could be due to viscosity effects being more dominant at these temperatures, limiting severe asperity interaction. At 100°C, clear differences in wear can be seen between the sample tested using base PAO10 and the PAO10 formulation. The wear was significantly higher when PAO was used without additives. Commonly, but not always, high friction may be associated with high wear. This finding is in agreement with the friction measurements of Figure 5.

Reciprocating Friction Tests with Coated Samples

Skirt specimens were either uncoated or coated with nickel-polytetrafluoroethylene (Ni-PTFE), a graphite-resin coating, or diamond-like carbon (DLC) coating. The first coating is a dispersion blend that provides up to 28 vol. % of PTFE. The second coating consists of a high-temperature-resistant resin with graphite and is applied by spray or silk screen printing. The third coating is an amorphous hydrogenated carbon (a-C:H) that was deposited by plasma-assisted physical vapor deposition .

Table 2: Materials and Coatings Used in Reciprocating Tests.

Material	Hardness (GPa)	Thickness (μm)
Graphite Resin	0.28	20-30
Ni-PTFE	4-6	15
DLC	7-8	1.2
Gray cast Iron	2.0	No coating
Al Alloy	1.4	Substrate

Table 2 lists the hardness and thickness of the materials used. The hardness of each of the materials was determined by microindentation or nanoindentation (for the DLC). The thickness of each coating, determined by cross-section microscopy, is also shown in this table. Both the Ni-PTFE and DLC coatings showed uniform coverage and a constant thickness that followed the surface topography of the original samples. The graphite-resin sample varied in thickness. Coating thickness and uniformity should be taken into consideration. For example, a soft break-in type of coating could have a beneficial role as it may offer a uniform transition in friction, whereas a thin and wear-resistant coating may be worn through after a certain period, leading to an unpredictable increase in friction coefficient and sudden failure.

Figure 7 shows the friction coefficient with time for all coated samples and an uncoated sample. Figure 7(a) presents the data obtained for fully formulated 10W30 oil at 120°C. During run-in (10 min), the uncoated sample showed the highest friction coefficient, while the graphite-resin coated sample showed the lowest friction coefficient. After run-in, the uncoated sample had the highest friction coefficient, and the sample coated with Ni-PTFE had the lowest. The most stable friction behavior was observed for the DLC-coated sample.

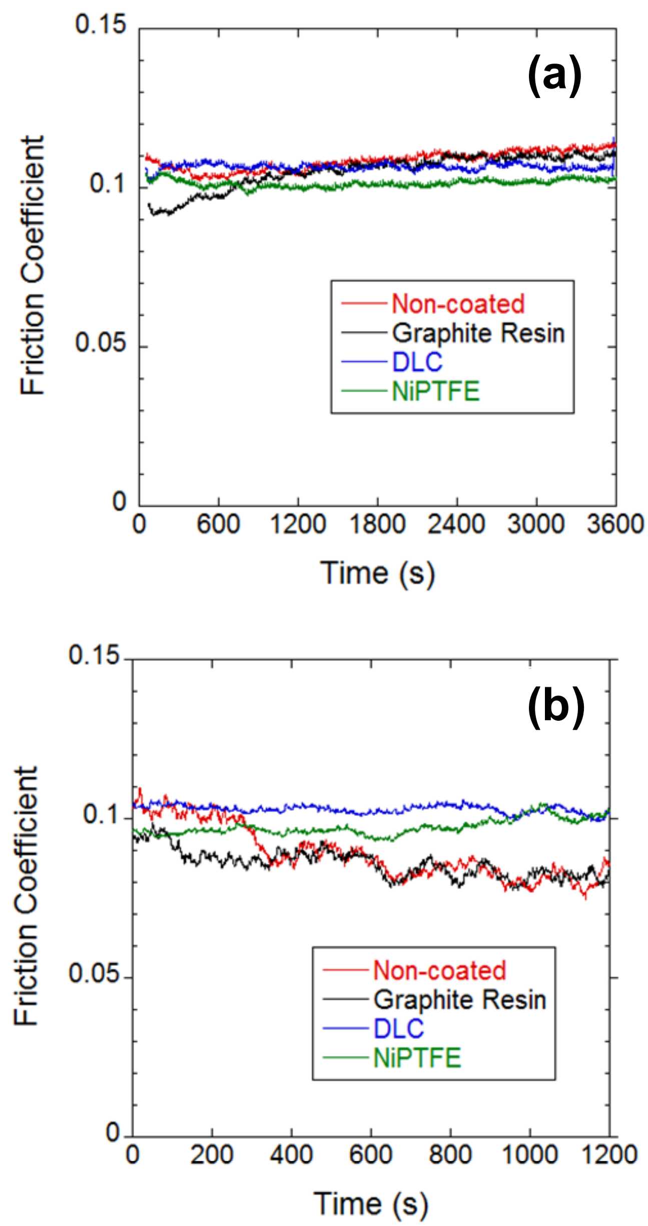

Figure 7: Friction coefficient as a function time for all samples tested using a load of 250 N in (a) fully formulated 10W30 oil at 120°C for 1 hour and (b) PAO10 oil at 20°C for 20 minutes.

Similar behavior was noted during run-in with PAO10 at 20°C, as shown in Figure 7(b). However, a pronounced lowering in the friction coefficient was noted for the uncoated and graphite-resin samples. Since graphite is a solid lubricant, its presence on the surface of the graphite- resin coating may be responsible for its initially low friction coefficient. After run-in at 20°C, the uncoated sample had the highest friction coefficient, while the Ni-PTFE coated sample had the lowest. The DLC-coated sample had the most stable friction. The friction coefficient of the graphite-resin-coated sample gradually increased. Graphite debris was evident at the end of the test, so removal of graphite may explain this increase. A lowering in the friction coefficient was noted for the uncoated and graphite-resin-coated samples. That decrease can be attributed to topographical changes; the topmost peaks are worn off, leading to subsequent change in the lubricating regime, i.e., transition from the boundary to mixed regime. Relatively stable friction behavior was observed for the DLC and Ni-PTFE coated samples because of the lower wear rates and a possible lack of change in the lubrication regime.

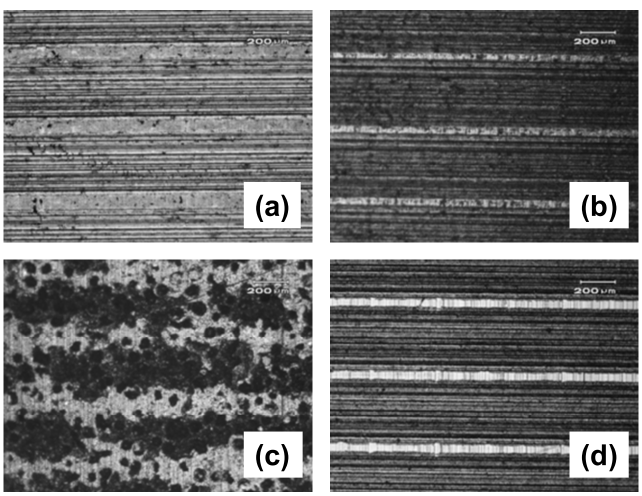

Figure 8: Microscope images of all samples tested using fully formulated 10W30 oil at 120°C using a load of 250 N: (a) uncoated, (b) DLC, (c) graphite-resin, and (d) Ni-PTFE

Figure 8 shows microscope images of all samples tested in fully formulated 10W30 at 120°C. Similar results were obtained when PAO10 at 20°C was used. In both cases, the most wear occurred in the graphite-resin-coated sample followed by the uncoated and Ni-PTFE coated samples, while the lowest wear was observed for the DLC-coated sample. However, the test duration was shorter in the 20°C case. The most wear occurred for the graphite-resin-coated sample. Removal of graphite particles can be seen from the topmost topographical features, which appear as bright areas. Graphite is not well adhered to the surface. Lower wear was observed for DLC and Ni-PTFE. The PTFE was well bonded in the Ni-PTFE co-deposit. Note that the topographical changes that occurred after testing using the same load (250 N) and reciprocating frequency in fully formulated 10W30 oil at 120°C for 1-hr long tests and PAO10 oil at 20°C for 20-min long tests are very similar. This finding indicates that the contact was more severe when PAO10 was used. Fully formulated oils contain anti-wear additives, which may be temperature sensitive.

Summary

A collaborative effort was initiated with TARDEC to identify common issues related to reducing parasitic friction losses in engines used for commercial, on-road, and military ground vehicles. While significant differences exist in terms of emissions and lubricant specifications and driving cycle, there are significant overlapping requirements for improved fuel economy and durability/reliability that would benefit from joint science-based projects to elucidate fundamental mechanisms associated with friction reduction and tribofilm formation. Work is continuing to define these projects, including hosting a workshop on advanced lubrication.

Experimental activities continued to examine the role of additives on the formation of low-friction protective tribofilms under extreme conditions. A FIBS technique was applied to investigate the chemical composition and structure of ultra-thin films that form as the result of tribochemical interactions between additives and the underlying substrate.

Results of friction tests performed using nanometer-sized BN particles showed promising results in terms of friction reduction. Preliminary data suggest that the introduction of 3 wt% nano-BN particulates reduced friction. These results are encouraging in that the nanolubricant, PAO-10 containing 3 wt%-70 nm BN, reduces both friction (20 to 50%, depending on the temperature) and wear. Further investigations are required to verify this effect and to separate the effect of the BN from that of the surfactant.

Tests on coatings indicate the benefits of the coating are mixed and are affected by chemical interactions between the coating and additives in the lubricant, and changes in the surface morphology. Coatings that function well with unformulated lubricants (no additives) behave differently when tested with formulated lubricants. Additional studies are in progress to further model the impact of coating composition and changes in surface finish.

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